THE NATURE AND ORIGIN OF FIORDS

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WITH DIAGRAMS AND ILLUSTRATIONS

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PREFACE

The indented coasts and deep fiords beside the northern and southern seas present a striking contrast to the even shores and shallow bights of the tropics. There are numerous exceptions to this rule, but they are insufficient to destroy its general truth. The walls of the fiords and of the valleys that continue them inland show many features characteristic of the work of ice. Hence the distribution of fiords and their trough-shaped form have led to the widespread belief, that fiords have been excavated by glaciers, and are the most striking proof of the great excavating power of ice.

A leisurely journey along the coast of Norway, from Stavanger to Tromsö in 1896, gave many opportunities for excursions ashore, during which I saw numerous facts inconsistent with the glacial origin of the fiords; but it was difficult either in Norway or Spitsbergen, which I visited the same year, to determine which features were due to denudation, glacial and preglacial, and which were due to valley-formation by movements of the earth's crust. Hence I secured other opportunities to examine a series of coasts indented by fiords and allied inlets. Amongst the coasts which I have observed in connection with the study of fiords have been Brittany in 1898, some fiord-like inlets in the West Indies in 1899, various indented parts of the New Zealand coast and the glacial trough-valleys north of its fiord-area in 1904, the fiord-area of the Baltic in 1907, the ria-coast of Spain in 1910 and 1912, British Columbia 1909, Dalmatia 1911, tours in Norway in 1907 and 1910, and numerous visits to the Scottish lochs since 1904.

Study of the literature on this subject and personal examination of these fiords and of various glaciated valleys have led me to the conclusion that all the fiord-systems of the world owe their characteristic features to earth-movements, and not to glacial action.

All the fiord-systems of the world have the same essential characteristics. Fiords occur in trough-shaped valleys, that are arranged along fractured lines or networks; their plan resembles that of cracks in a fractured sheet of brittle material, and does not agree with that of systems of valleys cut by rivers or glaciers. Fiords are restricted to plateaus, which are composed of firm and usually old rocks and to districts which are on the borders of sunken areas. All the fiord-areas have been affected by a similar succession of earth-movements; they were uplifted into plateaus after the great crustal disturbances which upheaved the existing mountain-systems of the world. During these uplifts the areas composed of hard rocks were cleft by radial or intersecting cracks, and the subsidence of belts of country along these cracks, or the removal by wind, water, and ice of the decayed materials along the clefts produced the great fiord-valleys. After the plateau-forming uplift, the fiord areas have undergone a series of oscillations, during which many of the valleys have been drowned by the entrance of the sea, while the unequal movements and tilting of the region have formed deep basins in many of the fiord-valleys.

The fact that most of the fiords are in the colder regions of the earth is a coincidence, due to the polar areas having been affected by greater oscillations than the equatorial zone. The mountainous coasts beside the warmer seas are indented by fiords in the occasional areas, where the edges of foundered regions have undergone a succession of movements similar to those around the heaving polar areas.

Students of each fiord-system have recognised that the fiord-valleys were preglacial in date and cannot therefore have been made by the glaciers which once occupied many of them. But these local opinions have been ignored or dismissed as of little weight against the general verdict that the fiords were ice-cut, while the evidence of unglaciated fiords has been rejected on the plea that they are "pseudo-fiords."

Conclusions based on the study of any one fiord-system are not likely to be convincing; a parochial or provincial or even national view of the subject is inadequate. Any one field might be exceptional. I have therefore summarised the evidence from all the chief fiord-systems in the world, so that the cumulative evidence may be considered. The book is divided into three parts: a preliminary statement of the fiord problem and its interest; a description of the fiord-systems of the earth; and finally a discussion of the evidence, which necessarily involves some consideration of that vexed question, the efficiency of glacial erosion; on this question I take an intermediate position between the two extreme views, and regard ice as a far less effective agent of excavation than water. This subdivision of the subject involves some repetition, but that seemed unavoidable in order to press home the conclusions at which I have arrived.

In describing the various fiord-systems, I have referred mainly to the writings of the local workers; for their detailed and repeated observations deserve more weight than those made during the hasty inspection of a hurried visitor; hence I have avoided, as far as possible, referring to my own observations, which have, however, enabled me to test the conclusions of the local workers in reference to many representative and especially instructive examples.

The literature of the subject is so voluminous that the bibliography, on the lines on which its compilation was begun, would have been ten times as long as it is. It has been restricted to the works referred to in the text, and only a selection of authorities on each field has been quoted. The list includes the chief general papers on the origin of fiords and those of most historical importance. Some of the later papers on the question of glacial erosion are also included. General text-books have been omitted, except when repeated reference is made to them.

The dates printed in thicker type, thus, **1910**, refer to the dates under the alphabetical arrangement of authors in the list of references in the Appendix.

A table of geological horizons and explanations of a few technical terms are given in a short glossary.

To avoid the use of different standards of length, heights and depths, except in quotations, have been given in feet.

I am indebted for the loan of photographs to Messrs. H. W. Monckton, H. MacRobert and W. Lamond Howie, and Rev. A. E. Robertson, for the preparation of some line-drawings to Mr. B. K. N. Wyllie, and for the census of the relative positions of the deeps in the Scottish freshwater lochs to Mr. A. Stevens.

The evidence of fiords, like that of the Great Rift Valley, to which my book on this work is a sequel, shows that the topography of the earth is more influenced by earth-movements than has been generally admitted. It has long been acknowledged that the fold-mountains of the earth are due to uplift; but there is a strong reluctance to admit that valleys, or even basins, are due to any other influence than denudation. The evidence seems to me clear that fiord-valleys are among the important geographical features, due directly to the heaving and fracturing of the earth's brittle and restless crust, as it adapts itself to the shrinking of the earth's internal mass.

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NATURE AND ORIGIN OF FIORDS

PART I

INTRODUCTION

CHAPTER I[1]

THE PROBLEM OF FIORDS

When we mean to build,
We first survey the plot, then draw the model.
SHAKESPEARE.

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1. The Influence of Fiords.—2. Fiords are sea-drowned valleys.—3. Rias, Fiards, and Fiords.—4. Chief Characteristics of Fiords.—5. The Origin of Fiords.—6. The Glacial Theory.—7. Faceting Action of Ice and Formation of Trough-valleys.—8. Pot-hole Formation under Glaciers.—9. Argument from the Distribution of Fiords.—10. Their Distribution Inconsistent with a Glacial Origin.—11. Preglacial Age of Fiords.—12. Relation to Earth-movements.—13. The Grouping of Fiords.—14. The Distribution of Fiords determined by Intersecting Fractures.—15. The Fiord Valleys Enlarged by Denudation.—16. The Earth-movements of the Fiord Areas.—17. The Two Fiord Belts.—18. Conclusion.

1. THE INFLUENCE OF FIORDS

FIORDS have become a powerful factor in modern life, for from them came the facility of intercourse by sea

[1] Most of this introductory chapter was published in *Nature*, vol. lxxxix., April 18, 1912, pp. 179–83.

which marks the most influential difference between modern and mediæval Europe. The Roman Empire was held together by its roads; *terra marique* was the phrase familiar to Roman ears, instead of "by sea and land"; and, as its conquerors from the wide plains of the East were neither sailors nor roadmakers, Europe was resettled on national, instead of on imperial, lines. While Europe thus fell naturally into independent States, the beginnings of modern seamanship were being developed in Scandinavia; for travel overland in that country, owing to its fiords, was even more difficult than through the forest-clad plains of north-central Europe. The fiords in Norway were the only practicable highways; with their labyrinth of smooth-water channels, with their tidal currents which carried boats to and fro independent of wind and oar, with their unfailing supplies of fish and oil, of whale-hide and seal-skins, the fiords attracted men to the sea, as much as the barren highlands repelled them from the land.

The poverty of their own country drove the Norsemen to the sea; the wealth of the more fertile southern coast-lands tempted them to that career of piracy which for centuries made the northern berserkers the terror of the shores of western and southern Europe. These pirates, however, amply repaid their debt to the world at large by their contributions to modern seamanship. It was probably their influence which led to the development of the Saxon shepherds into the British Sea-kings, and to the revival of the ancient sea-craft of north-western France. It was doubtless the descendants of the Norse settlers in Sicily who helped to beat back the Turkish corsairs and Barbary pirates, and thus saved the western Mediterranean from falling under the Mahometan power.

Modern seamanship, with its incalculable contribution to the wealth and comfort of mankind, was first developed in consequence of the peculiar geographical conditions of the Norwegian fiords. Eva Nansen's song is a true statement of the influence of the geographical environment of the fiords on the Norwegian race:

> Our mother, weep not! it was thou
>   Gave them the wish to wander;
> To leave our coasts and turn their prow
>   Towards night and perils yonder.
> Thou pointed'st to the open sea,
>   The long cape was thy finger;
> The white sail wings they got from thee;
>   Thou canst not bid them linger!

The white sails of the Norse and Danish Vikings carried the name "fiord" far and wide. It is found on the Irish coast, in Wexford, which is said to be derived from the Danish Weis-fiord, and in Waterford which comes from Vadre-Fiord; and the name "fiord" is now accepted as a technical term in general geographical nomenclature.

In Norway the word "fiord" is used for any arm of the sea, including various types of gulfs, bays, and straits. But in international geography the name is adopted for arms of the sea of a special character. A fiord, in this restricted sense, is a long inlet which extends far inland between steep, opposing walls; it usually consists of long, straight reaches, which turn and receive their tributaries at sharp and regular angles; and its walls are high, as fiords are restricted to mountain regions.

Fiord districts combine the features of mountain and coastal scenery. Many authors have been impressed by a sense of the monotony of fiord scenery, owing to the constant repetition of the same form; it is, however, popular from its ease of access along the smooth waterways, the especial beauty of its cloud-forms and exquisite colour effects, which do not pass with the flash of a tropical sunset, but last for hours in the prolonged twilight of most fiord areas. The charm of fiord countries is, moreover, enhanced by the survival of primitive conditions of life owing to their comparative isolation and cramped areas of cultivation.

2. Fiords are Sea-drowned valleys

The origin of the fiords has given rise to a controversy, which has sometimes been of a warmth reminiscent of the berserker rage. The difficulty of the problem is due to the peculiar combination of geographical characters. The fiords are clearly valleys, of which the lower ends have been drowned by the sea. Now sea-drowned valleys are of three main types.

3. Rias, Fiards, and Fiords

The most familiar type is that of ordinary river estuaries, which have been submerged by subsidence of

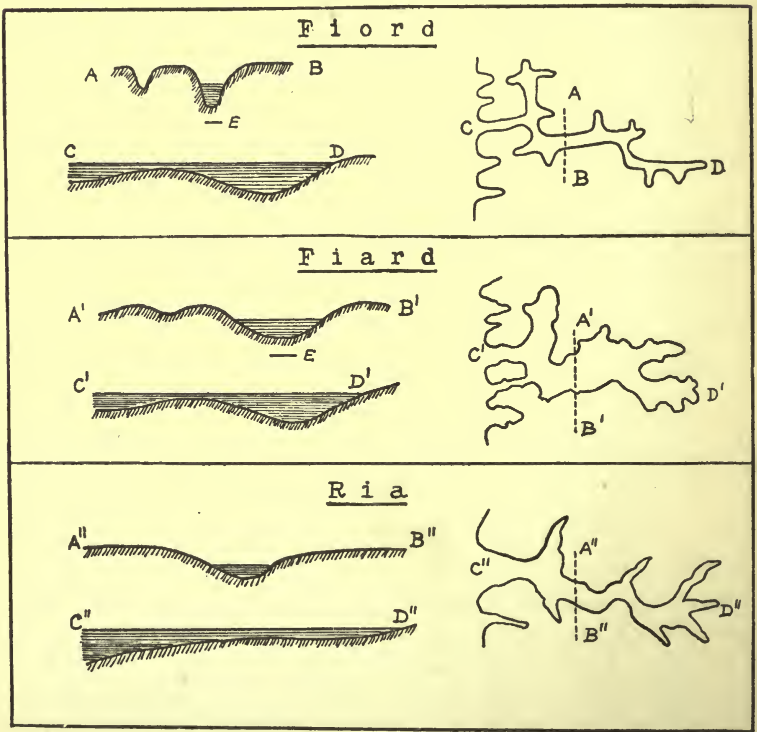

Fig. 1.—Comparative Diagrams of Fiord, Fiard, and Ria.
A–B, Cross Sections; *C–D*, Longitudinal Sections; *E*, the level of maximum depth in the Fiord.

the land. Such estuaries have gentle, rounded slopes and curved lines; they are typically funnel-shaped, as they increase seaward, both in width and depth. Their tributaries have the same sinuous characters and the same general direction. Their depth, moreover, apart perhaps from shoals at their mouths, increases regularly seaward and the sea outside is usually deeper than any part of the estuary. Such drowned valleys are familiar to us; the Firths of the Tay and Forth, the estuaries of the Thames, Severn, and Humber, and Bantry Bay in south-western Ireland, are examples. Such drowned valleys are well represented in north-western Spain, where they are called rias, and the term "ria" has been adopted as the technical name of this kind of drowned valley.

The members of the second type are known as "fiards," from their typical representatives in south-western Sweden. They agree with rias in having curved lines, gentle slopes, and indented shores. They differ, however, from rias, as they often include deep basins, which are separated from the sea by rock-bars, and the depth may not equal that of these basins for many miles out to sea. Fiards, moreover, usually have no large rivers draining into them, and they may receive only insignificant streams and brooks. Fiards are due to a lowland area, with an irregular surface of hard rocks, having been partially submerged beneath the sea. The essential difference between fiards and fiords is that fiards are characteristic of coast-lands which rise but slightly above sea-level.

4. Chief Characteristics of Fiords

The third group of inlets consists of the fiords, which, as seen from a steamer or on an ordinary map, have seven chief characteristics.

1. They are typically long, straight, narrow channels;

and they are usually so crowded and run so far inland that they add greatly to the length of the coast-lines. Thus, whereas in Norway the length of the coast from headland to headland is 1,700 miles, the actual length of the shore-line along the fiords and around the islands is 12,000 miles.

2. They have high and steep walls.

3. The fiord-channels usually have parallel sides, and the fiords bend or branch at sharp angles, and the same angle tends to recur throughout a district. There is accordingly a striking parallelism in the geographical elements of neighbouring fiords.

4. The fiord-valleys are often arranged along intersecting lines forming a network of cracks, in contrast to the converging tributaries of a river-system.

5. The fiords are characteristic of dissected plateaus. All the great fiord districts of the world were formerly plateaus.

6. Owing to the plateau structure the land extends backward from the fiord-walls with gentle slopes and wide, shallow valleys. Streams flow gently across the uplands until they reach the fiord-wall and then plunge down in picturesque waterfalls. In the spring, when the rivers are flooded by melting snow, these are one of the chief attractions of the Norwegian fiords. The highest waterfall in the world, the Sutherland Fall in New Zealand, sometimes consists of one leap of 1,900 ft. on to the floor of the fiord-valley of Milford Sound. The upland valleys which join the fiords have not been cut down to the level of the main valley, but enter abruptly high upon its side. They are therefore "hanging valleys."

7. Finally, the amount of land beside the fiords suitable for cultivation is usually limited to small tracts at the head of the fiord, or to small deltas along its sides. The amount of cultivable land in a fiord district is small, and fiord countries are therefore sparsely populated.

PLATE I

STROMNAES AND DAL FIORD.
A typical Norwegian fiord betroughed by truncation of the spurs.

6

The previous characteristics can be observed by a tourist from the deck of a steamer, but if we could remove the sea and travel over the fiord-floors three fresh features of geographical interest would be revealed.

The walls which rise high above the sea-surface would be seen to descend steeply to extraordinary depths. The deepest known fiord is the Messier Channel, in Patagonia, which reaches the depth of 4,250 ft. The Sogne Fiord is the deepest in Europe, with the depth of about 4,000 ft. Some of the lakes, which may be regarded as inland extensions of the fiords, are also surprisingly deep. Thus Lake Morar, a little south of Mallaig in the western Scottish Highlands, of which the surface is 30 ft. above sea-level, is 1,017 ft. deep; and this fact is all the more striking as the sea to the west does not reach so great a depth within 120 miles.

The deepest part of a fiord-basin is usually at some distance from the sea; its floor rises seaward until it is covered only by shallow water, or it may rise above the surface and the fiord become a lake.

Fiords are, therefore, often separated from the outer sea by submerged thresholds. This fact was first discovered by Captain Cook. The existence of a threshold is such a frequent feature of fiords that it is regarded by some authorities as an essential characteristic.

The removal of the water from a fiord would also show that it has a flat floor. The valley is a trough-valley, whether empty or partially filled with water. The flatness of the floors can be learnt from cross-sections on maps, or from the floors of the undrowned parts of fiord-valleys.

5. The Origin of Fiords

The problem presented by fiords is therefore that of the formation of systems of steep trough-valleys, which are arranged as a network, so that the land beside them is broken up into rectangular blocks, which are usually separated by deep inner basins cut off from the sea by shallow thresholds.

The simplest explanation of the formation of valleys is that they have been excavated by rivers; but river-action will not produce fiords. Thus our British fiords, the Scottish sea-lochs, are not in the river-valleys; the chief Scottish rivers, the Tay and the Forth, enter the sea through rias; the Clyde discharges into a compound basin, which is not a fiord; and the Tweed, Dee, Don, and Doon have no long arms of the sea at their mouths. The chief sea-lochs, on the other hand, receive only small streams. The river-systems of Scandinavia, North and South America, and New Zealand, all show the same independence of the fiords.

The fiords are, therefore, not the outlets of the main rivers. In fact, so far from fiords being made by rivers, their existence depends on the absence of large rivers, which would fill them with sediment and give them the form of ordinary valleys by wearing their walls into long, gradual slopes.

6. The Glacial Theory

The failure to explain the formation of fiords by rivers of water therefore led to the invocation of rivers of ice, and many features of fiord-valleys are consistent with their formation by glaciers. The essential difference between the action of rivers of water and rivers of ice, as agents of excavation, depends on their difference in plasticity. Water, being very plastic, readily adapts itself to the irregular resistance of the adjacent rocks; it easily rebounds off opposing hard surfaces, and thus carves sinuous channels.

Glacier-ice is also plastic, and therefore also flows around opposing obstacles; but, as it is less plastic than water, it never flows in eddies; and as it is deflected less readily; it bears with steady pressure against the rocks on its path; it rubs against them, and, if it is armed on its grinding surface with grit and rock-material, it wears away the rocks like a grindstone. Therefore, whereas denudation by water tends to cause rounded surfaces with curved lines, denudation by ice, where confined in valleys, often produces straight lines, flat slopes, and faceted surfaces.

7. Faceting Action of Ice and Formation of Trough-valleys

The difference between the rounding action of water and the planing or faceting action of ice may be illustrated by reference to the typical forms of pebbles in deposits laid down by rivers and by ice. The typical river-pebble is rounded and often egg-shaped. The typical ice-worn rock in a boulder-clay has flattened surfaces, which often meet sharply along straight edges like the facets of a gem. The same differences between ice- and water-wear can be recognised on a larger scale in the topography of a glaciated district (see Plate VII.).

Further, a river flows around the base of the spurs which project from the sides of its valley, and often tends to lengthen them, whereas ice slowly cuts away the toes of these spurs, so that each spur ends in a triangular facet. These faceted spurs are well shown on many of the ridges that run down to the Alpine glaciers, and they can be recognised in Scotland at the ends of many ridges and on the sides of many peaks and valleys.

The further wearing backward of the spur reduces it to a short, blunt ridge projecting like a gable from the wall of the valley. In time all these gables are worn away and then the sinuous river-valley has been converted into a straight, smooth-walled, canal-like trough-valley, which is the characteristic form of fiord-valleys.

There is also an important difference between the powers of ice and water in deepening valleys. A river cannot deepen its valley much lower than its outlet, although it may wear out deep holes in its channel where it plunges over waterfalls or rushes down a cataract. Deep rock-basins can only be made by river action when aided by earth-movements. Three processes are required: 1st, the elevation of the country high above sea-level; 2nd, the cutting of deep valleys by rivers through this highland; and, 3rd, the uneven subsidence of the land so that the mouth of the fiord either sank very slightly or remained stationary, and was thus left as a raised threshold. The existence of deep fiords and lake-basins and their thresholds cannot, however, be thus explained in many cases.

Ice has greater powers of irregular vertical excavation than water. It moves slowly, and it presses heavily upon its bed. Fragments of the loose material beneath the ice become frozen into the sole of the glacier and are thus carried away. There is much evidence that the power of glaciers to cut away fresh undecayed rock is very limited, except where it projects into the path of quickly moving ice; but ice that has come into contact with weathered decomposed rock can pick it up and remove it grain by grain. Mining experience shows that the depth to which rocks are weathered varies very irregularly (Fig. 70); in one mine the lode may be decomposed to a considerable depth in several places, which are separated by ridges of fresh, hard rock. A glacier has greater powers than a river in eating out such weathered material and thus forming rock-basins.

8. Pot-hole Formation under Glaciers

The attack of glaciers on the rocks beneath them is aided by a second process. Many geologists hold that rivers owe their main power of cutting down hard bars of rock to pot-hole formation. A boulder in a river-bed is spun around by the action of the current upon the underlying rock. Its rotation is aided by the pebbles and sand beneath it, which serve as ball-bearings and thus lessen the friction, while they act as abrading agents. Thus the underlying rock is worn away and the hollow, once started, is deepened by a succession of stones falling into it. Pot-hole action beneath a river cannot extend, however, far below the sea-level; but the limit of depth to which pot-holes may be bored beneath a glacier is less restricted; a stream of water plunging down a crevasse is known as a glacier-mill, or moulin, and a boulder at the bottom may be swirled around with sufficient force to drill a deep hole in the hardest material. Pot-holes usually occur in groups; and thus a sheet of rock may be riddled with holes which increase in size and number until their walls collapse, and the removal of the broken rock leaves a rock-basin. Hence, in hollowing out basins, a glacier has some powers which are greater than those of rivers. There are, however, other factors which counteract this process, and cause slowly moving glaciers and sheets of snow and ice to protect their beds; for the rock beneath them is preserved from the wear and tear of wind and water, from shattering by heat and frost, and from atmospheric decomposition.

9. Argument from the Distribution of Fiords

The distribution of fiords has also been claimed as proof of their glacial formation. There are nine main fiord districts in the world; and of these the most extensive and most typical are all in latitudes higher than 40°, and in districts which were formerly occupied by ice. Thus in Europe they occur in Norway, Scotland, Iceland, and Spitsbergen. In America they are found in Greenland and Labrador and along the western coast throughout Alaska and Canada. They disappear farther south, and reappear again in the far south of South America in a region where glaciers still exist upon the mountains and where there is convincing evidence of the former extension of the glaciers to sea-level.

The famous fiords of New Zealand are in the south-western corner of the South Island, and there the glaciers formerly reached sea-level; but in the North Island, where, according to many New Zealand geologists, there is no satisfactory evidence of low-level glaciers, there are no fiords.

It is, therefore, claimed that fiords are limited solely to countries that have been glaciated, and that their restriction to such regions is proof of their glacial origin. Nevertheless, in spite of its attractiveness, the simple theory which explains fiords as due to the action of glaciers is inadequate. Many fiords were no doubt once occupied by ice, and were influenced by it; but they were not made by it. Fiords are not limited to formerly glaciated areas, and even in glaciated countries their distribution is inconsistent with their glacial formation. Thus a sheet of ice covered nearly the whole of the British Isles; according to most authorities, this ice extended as far south as the line between the estuaries of the Thames and the Severn. The fiords of Great Britain are, however, almost limited to western Scotland, although the ice covered most of the eastern coasts, and there flowed over rocks of the same character as those beside the western fiords. Some of the glaciated areas in eastern England consist of soft beds, upon which glacial erosion should have been particularly effective. Yet there are no fiords in Yorkshire, for example, although its coast-hills were buried under deep ice and are composed of comparatively soft rocks. The most fiord-like of the English inlets are in Cornwall, where some of the harbours, like those on the opposite coasts of Brittany, have many characters which show that they were once true fiords; and Cornwall is one of the few English counties which admittedly lay outside the glaciated area.

Moreover, the plan of the fiord systems in each country does not appear to be that which would have developed as the result of glacial erosion. The chief fiord systems in the world have the same essential plan. Each fiord area is long and curved; fiord channels extend along the coast; other fiords run inland, and cross-fiords often divide the country into angular blocks.

This network is not the arrangement that would be found if the fiords had been excavated by glaciers; for, in that case, the main channels would be radial from the chief centres of snowfall. The fiords do not take such a course. Study of the fiord system of any country shows that the course of the fiords is inconsistent with the lines of flow of the chief glaciers. The glaciers discharged from the highlands or from the great domes of snow which sometimes formed on the lee side of the existing watershed; and the ice flowed by the most direct channels to the nearest lowlands or to the sea. Many of the fiords had directions which were quite useless to the outflowing ice; and they appear to have been simply filled with stagnant ice, while the main flow of the glaciers was above and across them.

10. Their Distribution inconsistent with a Glacial Origin

The inconsistency between the direction of the lochs and the lines of ice-flow is well shown in many parts of Scotland. In the Shetland Islands, for example, the main fiords, lochs, and other geographical elements trend north and south; but the ice-movement across the Shetlands was from east to west nearly at right angles to the fiords (Fig. 2).

It has been suggested that valleys may be worn out

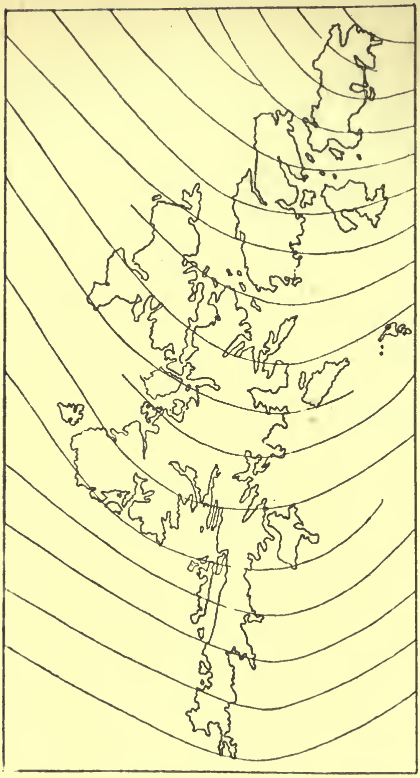

FIG. 2.—THE LINES OF ICE-MOVEMENT ACROSS THE SHETLAND ISLES.
According to Professor James Geikie.

by ice at right angles to its line of advance by the lower layers being forced aside by some obstacle; but this explanation seems inadequate to explain the facts, especially as glacial erosion has often failed, under even apparently most favourable circumstances, to deepen valleys below sea-level. Thus the valley of Sligachan in Skye was occupied by the great ice-stream which flowed north-eastward from the Coollin Hills; the floor of this valley was cut down to sea-level, but the ice then proceeded, like a river that had reached sea-level, to widen the valley instead of to deepen it.

11. PREGLACIAL AGE OF FIORDS

The final and most convincing argument against the glacial origin of fiords is that they are preglacial. They are older than the ice which once occupied them. They are due to a series of uplifts which happened mainly in Pliocene times after the great Miocene movements that formed the Alps and their associated mountain-chains. In all the fiord districts of which we have adequate evidence the fiord-valleys were excavated during the Pliocene period, so that the later ice of the Pleistocene period used the fiords and did not originate them.

12. Relation to Earth-movements

It is therefore necessary to find an explanation of these complex valley-systems independent of the ice-action, which has given some of them their most conspicuous features. Faceted spurs and straight valleys with parallel walls and hanging valleys upon their sides are formed by other than glacial agencies. They may be due directly to earth-movements, as in the fiords of Dalmatia. Thus the famous fiord of Cattaro in Dalmatia is flanked by faceted spurs and the formation of the facets is due to very recent faulting. The long, straight Dalmatian trough-valleys, with their high walls and hanging valleys, are due to recent earth-movements, aided by the weakness of the rivers owing to the porosity of the limestone which is the prevalent rock in the country. These fiords are due to the earth-movements which formed the Adriatic Sea. All the fiord systems of the world are related to earth-movements. Their networks do not resemble the arrangement of valleys cut by erosion, but systems of intersecting fractures.

13. The Grouping of Fiords

The fiord systems of all parts of the world are not arranged in radial lines from the highlands, but as angular networks resembling intersecting cracks in slabs of twisted glass. This arrangement was clearly shown by Kjerulf's sketch-map of southern Norway (Fig. 26), which shows that all the fiords, lakes, and main valleys of that country can be classified into groups, each of which has a definite direction, and crosses the others at regular angles.[1] The same arrangement occurs in Alaska, Patagonia, New Zealand, and Scotland. Thus the Scottish lochs and their valleys may be arranged into four series.

The first, including Lochs Hourn, Eil, Rannoch, and the lower part of Loch Etive, trend east and west parallel to the most conspicuous lines in the topography of Scotland, such as the Pentland Firth and the southern side of the Moray Firth. The second series of lines run north and south at right angles to the first series. The members of the third series trend north-east and south-west; they include Glen More, the line of the Caledonian Canal, the Kyle of Tongue, the valley of the Spey, the upper part of Loch Etive, Loch Awe, Loch Fyne, many of the lochs around the Sound of Jura, and the central part of Loch Tay. The direction of the fourth series is at right angles to that of the Glen More lines; its valleys and lochs extend north-west and south-east, and include Loch Broom on the north-western coast, the lower part of Loch Fyne, Loch Crinan, the Sound of Islay, and various inland lakes such as Loch Shin.

This arrangement of the valleys is not that which would have been formed by glacial erosion. The largest centre of glacial accumulation in Scotland must have been the Grampians of eastern Aberdeenshire, for though Ben Macdhui is slightly lower than Ben Nevis, it is surrounded by a far larger tract of highland. The eastern highlands were unquestionably covered by ice, and in no part of Scotland are glacial phenomena better displayed. Most of the ice probably flowed eastward and north-eastward toward the North Sea; but nowhere along the eastern coast are there any fiords; and, in spite of the great power of the glaciers of eastern Scotland,

[1] Reusch has also referred to the Norwegian Fiords and Valleys as forming a "réseau" (**1902**, p. 110).

even the long, narrow fresh-water lochs are confined to western Scotland (Fig. 32).

Ben Nevis was also intensely glaciated, and the chief ice-movements in that area were from south-west to north-east; for the great centre of accumulation was over the country between Ben Nevis and the coast owing to the heavy precipitation of snow piling up a huge ice-dome. Valley-glaciers radiated from Ben Nevis in the last stages of the glaciation; but the chief lochs in this district are not radial from Ben Nevis. They form a circular series around it.

Angular fiord networks also occur in regions where there are no indications of the former existence of glaciers. Thus the colony of Hong Kong, including the adjacent peninsula on the mainland of China, has a fiord-like series of intersecting valleys; and an excellent example of the same arrangement occurs in the peninsula of Sinai. Prof. Bonney has referred to the Gulf of Akabah as a fiord, and it has many fiord characters; and if Sinai were partially submerged, it would be divided into angular islands separated by parallel-sided, steep-walled valleys, which would form a most typical series of fiords.

14. The Distribution of Fiords determined by Intersecting Fractures

The explanation of fiord-valleys as due to intersecting fractures explains the chief facts of their distribution. It explains their restriction to plateau countries, as it is only where wide areas of hard rocks have been uplifted uniformly that they will be shattered by regular intersecting cracks. It also explains their restriction to areas of old rocks; for soft beds, and most of the younger rocks yield by stretching and not by cracking.

The origin of fiords as a result of uplift and fracture also explains why they so often occur upon western coasts; for the western sides of the continents have generally been uplifted more than the eastern sides, a result probably of the influence of the earth's rotation. The exceptional occurrences of fiords and rias on eastern coasts, as in Greenland, Labrador, and eastern China, are on plateaus of which the eastern continuation has foundered beneath the sea. Otherwise, as in Scandinavia, the British Isles, the Adriatic, North America, South America, and New Zealand fiords occur only on the western shores. A meteorological explanation of this fact has been offered on the ground that the western coasts have the heaviest rainfall and snowfall; but during part of the glacial period the snowfall in Scotland was apparently greatest on the eastern side of the country; and the difference in precipitation is quite insufficient to explain the restriction of lochs to the western coast. In Scandinavia also, during the latter part of the glaciation, the chief snowfall was to the east of the present watershed.

The restriction of fiords to old rocks and their absence from the coasts formed of young deposits are also intelligible if they are due to earth-rending; whereas, if due to glacial digging, they would be chiefly expected in the softer and younger rocks. Simple wedge-shaped fiords extend along the northern coast of Russia as far east as the old rocks extend in Lapland. The fiords do not occur on the coasts composed of the younger Mesozoic rocks to the east of the White Sea. In northern America the fiords are also restricted to coasts built of old rocks, except where the younger rocks are such hard materials as basalt. The absence of fiords from areas composed of the younger and softer rocks may be explained by the fact that, when these are uplifted, they yield by stretching and are not torn by deep rents. Some soft rocks are jointed, but if their bedding be horizontal then the tension due to uplift will open up all these small joints and thus weaken uniformly the whole sheet of rock, which then readily crumbles and is destroyed by denudation. When hard rocks are uplifted the separate blocks do not yield to tension, but the joints between them are opened into a network of gaping fractures, the largest of which are widened by denudation into valleys. Thus the country is divided as in Sinai, in Scandinavia, and Scotland into angular blocks separated by deep valleys.

15. The Fiord-valleys enlarged by Denudation

The gaping cracks were not of the full width of the fiord-valleys. The cracks caused narrow clefts, which have been widened by denudation; water and air enter them and cause the decay of the rocks. Streams remove the weakened rock-material and the clefts are gradually widened into river-valleys, and if the country be subsequently glaciated the ice enters the previously formed valleys and completes their formation. These valleys, however, are not fiords until the country has again subsided so that the lower parts have been flooded by the sea.

16. The Earth-movement of the Fiord Areas

Fiords are therefore due to a somewhat complex series of movements. All fiord countries were once wide coastal plains, which had been planed down by the action of rivers, or sometimes by the sea. Then followed an uplift, by which these plains were raised into plateaus. This period of uplifting appears to have been approximately synchronous in the fiord regions of the world. The uplift in north-western Europe was connected with the crumplings of the earth's crust which formed the Alps; the northernmost waves from the Alpine disturbances caused the south of England to buckle in a series of folds. The contemporary movements farther north caused the subsidence of large areas of land in north-western Europe, enlarged the basin of the North Atlantic, and separated Scotland from Scandinavia. These earth-movements appear to have formed a series of fractures across Scotland, running north and south parallel to the eastern and western coasts, and another series running east and west. This network of fractures formed lines of weakness which were eaten out into valleys. At the same time the widespread uplift and the foundering of the adjacent areas caused the gaping of old lines of weakness across Scotland, and thus led to the formation of new valleys along the ancient earth-fractures. One of the greatest of Scottish fractures lay along Glen More, and in it and in Loch Morar, an east-and-west valley passing across that glen, occur the deepest depressions in Scottish lakes.

The uplifted plateau was dissected by denudation and the fiord-valleys were cut through it along the fracture-lines; a submergence then drowned the lower parts of the valleys beneath the sea. This submergence happened at the time, when the highlands were covered by snow and ice, when glaciers flowed down the old valleys to the sea and moulded them to their trough-like form. At the end of the glacial period the country was again uplifted, so that the old beaches now stand 100 feet above sea-level. In New Zealand, Patagonia, and Norway well-marked raised beaches extend around the fiords, showing that in these countries the last movement has been an uplift.

The tropical regions, on the other hand, have not shared in these oscillatory earth-movements. Great changes between land and sea have taken place in the tropics in recent geological periods. There have been widespread movements of depression, and there are numerous raised coral reefs; but the uplifts have been comparatively local, and the tropical coasts of America, Africa, Australia, and Asia lack the long horizontal raised beaches which

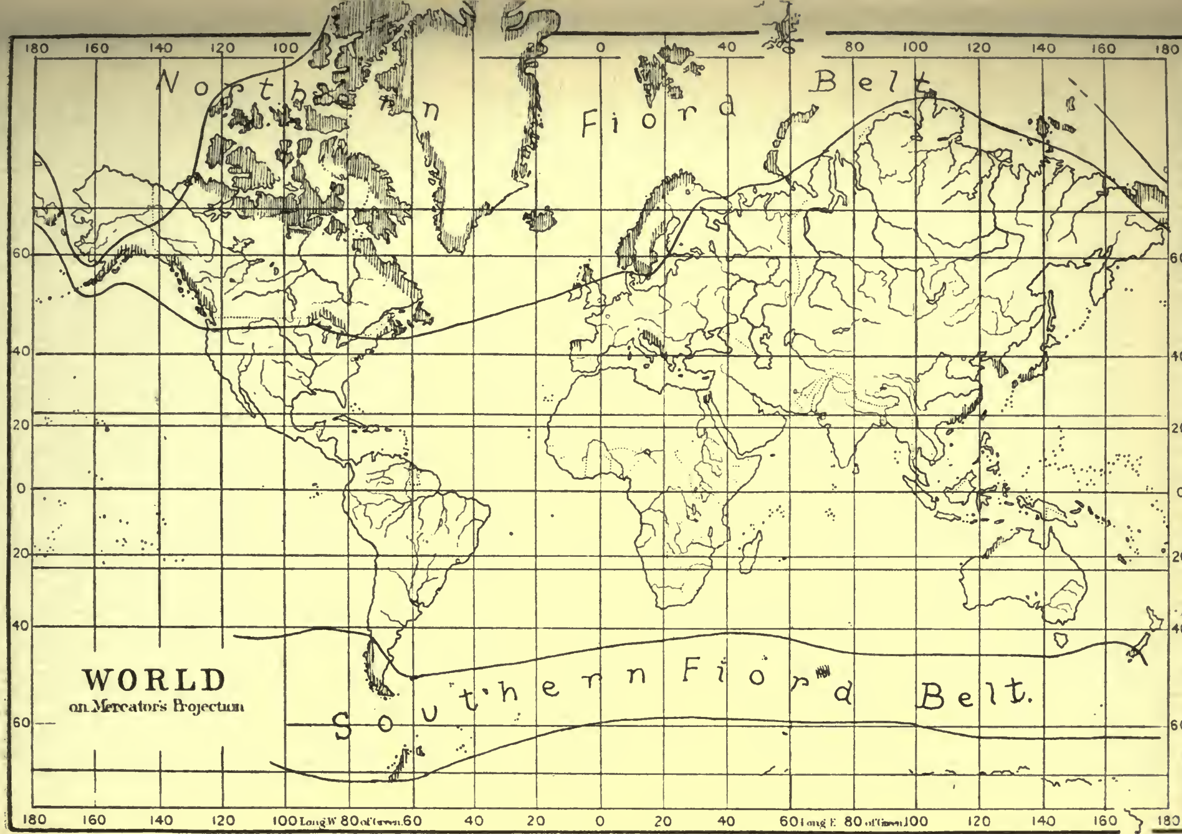

FIG. 3.—DISTRIBUTION OF FIORDS.
Showing the two Fiord-belts and the small Fiord-groups.

are so characteristic of the fiord districts of both northern and southern regions.

The association of fiords and raised beaches is not a mere coincidence. They are both restricted, in the main, to a circumpolar belt in each hemisphere (Fig. 3), and they are both the results of widespread movements in the crust of the earth which have affected the circumpolar and not the equatorial regions. There is evidence that the earth is less stable on lines running north and south than along lines trending east and west. The equatorial belt appears to have remained fairly level, while the polar regions have been subject to frequent oscillations.

The oscillating fiord-belts both vary in width. Thus the northern belt ranges from 48° to 60° on the western coast of America, and from 42° to 75° on the eastern coast, and from 55° to 75° in north-western Europe. Some fiords occur to the north of this belt, but they are not typical in character, being rather fiord-sounds and funnel-shaped fiords.

In the southern hemisphere the fiord-belt extends from 40° to 70° along the south-eastern coasts of the Pacific, and it includes the zone of from 45° to 55° in the Southern Ocean.

The fiords, therefore, help to map out certain great regions of oscillation upon earth. These movements appear to have begun in Miocene times, during the formation of the Alpine-Himalayan mountain-system in the Old World and the West-American mountain-systems in the New World. Owing to the disturbance of the whole crust of the earth during these upheavals, some regions were left unstable and the circumpolar regions have been subject to a series of heaving movements of alternate elevation and depression due to variations in the flatness of the polar regions; while the firmer equatorial belt of the earth did not share in these heavings.

If a flexible circular band of metal be spun rapidly, it becomes oval and the shorter axis is shortened more than the longer axis is lengthened. The flattened sides rise and fall more than the middle belt; and in a body with the shape of the earth, the polar regions may sink and rise, without equal movement in the tropics.

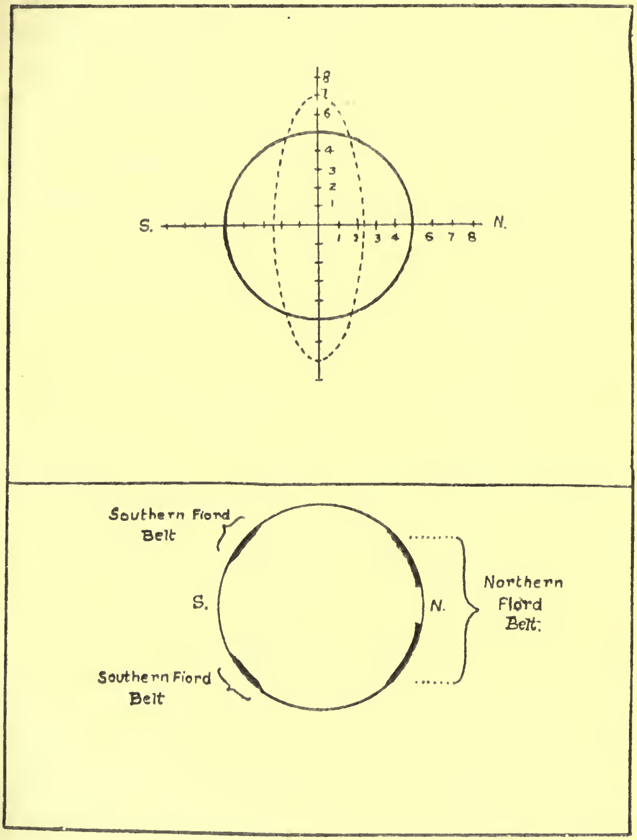

Fig. 4.—Diagram illustrating the Distribution of the Circumpolar Fiord-belts and the greater Movement of the Polar than the Equatorial Regions on the Deformation of a Rotating Body.

The most conspicuous feature in the plan of the earth is the antipodal position of land and water. Nearly every place on land has water at its antipodes. Each continent is antipodal to an ocean; or, otherwise expressed, every great elevation on the earth's surface is antipodal to a depression.[1] In accordance with this rule it is natural to find that, while the region around the North Pole has foundered beneath the Arctic Ocean, a corresponding region around the South Pole has been upraised. The typical fiord areas in the northern hemisphere do not extend north of 75°, though there are great fiords and fiord-straits formed as rift-valleys north of that latitude. There are also no fiords south of 70° in the southern hemisphere, owing to the land there having been uplifted to balance the Arctic subsidence. The lands around both the Arctic subsidence and the Antarctic elevation have been fractured during their repeated rise and fall, and thus form the two great fiord-belts of the world.

17. The Two Fiord-belts

These fiord-belts mark out oscillating zones around the sunken and upraised polar regions. In the temperate and tropical regions similar networks of fiord-valleys are only found on the borders of plateaus which have been rent by the subsidence of the adjacent areas.

18. Conclusion

The purpose of this introductory chapter is to point out the lessons taught by the facts stated in the second part of this work and to indicate the geographical interest of the fiord problem owing to its bearing on the structure and mobility of the earth. The spirit of maritime adventure bred in the Scandinavian fiords gave the European races the mastery of the sea and a political predominance which is world-wide in its influence. The geological study of fiords leads to geographical problems that are also world-wide in their range; for the view that fiords

[1] An explanation of this arrangement and its cause has been given by the author in *The Making of the Earth*, 1912, pp. 128–60.

are due to local superficial agents, chiselling furrows on an impassive earth, explains neither their features nor their distribution. Fiords teach much more significant and far-reaching lessons. They point to subtle and deep-seated forces which affect the earth as a whole. However greatly fiords may have been moulded by ice, wind, and water, they are not primarily due to those agencies, which have used the fiords, not made them. The ultimate cause of fiords is the rupture of wide areas of the earth by the pulsation due to the titanic forces started by those disturbances, which upheaved the existing mountain-systems of the world.

CHAPTER II

THE CLASSIFICATION OF COAST-TYPES[1]

For of all the runes and rhymes
    Of all times,
Best I like the ocean's dirges,
When the old harper heaves and rocks,
    His hoary locks
Flowing and flashing in the surges.

LONGFELLOW.

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1. Introduction.—2. Von Richthofen's Classification.—3. Prof. Suess's Classification.—4. The Western Coasts of the Pacific: (*a*) The Eastern Coast of Australia; (*b*) The Coast of China.—5. Redefinitions of the Coast-types.—6. The Coast-types of Antarctica.—7. The Atlantic and Pacific as Petrographic Provinces.

1. INTRODUCTION

As fiords are coastal-forms it is necessary, in the study of their origin, to consider the nature of the chief types of coastal structure.

The coasts of the world are built with most varied geographical characters, yet even the extreme varieties are linked by an unbroken chain of intermediate forms. A coast may consist in one place of lofty highlands which end abruptly in stupendous precipices scarred by the battering of the waves; elsewhere an inconspicuous lowland may sink slowly beneath the sea through a wide beach levelled by the unceasing scour of the surf. These two extreme types meet where a raised beach lies between the once seaworn foot of an old cliff and the present shore.

[1] This chapter is mainly republished from *Scientia*, vol. xi. 1912, pp. 36–63.

Again, a coast may extend in long, straight lines or in wide, open curves, with not a rock or islet between the sharply defined shore and the ocean's unbroken surface. Elsewhere a jagged coast-land extends seaward in many branched, straggling peninsulas and archipelagoes of countless rocks and islets, between which the sea extends inland in such a maze of gulfs and channels that only a careful survey will discover where the mainland ends and the islands begin.

These varied coastal types appear at first sight to be scattered irregularly along the shores of the world. Each ocean and continent has representatives of all the chief topographic types. Thus, on the western coast of Europe the highlands and fiords of Norway are followed by the wide plains and low-banked estuaries of Denmark and the dune-guarded marshes of Holland; and farther south the straight, sandy shores of south-western France give place to the indented rias-coast of north-western Spain. Fiord-coasts and coasts guarded by a fringe of islands, or, to use the Swedish name, skärgard, or guard of skerries, are found on both sides of both the Atlantic and Pacific. Long belts of sand-dunes, known by such names as the "Ninety Mile" beaches in Australia, are found on all the continents, even in such unexpected localities as the rocky coast of Portugal and in front of the Southern Alps of New Zealand, where these accumulations of sand have smoothed into an even line what would otherwise have been a very jagged strand.

Coastal forms are, in fact, the result of the interaction of many conflicting agencies including excavation and deposition, elevation and depression, frost and heat, wind and tide. Hence they present almost infinite variations in detail; but certain impressive facts indicating some plan in the general distribution of the chief types have long been recognised. It was not, however, until twenty-five years ago that these facts were arranged in a satisfactory scientific classification.

Then two great masters of physical geography, Suess and von Richthofen, independently suggested classifications which explained the distribution of coastal forms by continental structures. Professor Suess's illuminating and suggestive classification was issued in 1885, and was the more important, for it connected coastal types with the internal economy of the globe.

2. Von Richthofen's Classification

Baron von Richthofen's classification was issued a year later,[1] but it will be convenient to consider it first as it was the more precise and was mainly descriptive. He divided coasts into five varieties, and the classification may be summarised as follows (Fig. 5):

1. Longitudinal Coasts (Längsküsten). Coasts which are parallel to the trend of the nearest mountain-chains.
2. Transverse Coasts (Querküsten and Diagonalküsten). Coasts which cut across the adjacent mountain-chains.
3. Basin-rimmed Coasts (Beckenrandküsten). Coasts which are formed by the walls of basins due to the foundering of areas on the inner side of mountain-chains.
4. Crust-block, or Block Coasts (Neutrale Hochküsten, or Schollenküsten). Coasts bounded by the walls of block-mountains.
5. Regional Alluvial Coasts (Schwemmlandküsten, or neutrale Flachküsten). Coasts composed of recently deposited sediments.

These coast-types are scattered world-wide; each ocean has representatives of them all. The typical "longitudinal coasts" are those on the western side of North and South America; and to this variety von Richthofen referred the western coasts of Scandinavia, of the Balkan Peninsula and of India, the coast of Algeria, and the eastern coast of Asia from the Amur to Korea.

The "transverse coasts" include the shore of the

[1] *Von Richthofen*, 1886, pp. 292–6.

FIG. 5.—THE CHIEF COAST-TYPES.
According to von Richthofen.

Balkan Peninsula from the Danube to Greece, the western coast of Spain and Portugal, the western coasts of Great Britain, and in the Pacific the coast of southern China.

The typical coast of the third variety—coasts bounded by the rims of basins—is the western coast of Italy, which is due to subsidences along the course of the Apennines. Von Richthofen also included the western coasts of Kamtschatka and Japan, and the eastern coast of New Zealand, which he quotes as one of the rare instances of these coasts facing the open ocean.

The block coasts border all southern Africa from the Bight of Benin to Socotra (though according to the definition the southern coast of Cape Colony should be a longitudinal coast); they also form the shore of southern Australia, of much of eastern South America, the southern and eastern sides of the Levant, the north-eastern side of the Black Sea, and the Arctic Archipelago of North America.

The alluvial coasts include the coasts of northern Germany, western Siberia, and the plain of northern China.

It may be doubted whether von Richthofen referred some of the coasts to the right category according to his own definitions. The general distribution of these coasts, according to von Richthofen's identifications, is marked in the accompanying map (Fig. 5). It shows that the representatives of his four chief varieties are irregularly distributed, and are not restricted to special oceans.

The terms "transverse" and "longitudinal" used by von Richthofen are not very satisfactory, and those proposed by Supan (**1911**, p. 793) are more convenient, as they imply more definitely the dependence of the course of the coast upon the structure of the country. Supan's "discordant coasts" cut across the grain of the country; in his "concordant coasts" the trend of the shore and the grain of the land are parallel. A neutral coast has no definite relation between the structure of the country and the trend of the coast. The concordant type corresponds to von Richthofen's longitudinal type, the discordant to the transverse, and the neutral to the basin-rimmed, block-coasts, and alluvial coasts.

3. Professor Suess's Classification

Prof. Suess's classification introduces more fundamental and extensive geographical principles than that of von Richthofen. Suess divided coasts into two types; and, as the one is characteristic of the Atlantic and the other of the Pacific, he called them the Atlantic and Pacific types. He defined them in 1885 in the first volume of his *Antlitz der Erde* (p. 5). He described the Pacific coasts as bounded by more or less continuous mountain-chains, and the course of the shore-line as directly due to the structure of the continent. The Pacific type is therefore concordant; to it Suess referred the whole coast of Asia east of the Ganges and all the western coast of America from Alaska to Cape Horn with the exception of Central America.

The characteristic of the Atlantic type is the absence of any connection between the course of the coast and that of the adjacent mountain-chains. The coast is either discordant or neutral. Atlantic coasts cut transversely across the structure of the country, and where a mountain-chain does happen to occur near the shore the mountains turn their back upon the sea; and "no causal connection whatever," says Professor Suess, "is perceptible between the coast-line and the continental structure."

The Atlantic type Prof. Suess described as developed along all the western coasts of Europe and Africa with the exception of the northern coast of Spain; around all Africa except in the Mediterranean, along the coasts of Arabia and the Indian peninsula, and in south-western Australia.

A more detailed diagnosis of the two coast-types was given by Prof. Suess in 1888 in the fourth chapter of his second volume. The Atlantic type is there described as having four characters:

1. Mountain-ranges seldom occur parallel to an Atlantic coast, and, where they do, they are folded away from the ocean, and thus the inner sides of the mountain-ranges are nearest the shore.

2. Atlantic coasts are often indented by rias.

3. They are often formed by fractured horsts.

4. They often consist of the broken edges of tablelands.

Pacific coasts have also four main characters:

1. The coasts are always parallel to mountain-ranges which are folded toward the ocean.

2. The outer edges of the mountain-ranges form the boundary of the mainland or lie as peninsulas or islets outside it.

3. No part of any Pacific coast is formed by the edge of a plateau.

4. The existence of a Mesozoic marine series around the Pacific, which is completed in sections drawn towards the coast.

This distribution of the Atlantic and Pacific coasts as thus defined was shown by Neumayr,[1] in a map (Fig. 6). To the Pacific type he referred all the western coasts of America (including Central America), Cuba, Jamaica, the northern coast of Spain, Algeria, Italy, the Balkan Peninsula, Asia Minor, Beluchistan, southern Persia, and all the Asiatic coasts east of the head of the Bay of Bengal, and all the Malay Archipelago. To the Atlantic type he referred the eastern coasts of America (including Venezuela and the northern coast of the Gulf of Mexico), all the Atlantic coasts of Europe, except northern Spain, all the coasts of the Arctic Ocean, all those of Africa

[1] Neumayr, **1890**, vol. i. p. 345.

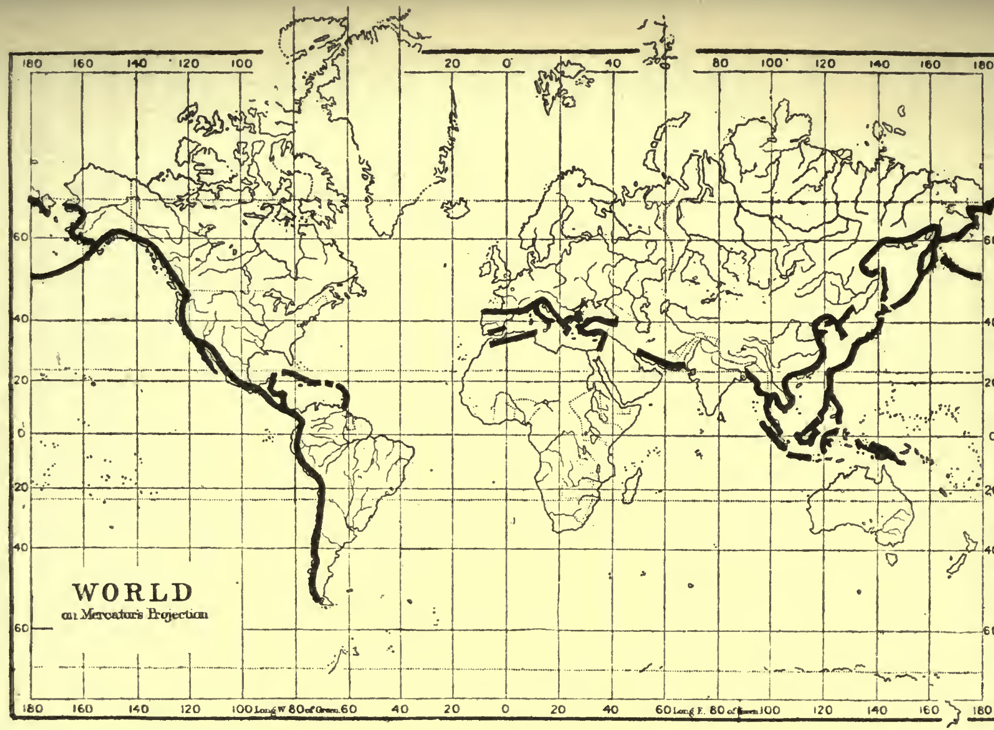

FIG. 6.—THE DISTRIBUTION OF THE ATLANTIC AND PACIFIC COAST TYPES (AFTER NEUMAYR).

Coasts marked by thick black line are of Pacific type (New Zealand probably omitted by accident). Thin coast lines mark Atlantic Coasts.

(except Algeria) and of the Peninsula of India and Australia.

The classifications of Prof. Suess and von Richthofen have some features in common. Suess's Atlantic type, as its coasts cut across the mountain-chains and are formed in part of horsts and tablelands and are indented by numerous rias, includes von Richthofen's transverse and block-coasts.

His Pacific type includes von Richthofen's longitudinal and basin-rimmed coasts.

Prof. Suess's classification has the great advantage over von Richthofen's that it represents each of the two coastal types as characteristic of one of the two chief oceans. The Atlantic and Pacific Oceans were each regarded as bounded on both sides by similar coastal types, because each ocean-basin was regarded as a geographical unit. The distinctive coastal features of the Atlantic and the Pacific were interpreted as the natural expression of their different geological histories.

In addition to the classifications of coasts based on their mode of origin, others have been proposed which are simply descriptive. Thus Dr. S. Günther [1] divides coasts into two main groups—coasts bounded by cliffs and flat coasts. The cliff-bounded coasts he subdivides into seven types. They are the Norwegian or fiord type, the Asturian or rias type, the Dalmatian type, the Swedish type, which is fringed with islands, the Cimbrian or Scottish type, including the Föhrden (see p. 68) and Firths, the Mediterranean or terraced type, and the Norman type, which has long lines of cliffs along the shore.

His group of flat coasts is subdivided into ten types: the Frisian, the Prussian with its Haffs, the Venetian with its lagoons, the types of Gascony (France), Further India, Guiana, Patagonia, East Africa, and the Balearic Islands (including the deep bays or "calas" of Malta), and Compensation Coasts.

[1] Günther, **1899**, 2nd ed. vol. ii. pp. 590–3.

Prof. Herbertson has recently (**1910**, pp. 36–9) accepted Prof. Suess's terms in a somewhat modified sense. He defines the "Pacific type" as mountain coasts, the "Atlantic type" as highland coasts, and he has introduced a third division, the "Indian type" for coasts bordering tablelands.

4. The Western Coasts of the Pacific

With further knowledge of the structure of the western coasts of the Pacific it became evident that Professor Suess's definitions required somewhat free interpretation; for neither the eastern coast of Asia nor of Australia is bounded by a well-defined mountain-chain comparable to those on the western side of America. The complex mountainous country behind the eastern coast of Australia was once regarded as a mountain-chain, and it had been named by W. B. Clarke the Australian Cordillera. Prof. Suess adopted this term, and he was probably led by the high authority of Clarke to regard the eastern highlands of Australia as a mountain-chain like the Andes.

The structure of the two areas is, however, very different, as there is nothing in Australia corresponding to the main chain of the Andes. The coast of China agrees still less with the definition of the Pacific type; it is very varied in structure and includes Korea, which is a fractured horst; the typical rias-coast of the world is in south-eastern China, where there is no long coastal mountain-chain.

Before the date of Prof. Suess's classification von Drasche (**1879**, pp. 268, 269) had indeed proposed that the true boundary of the Pacific Ocean was the line from Kamtschatka through Japan, the Philippines, New Guinea, New Caledonia, New Zealand, and South Victoria Land. If the Pacific coast be thus moved eastward, the mainlands on its western side are of the Atlantic and not of the Pacific type.

Such a change would render the terms "Atlantic" and "Pacific" no longer appropriate. There are, however, many arguments in support of Professor Suess's view, and with some unessential modifications in the definitions it is still possible to regard the western coasts of the Pacific as belonging to the Pacific type.

In the first place, the direction of folding may be ranked as of secondary value. Thus this feature can only be found occasionally along the Atlantic coasts, where parallelism with a mountain-chain is an accidental coincidence. The most striking case of parallelism between an Atlantic coast and a mountain-line is in the United States, where the shore is parallel to the Appalachians; but the structures in these mountains were due to movements much older than the formation of the Atlantic basin, and the direction of their movement is immaterial. Moreover, in various localities around the Atlantic the earth-movements have been towards, and not away from, the coast.

Secondly, the definition that Pacific coasts are parallel to mountain-chains cannot be applied rigidly; neither the eastern coast of China nor of Australia is bounded by modern chains of fold-mountains; but they are bounded by folds and fractures that follow the course of a great chain of fold-mountains, of which the fragments lie outside them. The coasts belong to the Beckenrand-küsten, or Basin-rimmed Coasts of von Richthofen. The inclusion by Prof. Suess of the typical coast of that class in the Pacific type is a good precedent for retaining the Chinese and east Australian coasts in the same category.

Thirdly, some latitude must be allowed to the parallelism of the coast with the grain of the country. Neither in China nor in eastern Australia does that parallelism hold throughout. But the exceptions are no more numerous than on other coasts, which are still universally admitted as Pacific representatives, viz. New Zealand, Japan, the United States, and South America.

If the preceding modifications in the definitions be accepted—and if not, I fail to see that any considerable extent of coast anywhere in the world is of the Pacific type—then the eastern coasts of Australia and China may be retained as of the Pacific type.

(*a*) *The Eastern Coast of Australia*

Eastern Australia has four points of agreement with the Pacific type:

First.—The modern folds, such as they are, may be regarded as toward the Pacific: for the eastern boundary of the Blue Mountains, west of Sydney, has been proved by Prof. David and Mr. Carne to be a great monoclinal fold, dipping down toward the sea; and the eastern edge of Australia in other districts is due to subsidence along step-faults, as suggested by Wilkinson, supplemented by some gentle monoclinal folds.

Second.—The trend of the rocks is in general parallel to the coast; there are some exceptions, but they are not more numerous than on the Pacific coast of North America.

Third.—The older rocks usually occur near the coast: newer rocks form the western slopes of the East Australian Highlands and wide areas of marine Cretaceous and Kainozoic deposits are found in the great plains beyond the Highlands.

Fourth.—Prof. Suess has called attention to the intimate connection in structure between eastern Australia and New Zealand: he pointed out the striking resemblances, geographical and geological, between the sequence from the Pacific eastward across South America and westward across Australasia. The essential similarity has been obscured by the separation of Australia from New

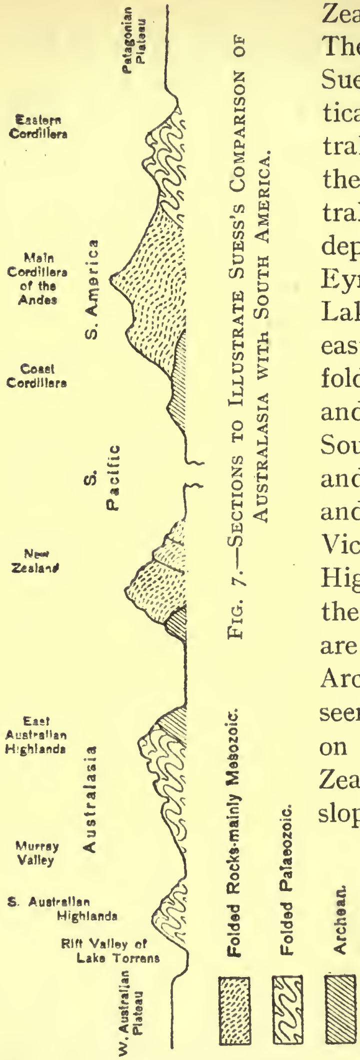

FIG. 7.—SECTIONS TO ILLUSTRATE SUESS'S COMPARISON OF AUSTRALASIA WITH SOUTH AMERICA.

Zealand by the Tasman Sea. The comparison made by Prof. Suess is illustrated diagrammatically by Fig. 7. The Australian sequence begins with the plateau of western Australia. Then follows the low depression occupied by Lake Eyre and the rift-valley of Lake Torrens. Next, to the east is a wide area of intensely folded Lower Palæozoic slates and grits; it begins with the South Australian Highlands, and includes the Ordovician and Cambrian rocks of the Victorian and East Australian Highlands. Farther east, near the eastern coast of Australia, are extensive outcrops of Archean rocks, which are also seen across the Tasman Sea on the western coast of New Zealand. The long eastern slope of New Zealand consists of folded rocks, including representatives of all the Mesozoic and of some Kainozoic systems; and the beds are contorted and disturbed by overthrusts and overfolds due to pressure, which acted eastward toward the Pacific.

Now in South America the sequence begins on the east with the plateau of eastern Patagonia, which is bounded to the west by a depression occupied by lakes and lagoons. Then follow the highly contorted, lower Palæozoic rocks of the Sierras of Cordova in the Argentine, which correspond to the East Australian and Victorian Highlands. The next member of the sequence is the Cordillera of the Andes, built up, like its Australian equivalent, New Zealand, by Palæozoic and Mesozoic sediments overthrust toward the Pacific; and, finally, there is the Coast Cordillera composed essentially of Archean rocks.

Prof. Suess states emphatically (**1906**, vol. ii. p. 162) that the mountains of eastern Australia and the South Australian Highlands and the mountains of New Zealand are as much "parts of a single system similarly constructed on a common plan," as the Sierras of Cordova in the Argentine are inseparably part of the same system as the principal chain of the Andes.

After consideration of the structure of eastern Australia in a *Geography of Victoria*, published in 1903, I accepted Prof. Suess's conclusion that the eastern coast of Australia, like that of New Zealand, is of the Pacific type. Clarke's term, "the Australian Cordillera," seemed misleading, as the mountainous country behind the eastern coast of Australia is not a mountain-chain like the Andes, but is simply a dissected plateau on the site of a very ancient mountain-chain. It is not the representative of the Cordillera; it can be better described as the East Australian Highlands than as the Australian Cordillera. Yet, though Eastern Australia is a dissected plateau, its characteristics differ essentially from those of the Atlantic coasts. The eastern coast of Australia is approximately parallel to the grain of the country, and the plateau descends to the sea either by gentle monoclinal folds or by a series of step-faults parallel to the coast. It is a coast which has been formed by the subsidence of the two basins, the Tasman Sea and the Coral Sea, on the inner side of the fold mountain-chain, of which New Zealand is a fragment. The eastern coast of

Australia is, therefore, one of von Richthofen's basin-rimmed coasts; and the typical member of that variety, the western coast of Italy, Suess claims as a Pacific coast, and it is represented as such on Neumayr's map (Fig. 6).

(*b*) *The Coast of China*

The eastern coast of China is on the same general plan as that of eastern Australia. Eastern Asia sinks below the Pacific by step-faults and probably also monoclines, and the course of the coast has been determined by great fractures. These coastal fractures, as in eastern Australia, are due to the foundering of great basins on the inner side of the system of fold-mountains; this is represented by Japan, and traverses the Malay Archipelago. With the exception of Korea, which is a horst with its grain transverse to its two longest shore-lines, the grain of eastern China is in general parallel to the coasts. This agreement between the strike of the rocks and the trend of the coasts is well shown in Annam. In southern China the coast has a long course to the west, nearly parallel to the strike of the rocks; but in Annam the rocks strike to the south-south-east and the coast projects eastward in conformity with this strike.

The parallelism of the coast and the rocks is not complete; thus along most of the south-eastern coast the rocks are Palæozoic, but, as the coast fractures are slightly oblique to the strike of the rocks, the crystalline axis of the Palæozoic belt reaches the shore near Canton in the south-west, and near Wen-chow (Lat. 28° S.) to the north-east. The Pacific coast of North America shows similar exceptions to the general parallelism.

5. Redefinitions of Coast-types

I feel, therefore, bound still to regard the eastern coasts of Australia and Asia as of the Pacific type. There are, however, important differences between them and those Pacific coasts which are directly determined by the proximity of a chain of fold-mountains. Hence I proposed in **1908** (p. 61, Plate VII.) to subdivide the Pacific type into two varieties—the Primary Pacific type along the outer edge of the fold-mountain chains, and the Secondary Pacific or Sub-Pacific type, where the coast is less directly connected with the border-chains of the Pacific, but is due to subsidences within the mountain-chains.

It is therefore suggested that the coast-types be defined as shown on page 42 (see Fig. 8):

1. *Atlantic coasts* are in the main discordant with the grain of the coastlands, and where they happen to be parallel to an adjacent mountain-chain it is turned and folded away from the coasts. Coasts of the Atlantic type vary greatly in structure according to the varied structures of the lands which they cut across.

2. *Primary Pacific Coasts* are determined by the proximity of long lines of fold-mountains, to the trend of which the coast is in general parallel. The mountains bounding these coasts are of comparatively young geological age. Over-thrusts and over-folds, if present, are mostly directed toward the ocean.

3. *Secondary Pacific, or Sub-Pacific Coasts* are due to the subsidence of basins on the inner side of mountain-chains along coasts of the Primary Pacific type. They are frequently bordered by active or recent volcanoes. The oldest rocks usually occur along the coast and are followed by younger rocks further inland. Except where horsts project into the sea, the coast-line is approximately parallel to the average grain of the adjacent country.

If these definitions be accepted, eastern Asia and Australia would come under the Pacific-coast type as representatives of the Secondary Pacific variety. Otherwise very little coast can be retained under the Pacific type.

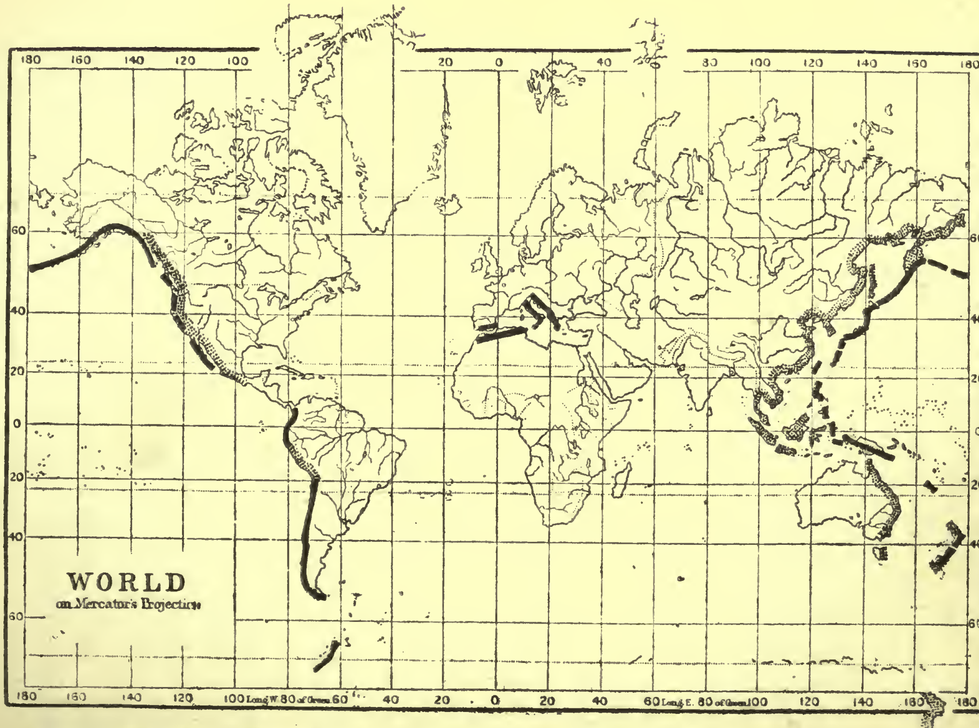

FIG. 8.—THE DISTRIBUTION OF COAST TYPES.

The whole of the western coast of the mainland of the Pacific would have to be excluded from it, and even if, in accordance with Drasche's view, the Pacific coast be moved eastward to the line through Japan and New Zealand, only some parts of this line can be left as of the Pacific type. The southern end of the South Island

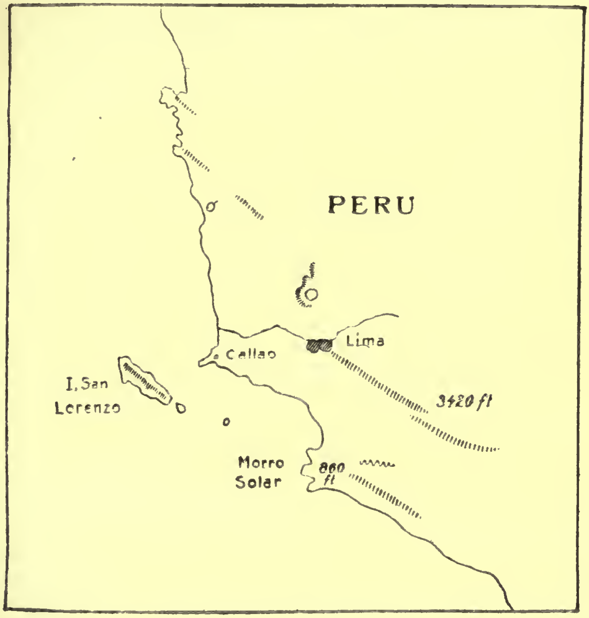

FIG. 9.—THE TRANSVERSE STRUCTURE OF THE COAST OF PERU NEAR LIMA.

(After Admiralty Chart, South America, Sheet xiv. 1836.)

of New Zealand and the northern end of the North Island are both discordant coasts and would have the Atlantic structure. On the eastern shores of the Pacific large tracts of the American coasts would also have to be excluded from the Pacific type. Thus in North America the mountain-chain, which extends parallel to the shore of Alaska to the latitude of 55°, there passes out to sea through the Queen Charlotte Islands, leaving nearly all the coast of Canada as of the Sub-Pacific type. The mountain-lines curve into the coast again through Vancouver; but there, as in the north-western part of the state of Washington, the land is bounded by a discordant coast.

Farther south, in the latitude of Oregon, the coast is parallel to the grain of the country; but in California the coast is discordant in latitude 40°, about Cape Mendocino. It is oblique to the grain of the country for some distance

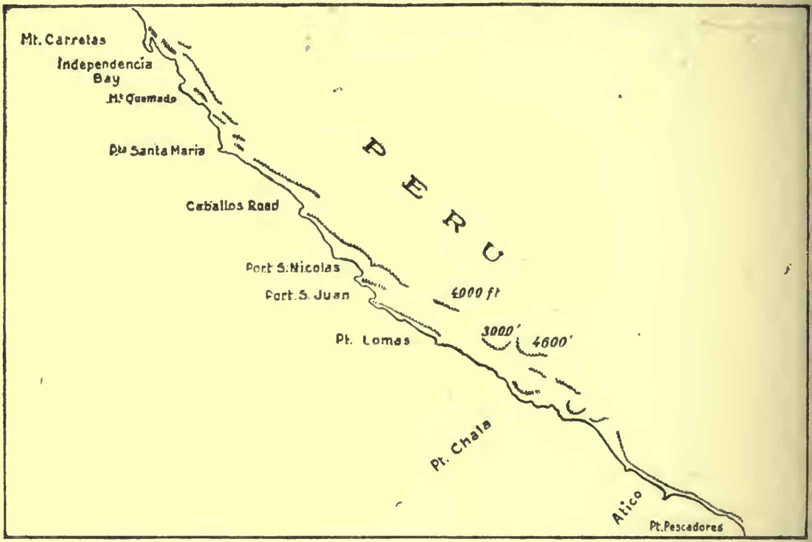

FIG. 10.—PART OF THE COAST OF SOUTHERN PERU.
Showing the oblique trend of the mountain-lines. (After Admiralty Chart, South America, No. 1,279.)

farther to the south, and it is again almost at right angles to the grain in latitude 35° and thence past Los Angeles. The long peninsula of California might be of the Pacific type, but the mainland can only be of the Sub-Pacific type; and, where the Mexican plateau comes to the shore and in central America, the country admittedly does not correspond in structure with a Pacific coast. Much of the coast of Peru would also have to be excluded from the Pacific type, for its course is discordant (Figs. 9 and 10).

6. The Coast-types of Antarctica

How completely the terms "Atlantic" and "Pacific" types have lost their original and useful meaning may be seen by reference to Antarctica. That Graham Land is of the Pacific type and that Wilkes Land and the coast explored by the German Antarctic Expedition are probably of the Atlantic type is universally agreed; but all the authorities, including Prof. Suess, regard the eastern coast of South Victoria Land as of the Atlantic type. It seems to me, however, referable to the Sub-Pacific type.

Until the publication of the full observations by Prof. David and Mr. Priestley on the Shackleton Expedition, our main source of information as to the structure of the eastern coast of the Ross Sea is found in the work of Dr. Prior and Mr. Ferrar. Their reports show that the structure of that coast is strikingly like that of many Pacific coastlands. The general character may be illustrated by the accompanying figure (Fig. 11), which is a

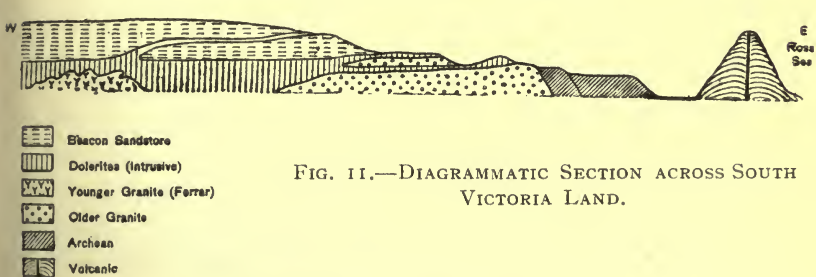

Fig. 11.—Diagrammatic Section across South Victoria Land.

diagrammatic compilation from several by Mr. Ferrar. Along the shore is a tract of gneisses and schists, which correspond to the Archean Coast Cordillera of California, the Cordillera Maritima of South America, and the Archean rocks on the eastern coast of Australia. Farther back is a high plateau composed mainly of the Beacon Sandstone, the age of which is uncertain[1]; but the

[1] Prof. David's preliminary conclusion as to the age of this forma-

presence of Lower Palæozoic rocks to the south has been proved by Taylor from specimens collected by Sir Ernest Shackleton. Cape Adare is formed of slates, which, from their resemblance to those of Victoria, are probably also Lower Palæozoic. The coast itself appears to be determined by fractures, the former eastward continuation of the land having foundered beneath the Ross Sea. Volcanic action is, and has been, vigorous at intervals along the coast. Some of the volcanic lines are along planes of weakness at right angles to the shore, as is also the case in Japan.

The general strike of the rocks in South Victoria Land appears to be approximately north and south.[1] Hence the structure of the coast appears to agree far better with that of eastern Australia than with any coast of the Atlantic type. For South Victoria Land has a young volcanic belt along the eastern shore; it has Archean coast-hills covered inland by sandstones containing plant-remains and coal-seams, and intrusive dolerites; it includes Lower Palæozoic limestones and slates like those of Victoria and South Australia; and it has no marine Kainozoic or Mesozoic rocks. I know of no such association of characters on the Atlantic coasts.

Prof. Suess, however, in his last volume (**1909**, vol. vi. pp. 293–4) remarks that the coast of South Victoria Land recalls the fractures of East Africa rather than a Pacific arc. The points on which he lays stress are the horizontal position of the sandstones—the wide distribution of gneiss and granite, and the contours. I fail, however, to see any particular resemblance between this coast and that of the fractured area of eastern Africa. There the land is a high plateau composed mainly of

tion is that it "is perhaps as old as Palæozoic, possibly Older Palæozoic." In the absence of certain evidence the coal-seams in the Beacon Sandstone, discovered by Shackleton, are rather in favour of the formation being Carboniferous or later. This coal-bearing formation is another point of resemblance to the east Australian coast.

[1] This view is confirmed by David for Depot Island (**1910**, p. 296).

Archean rocks; it is flanked at intervals along the coast by marine Mesozoic shales, and limestones; its volcanoes are inland, upon the plateau and not at its foot; and there are no representatives along the coast of the Lower Palæozoic slates of Cape Adare or of the Archæocyathus limestone of the Beardmore Glacier. The coast of South Victoria Land seems to agree both in the character of its rocks and their arrangement with eastern Australia, and should accordingly be assigned to the Sub-Pacific type.[1]

This conclusion naturally raises the question whether there be any Primary Pacific Coast on the southern side of the Pacific Ocean; for, if not, then Suess's great conception of the Pacific as one geographical unit would be seriously weakened. There are alternative views as to the nature of the southern side of the Pacific. Either the Pacific-coast type of Graham Land may continue westward to King Edward VII. Land and thence to New Zealand; or this Pacific chain may be separated from the mainland of Antarctica by a large rift-valley extending from the Ross Sea to the Weddell Sea. If so, the whole Pacific face of the Antarctic plateau, extending from South Victoria Land past the neighbourhood of the Pole to the eastern shore of the Weddell Sea, would be a coast of the Sub-Pacific type and would agree geographically, as it appears to do geologically, with the coast of eastern Australia. I noted the possibility of such an arrangement in *Nature* in 1900 (vol. lxiii. p. 610), owing to the sudden change in the strike at the southern end of New Zealand. The trend of the rocks in Otago suggested that the extension of the New Zealand line might pass east of the Ross Sea. Nevertheless, owing to the exaggerated estimate of the proportion of volcanic

[1] Prof. David concludes that the coast is of Atlantic type from the absence of post-Palæozoic folding, and the formation of the coast by step-faults; both these characters are consistent with the Sub-Pacific coast-type.

material in South Victoria Land, I inclined to the view that the continuation of the New Zealand line would cross South Victoria Land and extend to Graham Land, leaving Antarctica, as has been strongly supported by subsequent exploration, as a vast plateau sloping downward across the Pole to the South Atlantic and Southern Oceans.[1]

The information now available shows that South Victoria Land is more similar, geologically, to eastern Australia than to New Zealand. Hence it appears most probable that the continuation of New Zealand and of the Primary Pacific Coast lies through King Edward VII. Land towards Graham Land. Hence I should be disposed to classify the coasts of Antarctica as shown on Fig. 12 thus: South Victoria of the Secondary Pacific type, the line from King Edward VII. to Graham Land of the Primary Pacific character, and the remaining coasts of the Atlantic type.

If that classification prove correct and the coast of King Edward VII. Land and Graham Land include foliated Mesozoic rocks, then the evidence of Antarctica would support Suess's conception of the Pacific as a geographical unit bounded on all sides by coasts of a Pacific type.

Since the previous paragraphs were written the expedition of Captain Amundsen has made one very important step towards the solution of this problem. For he has discovered that the depression to the south of the Ross Sea occupied by the Great Ice Barrier ends in the latitude of between 85° and 86° S. He has thus disproved the connection which has been suggested between the Ross Sea and the Weddell Sea, and strengthened the conclusions of the two previous paragraphs.

The main value of the distinction between the Atlantic

[1] This view is described as the more likely in the light of our present knowledge by Dr. D. Mawson in "The Australasian Antarctic Expedition," *Geog. Journ.*, vol. xxxvii. June 1911, p. 612.

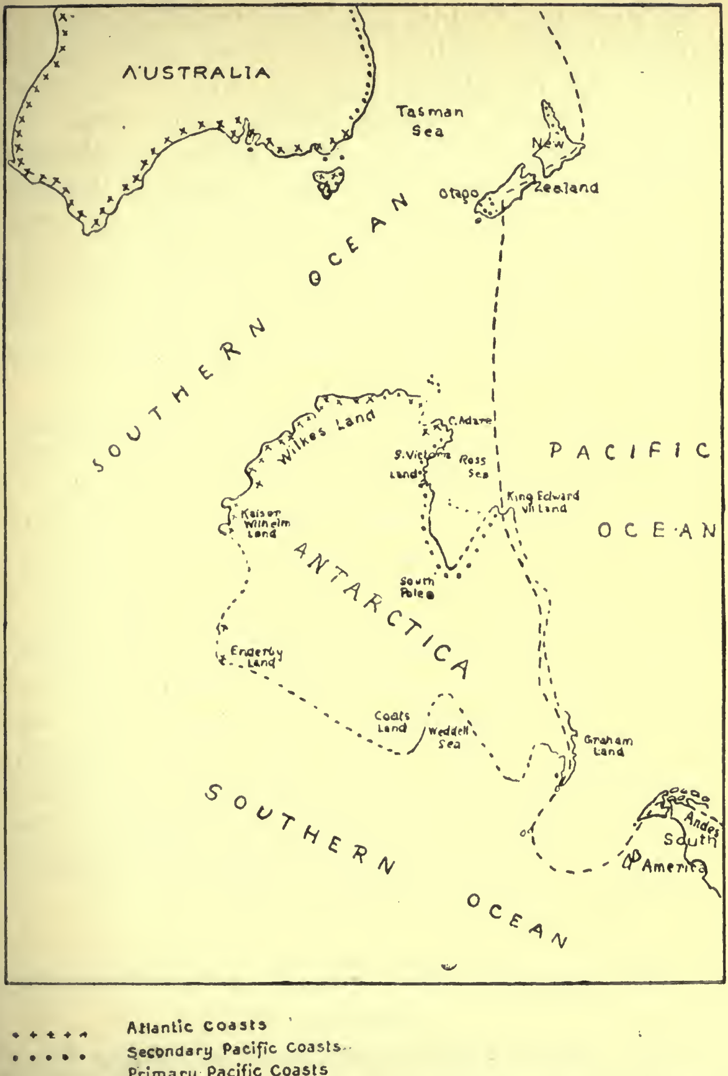

FIG. 12.—SKETCH-MAP OF THE DISTRIBUTION OF THE COAST-TYPES IN ANTARCTICA.

and Pacific coast-types is not in topographic description but in the elucidation of geographical evolution. It represents the Atlantic and Pacific Oceans as two geographical units, each of which developed at different dates, and by different processes, which are revealed by the different structures of their boundaries. The basins of both oceans are attributed to the continued shrinkage of the earth ; but in the Atlantic the shrinkage caused the subsidence of a long band, which cut across the structures of the adjacent lands; in the Pacific, on the other hand, the basin was caused by subsidence, accompanied by the buckling of the land on its border into great folds, inclined towards the sunken ocean-floor.

The progress of research, since the original definition of these two coast-types, has strengthened Prof. Suess's view as regards the Atlantic, by dismissing the supposed exceptions, in which Atlantic coasts were thought to have a Pacific structure, such as Norway (*vide* von Richthofen), northern Spain (*vide* Suess) or South Africa.[1]

As regards the Pacific type, however, the original definition requires modification ; for, if it is to be rigidly applied, then only approximately one-third of the known coast of the Pacific Ocean is of the Pacific type ; and, if two-thirds of the Pacific Ocean coasts (excluding Antarctica) are of the Atlantic type, then the division of the coasts of the world into two equivalent types would have broken down and its important geological corollaries would be no longer valid.

7. The Atlantic and Pacific as Petrographic Provinces

Prof. Suess's original classification appears to me to state a great geographical truth ; but its abandonment is threatened by the attempt to give it a petrographic as well as a tectonic basis.

[1] There is also much to be said for the view that the West Indian area is not Pacific, either tectonically or historically.

It is proposed by Harker, Prior, and Becke to characterise all igneous rocks rich in alkalies as the Atlantic "branch," and all those poor in alkalies as the Pacific "branch."[1] The author has pointed out that the distribution of these two types of igneous rocks does not coincide with the Atlantic and Pacific coast-types, or with the Atlantic and Pacific regions, or with the geographical structures characteristic of those two coast-types.[2] Moreover, areas which at one time discharged lavas that belonged to the Atlantic branch, at another time discharged those of the Pacific branch.

Prof. Suess's classification of coast-types is still valid, if slightly modified in terms and left on its original structural basis. Hence we may proceed to consider the nature of fiords and their distribution, recognising that the ocean-borders which they indent are built upon two very distinct types of structure.

[1] The development of this view is summarised by Harker in his *Natural History of Igneous Rocks*, 1909, pp. 90–109.

[2] Some of the petrographic evidence on which these conclusions are based is stated in a paper in *Scientia*, vol. xi. 1912, pp. 56–63. Since then further occurrences have been announced of alkaline rocks in the Pacific area. Dr. H. J. Jensen has proposed (*Proc. Linn. Soc. N.S. Wales*, vol. xxxiii. 1908, p. 188) to name the alkali-rich group of igneous rocks "Katepeirean" (concerned in the destruction of continents), and the group poor in alkalies the "Anepeirean" (concerned in the upbuilding of continents), owing to the unsuitability of the terms "Atlantic" and "Pacific" for groups of rocks.

CHAPTER III

FIORDS AND ALLIED COASTAL STRUCTURES

The deep, divine, dark dayshine of the sea,
Dense water-walls and clear dark water-ways,
Broad-based, or branching as a sea-flower sprays
That side or this dividing.

SWINBURNE.

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1. The General Features of Fiord Coasts.—2. Fiords defined as Drowned Valleys in Highlands.—3. The Classification of Drowned Valleys—Dana's Establishment of Fiords as a Special Geographical Type; von Richthofen on Fiords as characteristic of Longitudinal Coasts.—4. Are Fiords limited to Glaciated Areas?—5. Fiord Thresholds; discovered by Cook; described by Darwin; in some Cases formed by Banks of Sediment.—6. Allied Types of Drowned Valleys.—Fiards, Föhrden, Rias.—7. General Terms for Drowned Valleys.—Gulfs, Sounds, Lochs, Firths.

1. THE GENERAL FEATURES OF FIORD COASTS

THE term "fiord" has been adopted for long, narrow arms of the sea in high coast-lands. Fiord-coasts are the most remarkable of all coastal types. Long, straight, low-lying coasts are comparatively uninteresting, for long stretches can be seen at a glance, and the mind turns with relief from the monotonous shore-line to the wide expanse of the boundless sea.

I never was on the dull, tame shore,
But I loved the great sea more and more,

is B. W. Procter's expression of this feeling. A fiord-coast, on the other hand, appeals at once to the imagination, and fastens it on the land. Even a map of a fiord-coast attracts attention by its complexity; and the view from the sea of a fiord-indented country, with its jagged outline, with its quiet channels leading to unseen recesses, and the uncertainty whether its steep cliffs belong to islands or to the mainland, suggest questions which can only be answered by a detailed survey of the area.

The long, narrow seaways, with their quiet waters, offer tempting passages inland, and the visitor is lured farther and farther up them, now by a waterfall which leaps from some high-lying valley into the sea, now by the close approach of the opposite cliffs forming a gateway, again by the desire to round a sudden bend, or explore a remoter branch, or reach the green pastures at the fiord head.

Fiords have many sources of attraction. They combine mountain and coastal scenery, their cliffs and waters are illuminated by ever-varying colour-effects, and the sky is the scene of constantly changing cloud-forms, as the moist air is chilled by cold winds from the snow-clad summits or glacier-valleys. Fiord countries offer the student of history and social politics opportunity for study of special conditions of life and industry; to the geographer and geologist they present puzzling problems connected with the origin of their valleys, which are often of such artificial regularity that many fiords have been named "canals."

The special feature of a fiord-coast is the invasion of the land by numerous arms of the sea, which may repeatedly subdivide; they thus cut the land into long branching peninsulas, or, when the branches of the fiords unite, break it up into islands. The land, moreover, is always high, and the fiords are bounded by steep cliffs, which often extend in unbroken precipices for considerable distances; hence, though much of the land is difficult of access, the surface may be fairly level.

There is, too, a rarity of bays and a scarcity of sites for human settlements. As the fiords have straight, parallel sides, and as the sea within is quiet, the cliffs are not worn by waves into bays, which, when subsequently silted up, provide excellent positions for seaside villages. The chief settlements are little hamlets on the valley floors, where the fiord begins; and, as these areas are small and widely scattered, fiord-lands are sparsely populated.[1] Thus Norway, the chief European fiord-country, has the thinnest population of any country in Europe; the total population is only sixteen to the square mile, and two-thirds of the people live in the one-eighth part of Norway which lies lower than 500 feet above the sea. The high plateau which forms the interior of Norway has only one inhabitant to every ten square miles.

Another important feature is that in typical fiord-countries the main rivers do not discharge into the fiords, but reach the sea after crossing nearly the whole width of the land behind the fiord-coast. Thus, in Scandinavia, the chief rivers rise near the fiords, but flow south-eastward across Sweden into the Baltic; in New Zealand the rivers which rise close to the western fiords flow south-eastward across nearly the whole width of the country to the eastern coast; and in America, both in the far south in Patagonia and in the north-west in Alaska and north-western Canada, the rivers flow away from the fiords and either after a sinuous course reach the sea to the north or cross America to the Atlantic. Hence, owing to the comparative shortness of the rivers that flow into the fiords, the alluvial plains beside them are small and scattered.

Great river-valleys are usually the chief routes into the interior of a country, but the valleys at the heads of the fiords are usually so short and steep that the roads along them are costly to build and difficult to maintain,

[1] The influence of the fiords on the distribution of the population is shown by Dr. Hagbart Magnus, "Zur Siedelungskunde von Norwegen," *Zeit. Ges. Erdk. Berlin*, vol. xxxiii. 1898, pp. 367–92, pls. xii., xiii.

and railway construction in them is so expensive that it is generally impracticable, except where required for mining development or by a large tourist traffic.

Hence the dominant conditions of a fiord-country are its intersection by deep sea-filled valleys which render land communication difficult; the comparative inaccessibility of the best agricultural land; the smallness and isolation of the fertile plains, and the restriction of trade to the sea-routes, as the valleys that lead inland are of little commercial value. Thus in Norway only three railways lead from the coast inland to Sweden, and in 1898 these lines took only a third of 1 per cent. of the foreign trade of Norway; and, in spite of its long land frontier, 95 per cent. of the foreign trade of Norway was by sea.[1]

Fiord-countries accordingly remain thinly peopled; and, so long as their population is small, the shoals of fish that frequent the fiords, the flocks of birds that breed on the cliffs, the good pasturage on the upland meadows, and cultivation on the sheltered fields beside the heads of the fiords, provide adequate supplies of food and clothing. Reared in these sheltered and scattered homes, the people show in a strong, independent character the unusual conditions of their environment.

2. Fiords defined as Drowned Valleys in Highlands

The essential nature of fiords was correctly stated by Harriet Martineau[2] as "in fact, long, narrow valleys, filled with sea." Fiords are, indeed, old valleys that have been drowned by the entrance of the sea. There are, however, many drowned valleys and arms of the sea which are not fiords. River estuaries in lowlands such as that of the Thames, and the vast marshes and lagoons such as those on the north-western coast of the

[1] *Norway* (Kristiania, 1900, p. 6).

[2] H. Martineau, *Feats on the Fiord: a Tale of Norway*, chap. i.

Black Sea are not regarded as fiords, although subsidence may have aided in their formation.

It is difficult to draw up a definition of a fiord which will at once separate true fiords from other arms of the sea; but the popular idea of a fiord is essentially correct. Thus Harriet Martineau lays stress on the fact that fiords have high banks: "The high, rocky banks shelter these deep bays (called fiords) from almost every wind."[1]

The definitions in various dictionaries adopt the presence of high banks as an essential character. Thus, according to *The New English Dictionary*, a fiord is "a long narrow arm of the sea running essentially up between high banks or cliffs, as on the coast of Norway." *The Century Dictionary* is even more explicit. A fiord is there defined as "A deep indentation of the land, forming a comparatively narrow arm of the sea, with more or less precipitous slopes or cliffs on each side. The coast of Norway offers the best examples. True fiords can exist only where a steep and lofty mountain-range borders closely on the sea." These definitions are, however, inadequate, because they do not distinguish fiords from such arms of the sea as those on the south-eastern coast of China and the north-western coast of Spain; and they would be as applicable in New Zealand to the gulfs at the north-eastern corner of the South Island as to the famous fiords along the south-western coast. Though the popular definitions do not explain the difference, it has always been recognised that many gulfs in mountainous countries are not fiords.

3. The Classification of Drowned Valleys

The long, narrow arms of the sea to which the term "gulf" is properly restricted are valleys which have been drowned by the inflow of the sea in consequence of the subsidence of the land. These drowned valleys belong

[1] H. Martineau, *Feats on the Fiords*, chap. i.

to several distinct kinds, which must be separated in a scientific classification. The different variations include fiords, fiards, rias, lochs or loughs, firths or friths, and föhrden. The last five of these are local Scottish, Irish, and German terms; and the three chief groups are the fiords, fiards, and rias.

The first attempt to establish fiords as a distinct class of arms of the sea was by J. D. Dana in 1849, in his *Report of the Wilkes Expedition*, when he compared the channels running into the western coast of America north of 48° to the fiords of Norway. His idea of the essential character of a fiord may be inferred from the following extract:

"These deep but narrow channels have the most irregular forms, often extending to a length of fifty or sixty miles, and by their intersections making a complete network of water, for internal navigation" (Dana, **1849**, p. 379).[1]

He laid stress (p. 380) on the fact that fiords occur only in high latitudes. He remarked their occurrence north of 43° N. on the eastern coast of America, and south of 42° S. in South America.

"In Europe," he says, "the fiords of Norway and the deep bays of Scotland are well known; the coast contrasts strikingly with the outline of France, Spain, and Africa. The African continent does not reach below lat. 36° and has a simple outline throughout.

"There are, then, certain fiord latitudes—or a fiord-zone for the globe, both north and south of the equator. New Zealand and the Auckland and other islands partake much of the same character, and are the only lands in the southern hemisphere, besides the extremity of America, which reach into the southern fiord-zone.

[1] Subsequently, in his *Manual of Geology* (1871, p. 541), Dana defined fiords as "deep, narrow channels occupied by the sea, and extending inland often for 50 and 100 miles." He accepts those of the north-western coast of the British Isles as fiords, and holds that the distribution of fiords is coincident with the distribution of glacial drift.

These facts lead to interesting conclusions respecting extended areas of subsidence encircling our globe ; for the fiords may be shown to be former valleys of the land now filled with the sea" (Dana, **1849**, p. 380).

Oscar Peschel in **1866** adopted a definition of fiords which was essentially the same as Dana's, though, as we shall see later, he made a great advance towards the explanation of their ultimate cause. According to his definition "fiords are deep and steep gorges [*Schluchten*] on the coasts of continents or islands. These indentations very frequently extend inland perpendicularly or at a very high angle," and he adds that the feature which "strongly separates fiords from all similar coastal divisions is their local aggregation and gregarious occurrence." He, however, accepted Dana's view that fiords are only met with in high latitudes ; but he explains their limitation in distribution to various climatic factors as well as to the action of ice.

Dana's view was also adopted by Prof. Penck (**1894**, vol. ii. p. 563), who accepted a simply descriptive definition of fiords. He said : "long-extended, narrow, much-branched inlets [*Buchten*] which run inland up to over 100 kilometres we call Fiords." He attributes to them a double dependence on glacial action, since the glaciers first modelled the valleys, and then, by their occupation, prevented their being filled up by sediments (Penck, **1894**, vol. ii. p. 574). Fiords, according to Penck, are ice-modelled, drowned valleys which have escaped being filled by sediment.

Penck had clearly remarked earlier (**1882**, p. 372), that fiords were old valleys that had been modified by ice.

These definitions are, however, inadequate, as there are many deep, narrow channels occupied by the sea in areas nearer the Equator than the range of low-lying glacial deposits ; Dana would, therefore, have declined to accept these inlets as fiords. This difficulty was recognised by the great German physiographer F. von Richthofen, who accordingly proposed, in 1886, to separate many narrow arms of the sea from fiords under the name of "rias." Von Richthofen based his distinction between fiords and rias largely on his classification of coast-types (see pp. 28–31).

According to him fiords are inlets on longitudinal (concordant) coasts. The corresponding narrow inlets on transverse (discordant) coasts he regarded as a distinct class, and he called them "rias."

This distribution has been accepted by Suess, and is best known owing to its adoption by him.

Fiords, according to von Richthofen (**1886**, p. 300), have the following characteristics: "Fiords are arms of the sea which go far into the interior of mountain districts. They are narrow and deep, and branch at their upper ends. Take away the sea, the valley-system remains." He supplemented this definition by the statements that fiords are limited to areas that have been glaciated, and attributed the formation of the fiord-valley to the "effect of water, aided to some extent by ice." "Fiords," he says (Richthofen, **1886**, p. 254), "are, in the first instance, pure valley formations made by 'flowing water.'" Fiords are also limited to coasts washed by warm currents, as under such conditions precipitation is heavy and water-erosion is powerful. Typical fiords are almost exclusively characteristic of concordant coasts (see p. 30), and are found only in firm rocks (Richthofen, **1886**, p. 300). Von Richthofen lays stress on the most unique feature in fiord-valleys, the gradual rise of the floor, instead of a down-slope of the floor toward the mouth of the valley. "The floor of a fiord," he says (p. 300), "has nevertheless only seldom the form of a valley-channel in that it usually rises near its mouth to a more or less high threshold." He attributes this threshold to the accumulation of sediment near the mouth of the fiord, and admits that if it be composed of hard rock his theory of fiord-formation would be untenable (Richthofen, **1886**, p. 302).

Von Richthofen, therefore, regarded fiords as long, deep, branched arms of the sea, as occurring in valleys excavated by river-erosion, as especially characteristic of coasts in which the mountain-system is parallel to the shore-line, and as restricted to glaciated regions. He adds as a common, but not essential character, the presence of a threshold separating the deep water within the fiord from the sea outside.

This definition is, however, open to serious objections; it is impracticable to limit fiords to concordant coasts, as some of the most typical Norwegian and American fiords occur where the coasts are discordant; moreover, many inlets which von Richthofen regarded as rias are on concordant coasts, as in part of south-eastern China, which von Richthofen selected as the typical rias-coast. Hence many later authors use either of the two characters—occurrence in a glaciated area or the presence of thresholds—as the essential feature of a fiord. Several geographers who have made detailed studies of fiords—including Oscar Peschel (**1866**), Dinse (**1894**), and O. Nordenskjöld (**1900**), have refused to accept as a fiord any inlet which has not been occupied by ice.

4. Are Fiords limited to Glaciated Areas?

The restriction of fiords to glaciated areas has been a very widespread belief, since attention was called to the prevalence of fiords in high latitudes by Dana in 1849. There can be no doubt that fiords are best developed in areas that were formerly glaciated. Thus the typical fiords of Europe are in Norway and Scotland, and they disappear as the coasts are followed to the south; in America they occur in Alaska, Labrador, Greenland, and Patagonia. In New Zealand they are found in the southern part of the South Island and the arms of the sea in the warmer and more northern regions have never been called fiords.

Many authors have, however, rejected the view that fiords are restricted to high latitudes. Thus, according to Sir Henry Howorth (**1893**, vol. ii. p. 627):

> "It is sometimes said that fiords only exist in Arctic lands. This is not so. In the Arctic lands they have been cleared of debris by the glaciers, while elsewhere they are choked. Thus fiords exist in Asia Minor, in Dalmatia, in the Asturias in Spain, in Brittany, in the desiccated Gulf of Carentan in Normandy, and in Granada between the Atlantic and the lake of Venezuela."

He refers also to fiord-like fissures in Provence, and to valleys in the basins of the Rhône, Isère, Saône, and among the Maritime Alps, which, if filled by the sea, would be fiord-like. Subsequently he gave a similar list (Howorth, **1905**, vol. i. p. 434) of fiords in warm countries, and added the occurrence of fiords in the Andaman and Nicobar Islands, and in Central America; he claimed as fiords the submerged valleys opposite the mouth of the Congo and off the Golden Gate of San Francisco, and various filled valleys, as in Dorsetshire. The supposed restriction of fiords to formerly glaciated districts he repudiated as "a more than usually preposterous argument," and claims that his list of fiords in non-glaciated areas "entirely destroys" Dana's view.

The existence of non-glaciated fiords depends on the definition of fiords and on the characters of the valleys mentioned in Sir Henry Howorth's lists. Consideration of the glacial criterion, therefore, requires a definition of fiord, and determination of the actual geographical distribution of fiords.

There is a considerable body of authority for the occurrence of fiords in non-glaciated areas, including Burat, Rutimeyer, Hahn, Howorth, and Lawson. And unless the occupation of a fiord by ice has impressed on it some special character which is not present in non-glaciated arms of the sea, the glacial test for separation of fiords from inlets which are not fiords is of no practical value. If fiords can only be characterised by a hypothetical character, the distinction is of little or no geographical value.

5. Fiord-thresholds

The presence or absence of a shallow threshold at the mouth of the fiord is a character of more definite classificatory value. The fact that fiords often have a shallow mouth which, like a threshold, separates the basin within from the sea without was first recognised by Captain Cook by soundings in Tierra del Fuego. On December 19, 1774, he entered Christmas Sound and found depths 240, 222, 300, and 360 ft., the last being "nearly in the middle between the two parts that form the entrance to the inlet." Sailing up the sound, he passed a rocky islet and "we sounded and found no bottom with a line of a hundred and seventy fathoms [1,020 ft.]. This was altogether unexpected, and a circumstance that would not have been regarded if the breeze had continued; but at this time it fell calm, so that it was not possible to extricate ourselves from this disagreeable situation."[1] He continued up the Sound, and he says, "we continued to sound, but always had an unfathomable depth."[2]

Farther up the Sound he discovered the harbour which he named "Devil's Basin," divided into two parts—an outer basin with 78 and 102 ft., and an inner basin with depths of 102 and 138 ft.—and surrounded by "savage rocks" rising to "a vast height." The passage between the two basins is narrow and only 30 ft. deep.[3]

[1] J. Cook, *A Voyage Towards the South Pole*, 1777, vol. ii. p. 175, Chart No. VII.

[2] *Ibid.* p. 176.

[3] *Ibid.* p. 179.

The South American sealers, says Darwin (**1846,** edit. 1890, p. 300), were so familiar with the existence of the thresholds that they always looked out for an anchorage near the entrance of the creeks. Darwin recorded the fact for many of the Patagonian fiords. He remarks:

"I may take this opportunity of remarking on a singular, but very common character in the form of the bottom, in the creeks which deeply penetrate the western shores of Tierra del Fuego, namely, that they are almost invariably much shallower close to the open sea at their mouths than inland.

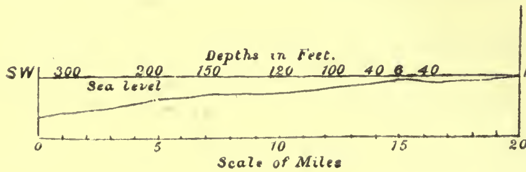
"This shoalness of the sea-channels near their entrances probably results from the quantity of sediment formed by the wear and tear of the outer rocks exposed to the full force of the open sea. I have no doubt that many lakes, for instance in Scotland, which are very deep within, and are separated from the sea apparently only by a tract of detritus, were originally sea-channels with banks of this nature near their mouths, which have since been upheaved."

Thresholds were found in many other fiords, and in 1879 Gustav Leipoldt, in his edition of Oscar Peschel's *Physische Erdkunde,* claimed the presence of a threshold as an essential characteristic of a fiord (**1879**, vol. i. p. 480). "In all fiords the floor at the outlet is much shallower than in the interior."

Von Richthofen, in 1886, regarded the thresholds as not essential, as he recognised that they were not present in many fiords, and if, as he expected, they are always made of heaps of sediment, and not of rock *in situ,* they would be of comparatively little significance.

The chief modern champion of the threshold as the essential character of fiords is Dinse in an important monograph on Fiord Formation published in 1894. This character, though at first sight the most promising test of a fiord, proves unsatisfactory; since, as will be shown subsequently, the threshold is absent from many fiords, and it is well developed in many inlets which are not fiords.

Some thresholds, such as that at the lower end of Milford Sound, New Zealand (see Fig. 13), are so massive that



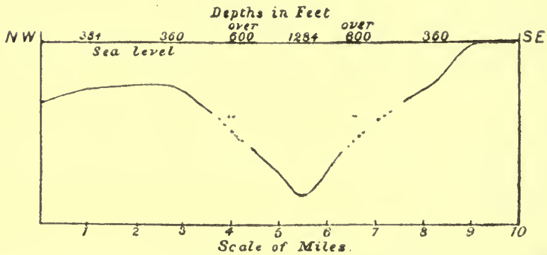


FIG. 13.—(*a*) SECTION ALONG A TYPICAL RIA (THE RIA DE MUROS, SPAIN); (*b*) ALONG A FIORD WITH A MASSIVE THRESHOLD (MILFORD SOUND, NEW ZEALAND).

they may be rock-ridges due to earth-movements; but the formation of many thresholds by banks of sediment can be satisfactorily explained. Morainic material was likely to have been deposited in especial abundance as terminal moraines at the mouths of glacier-valleys, where the ice would have been dissolved rapidly by the sea-water; and many of the Norwegian thresholds, such as that at the mouth of Ofoten Fiord, appear to consist of a bar of moraine, though of course it is impossible to say that there may not be a foundation of rock beneath. Mr. Monckton (in Kolderup and Monckton, **1912**, p. 3) explains the shallow entrance to the Bergen fiords as " at least partly due to the deposit of moraine-material in the outer parts of the fiords," though he adds that "some or all of them may be rock-basins to a certain extent."

Lateral moraines may also give rise to thresholds in consequence of landslips. Large quantities of morainic material may be deposited upon the sides of the valleys, and, so long as it is dry, will remain with high, steep banks. But if the moraine matter becomes saturated with water, as readily happens to such permeable deposits, it will slide in landslips on to the floor of the valley. This process can be observed on a great scale in the Himalaya, and has been graphically described by Sir Martin Conway, and more recently by Dr. A. Neve, who, in a reference to various Himalayan landslips, both of drift and of solid rocks, remarks (**1911**, p. 347): "There is, then, no difficulty in accounting for the vast accumulation of mountain-ruin which fills some of the wider valleys to a depth estimated at possibly 4,000 ft." Some high thresholds may thus have been formed across fiords by the fall of morainic material in land-slips from the sides.

The existence of fiord-thresholds cannot be relied upon as an essential character of fiords. For, on the one hand, many fiords have no such threshold, and the floor slopes gradually seaward as in an ordinary estuary; and, on the other hand, the fiord-thresholds are often simply alluvial bars such as occur at the entrance to rivers and estuaries. Their formation is easily explained. It is partly a mechanical and partly a chemical effect. The coarse sediment that is being carried seaward by the river is deposited owing to the stoppage of the current, while fine silt is quickly precipitated by sea-water, owing to the coagulating effect of the salt.

Alluvial thresholds occur off estuaries and harbours which are certainly not fiords. Thus the land-locked basin of San Francisco ranges in depth to 100 ft.; it communicates with the Pacific through the narrow passage of the Golden Gate, which has depths of 360 ft., whereas off its inner end the depth is only 36 ft., and off the outlet to the Pacific is a crescentic shoal from 30 to 40 ft. deep.[1]

Rio Janeiro Bay is of the same type. It consists of a large basin with the longer axis parallel to the coast. It is surrounded by lofty mountains which trend parallel to the coast. These ranges project into the entrance channel as a series of jagged headlands, which have the characteristic shapes of drowned ridges, as far as can be judged from the Admiralty Chart No. 541, 1857. The main basin is comparatively shallow, the deepest trenches on the floor being 84 ft. deep. The channel which leads to the sea is deeper; the maximum shown on the chart is 162 ft. The mouth is shallower, 66 ft. being the greatest depth recorded in one line of soundings across it. Sydney Harbour, which resembles a föhrden in type, affords another illustration. It is 136 ft. deep near the city; toward the sea the depths are less. In one section across the harbour, east of Kiribilli Point, the greatest depth is recorded as 42 ft.; then succeeds another basin, which is 84 ft. deep in one place, and is bounded by a threshold.

6. Allied Types of Drowned Valleys

The essential characteristics, therefore, of fiords, omitting for the present any theoretical consideration respecting their origin, may be summarised as follows: A fiord is a long and narrow drowned valley, which runs between high cliffs far into highland or mountainous country. No great river flows into a fiord, for the main drainage of the land is away from the fiord coast. A fiord often includes deep rock-basins, which are separated from the sea by a single threshold near the mouth, or are separated from one another and the sea by a series of thresholds. A fiord is usually branched; the branches

[1] Admiralty Chart No. 591.

are usually straight, and the branching is angular; and the branches may unite to form a network enclosing islands.

This description excludes arms of the sea in lowland countries, many of which have been regarded by high authorities as fiords. Thus Penck (**1882**, p. 349) expressly rejected Peschel's restriction of fiords to mountainous coasts. Shaler, in his memoir on harbours, also accepted fiords in lowlands (**1893**, p. 114). Günther does the same, for he includes the Scottish firths as fiords (**1899**, p. 604; in his main classification, however, pp. 590–93, he refers them to föhrden). Nevertheless, the balance both of opinion and convenience appears strongly in favour of restricting fiords to high coast-lands.

Fiards.—The eastern coast of Sweden has many long inlets, which are studded with rocky islands, separated by irregular peninsulas, and connected by a maze of channels. The area around Vestervik is a typical example (Fig. 28). These inlets are known as "fjärden"; and the term "fiard" may be conveniently adopted for this geographical type. The Swedish fiards agree with fiords in five characteristics—they have rocky coasts; their shores are composed of old, hard rocks; they are drowned valleys; the adjacent country was once entirely covered by an ice-sheet; they often consist of a basin separated from the sea by a threshold. The essential difference between fiords and fiards is that the latter occur in coasts where the land is low. The outline of a fiard-shore is therefore determined by the upper edges of the valleys and not by the lower rock-walls near the bottom of deep gorges. The Norwegian fiords, if submerged much deeper, would acquire similar outlines to the fiards, as is shown by Fig. 69.

"Fiard," of Swedish origin, seems therefore a very useful term for sea-drowned valleys, which are not river-estuaries, and occur in lowland countries composed of hard rocks. They occur in many places along the Norwegian and Swedish coasts (Pl. II. Fig. 2).

Föhrden.—A special form of inlet occurs along the shores of the western Baltic through Denmark and Schleswig-Holstein to Kiel (Fig. 29). This coast is indented by long, parallel-sided arms of the sea, which are not now river-estuaries, and thus present several of the characteristics of fiords; like fiards, they belong to lowland country, but they are shallow and have no well-defined thresholds. They are locally known as "föhrden," or "förden," which is doubtless a variation of the word "fiord." Muret-Sanders's *Encyclopädisches Wörterbuch* (vol. iii. p. 747) translates the term as cove or inlet. The relations of fiords and föhrden have been often overlooked, but they were remarked by Penck (**1894**, vol. ii. p. 568), Dinse (**1894**, p. 241), Hubbard (**1901**, p. 337) and have been discussed by Werth (**1908** and **1909**). The föhrden have been often regarded as fiords; thus Lord Avebury refers to "the sheltered and shallow fiords of Denmark,"[1] and the series of straits and wide, shallow lagoons which together convert the northern part of Denmark into an island are known as the Liim Fiord. Farther south, on the western coast of Denmark, are the shallow lagoons known as Nissum Fiord and Stavning Fiord. This south-western part of the Danish coast is a liman coast and not a fiord coast, and its inlets should be separated from fiords. Von Richthofen (**1886**, p. 306) regarded it as his Cimbrian coast-type, due to the combined action of ice on a lowland, and ordinary shore-action.

Föhrden are regarded by Dinse as related to fiards, as they occur in low-lying country. They are, however, found in districts composed of rocks which are geologically young. The rocks along this coast range in age from Cretaceous to Miocene, but they are mostly covered by a deep sheet of drift, and they are the youngest rocks in Europe with inlets which have been assigned to the fiord type. Dinse (**1894**, p. 241) regards Kiel Föhrde, or Hafen, as the most fiord-like of these föhrden.

[1] Avebury (J. Lubbock), *Prehistoric Times*, 1865, p, 81.

Föhrden are related to fiords by their length, narrowness, and angular branching. But if föhrden are to be included among fiords owing to these characters, then many inlets in warmer regions should also be regarded as fiords. Föhrden, as shown later, were estuaries in lands composed of soft beds; but they have lost the rivers that once flowed into them, and have been partially filled by silting.

Rias.—The inlets which most closely resemble fiords are those for which von Richthofen suggested the name of "rias," from the inlets on the coast of Galicia in north-western Spain.

Rias are the submerged valleys found between the ends of mountain-lines which run out to sea. Such coasts, according to von Richthofen, are extraordinarily irregular and are fringed by numerous islands.

The characteristics which, according to von Richthofen (**1886**, p. 303), separate fiords and rias are (1) that fiords are features of longitudinal and rias of transverse coasts; (2) that in rias, water and wave action both helped in the formation of ridges of hard rock separated by furrows; whereas fiords are protected from marine abrasion and from deposition of alluvium by rivers; (3) that the agencies of denudation have free scope in acting on the ridges around rias, which have the normal forms of highlands and mountains.

Prof. Penck distinguishes rias from fiords as follows (**1894**, vol. ii. p. 566):

"Rias never extend into the land so deeply, the average being merely 10 to 20 kilometres (6 to 12 miles), and the maximum is 50 kilometres (31 miles); their branching inland is unimportant, and they increase outward both in depth and width, so that they widen seaward like a funnel. Here, also, is their greatest depth, which seldom exceeds 100 metres (328 ft.), and it sinks either not, or only to a trifling extent, below the floor of the fore-lying sea."

The meaning of the word "ria" has been greatly extended by some authorities. Thus Gulliver uses it for any drowned valley. He says (**1899**, p. 220): "The term 'ria,' from the Spanish, may be advantageously used to cover all types of subaerially carved troughs, including von Richthofen's fjord, ria, Dalmatian, and liman types." *The New English Dictionary* (vol. viii. 1908) defines ria as "a river-mouth." De Lapparent [1] adopted the same definition as Penck; but, according to de Martonne (1906, p. 300), he attached most weight to the unbranched nature of rias. De Martonne himself regards rias as specially characteristic of ungrained coasts (**1903**, p. 9).

In spite of these varied uses of the word "ria," the distinction between fiords and rias appears convenient. It seems unnecessary to restrict rias to discordant coasts. They are drowned river-estuaries in mountainous or highland areas. They usually receive large rivers and the main drainage of the adjacent country. Their floors have a steady seaward slope and usually there is no rock-barred threshold.

The typical rias occur in non-glaciated areas, such as the north-western corner of Spain and the south-eastern coast of China, which von Richthofen has selected as the best-developed ria-coast. The most typical British rias are those in south-western Ireland, such as Dingle Bay, while the Firth of Forth may also be regarded as a ria.

7. General Terms for Drowned Valleys

The remaining geographical terms which it is advisable to consider in connection with the classification of drowned valleys are "gulfs," "sounds," "lochs," and "firths."

Gulfs.—The term "gulf" is applied to all long and comparatively narrow arms of the sea; and gulfs should be divided into various classes. "Gulf," it must be remembered, is a geographical name which has been very vaguely used. Thus, on the one hand, the Bay of Fundy should

[1] A. de Lapparent, *Leçons Géogr. Physique*, 3rd ed. 1907, pp. 266–7.

be a gulf, and not a bay; and on the other hand, the Gulf of Venice, the Gulf of Taranto, the Gulf of Mexico, the Gulf of Martaban and the Gulf of Guinea are bays, or seas. The general rule has been to regard gulfs as essentially long and narrow. The typical gulfs are those like the Gulf of California, Spencer Gulf, the Gulf of Tartary, the strait between Saghalien and the mainland of eastern Asia, the Gulf of Finland, the Gulf of Salonica, and the Gulf of Lepanto in Greece. Moreover, many of the baylike gulfs, such as the Gulf of Otranto in southern Italy and the Gulf of Carpentaria in northern Australia, though as wide as they are deep, by their parallel sides approximate to normal gulfs. Others, such as the Gulf of Mexico, have narrow entrances, though it is inconsistent to call that great inland sea a gulf while Hudson Bay is called a bay.[1]

"Sound" is another popular and variable term, as it is used both for straits and gulfs. The name was perhaps originally used for straits. The word is derived from a different source from that for an audible sound; it came from the Anglo-Saxon *Sund*, which is still used in German, and meant a place of swimming. The many sounds among the Scottish islands, The Sound between Sweden and Denmark, Kalmar Sound between the island of Oland and Sweden, and the sounds in the Arctic Archipelago of North America, are all straits; while many sounds are gulfs—such as Picton Sound, Milford Sound, and George Sound, in New Zealand, Prince William Sound in Alaska, Howe Sound in British Columbia, Eyre Sound in southern Chile, and Nimrod Sound in China.

It might have been better to restrict the term "sound" to straits; but that course is now hardly practicable owing

[1] The distinction between gulfs and bays based on form is more observed in English than in French, in which *golfe* is generally used for a large bay. Thus the Bay of Biscay is the Golfe de Gascoigne; and the "Golfe de Besika Baie" shows both terms applied to the same locality. The French Dictionary, *Petit Larousse*, 1910, defines "baie" as a "rade, petit golfe," and "golfe" as "partie de mer qui s'enfonce dans les terres."

to its world-wide use for gulfs. "Sound" is, therefore, an indefinite term, the meaning of which varies with the locality.

Lochs.—The term "loch" is the Scottish form and equivalent of the Irish "lough"; and both are connected with the Welsh *lloch*, the Cornish *lo*, and Latin *lacus*, a lake. The term is used for lakes and arms of the sea. The Scottish lochs include fiords and rias, as well as freshwater lakes.

Firths.—Firths are Scottish arms of the sea, which are drowned valleys, though the term is also used for straits such as the Pentland Firth. The word, according to *The Century Dictionary*, is Anglo-Saxon. Its Celtic equivalent, *ffridd*, means peace and protection, and may refer to the sheltered position of these arms of the sea. The name is sometimes spelt "frith," which has been explained, some think erroneously, as based on a supposed connection with the Latin *fretum*, strait, instead of with the Scandinavian "fiord."

The firths, according to Dinse, approximate to föhrden; and they appear to be normal rias, as they are usually funnel-shaped instead of having parallel sides. They are not characterised by angular branching or headlands, and they are not restricted to geologically young rocks. They are essentially drowned river-estuaries in rocks of any age.

Drowned valleys, therefore, include three definable classes—fiords, fiards, and rias. The words "gulf," "sound," "loch," and "firth" are all indefinite and variable in meaning.

The distinctions between fiords, fiards, and rias involve characteristic connected with their mode of formation and the value of these characteristics can best be determined after consideration of the leading fiords in different parts of the world. Meanwhile, it should be remembered that fiords occur in highlands of hard rocks; fiards in lowlands of hard rocks; rias are drowned river-estuaries; föhrden are a variety of beheaded rias.

PART II

THE FIORD-SYSTEMS OF THE WORLD

CHAPTER IV

THE FIORDS OF NORWAY

A sheer surf-beaten island fronts the shore
  Close to the headland cliffs, whence stormy waves
  Have rent it; there the sea, imprisoned, raves
Between dark dungeon walls, and evermore
Deep in that chasm, with sullen, booming roar,
  Comes surging in a rushing, raging tide
  That pants and boils, and climbs each dripping side.

E. G. A. HOLMES.

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1. Norway the Typical Land of Fiords.—2. The Three Coastal Divisions.—3. The Representative Fiords of South-Western Norway—The Sogne, Hardanger, and Bukken Fiords.—4. The Depths of the South-western Fiords.—5. The Origin of the South-western Fiords.—6. The Christiania Fiord.—7. The Fiord-network near Trondhjem.—8. The Arctic Rias.—9. The Geological Relations of the Fiords.—10. The Fiords and the Structural Lines of Norway.—11. Summary—the Norwegian Evidence as to the Essential Characteristics of Fiords.

1. NORWAY THE TYPICAL LAND OF FIORDS

THE term "fiord," or "fjord," is of Norwegian origin, and the typical fiords of the world are those of Norway. It is, then, from Norway that we must learn what are the essential characteristics of a fiord.

Norway is the most fiord-dissected land in the world. It is so deeply indented that, while the coast-line following the general course of its outer rocks and capes is only 1,700 miles long, the actual shore-line along the fiords and around the larger islands is 12,000 miles. Norway has one mile of coast to every 10½ square miles of land; whereas France has the same length of coast to every 122 square miles; England and Wales have one mile of coast to every 25 square miles, and Scotland, with its indented coast, has one mile of coast to every 13 square miles.

On so great a length of coast as that of Norway there are naturally many different kinds of arms of the sea; but the term "fiord" is used in Norway for any arm of the sea, including bays, gulfs, and straits, and some of them are rias and others fiords. Nevertheless, there is one well-marked type of inlet in Norway so different from the ordinary inlets on the coasts of Europe and the eastern United States, that it has been regarded by European and American geographers as the typical fiord. It was owing to the special characters of these inlets that the term "fiord" has been adopted into the geographical language of the world.

2. The Three Coastal Divisions

The Norwegian coast can be divided into three main divisions. The first section extends north-eastward from Lindesnaes, the southernmost point on the mainland, to Christiania and the Swedish frontier. This section is rocky; it is fringed by many small islands and reefs, and is indented by occasional bays and gulfs, of which the most important is the fiord leading to Christiania.

The second section includes all the western coast and the most typical fiords of Norway.

The third section is along the shore of the Arctic Ocean from near Tromsö to the Russian frontier. It is indented by numerous great arms of the sea, such as Laxa Fiord, Tana Fiord, and Varanger Fiord. These are called fiords, but they are triangular in shape and widely open, and the valleys which they occupy are shallow in pro-

Photo by H. W. Monckton.

FIG. 1.—FJÄRLANDS FIORD.

A deep trench in a dissected plateau, with the tributary's valleys cut down almost to sea-level. (*Vide* pp. 79 and 87.)

Photo by H. W. Monckton.

FIG. 2.—THE TRANÖ ISLANDS,

Showing fiards in Northern Norway (Lat. 69° N.). (*Vide* p. 67.)

portion to their breadth; such inlets are rias rather than fiords, though they have true fiords as branches (Fig. 25); and it is not areas of this type which geographers have

FIG. 14.—SKETCH-MAP OF SWEDEN AND NORWAY.

Showing the distribution of the fiords and some of the structural lines. The area shaded in horizontal lines are drowned rift-valleys and sunklands.

had in mind when adopting the term "fiord" for a special geographical type.

The fiords of southern Norway occupy the seaward ends of valleys which radiate from the interior of the country. Thus, following round the coast from Aalesund to Christiania, Jörund Fiord and other branches of the Stor Fiord near Aalesund open towards the north-north-west. The Volden Fiord trends north-westerly ; the Nord Fiord and Sogne Fiord lie approximately east and west.

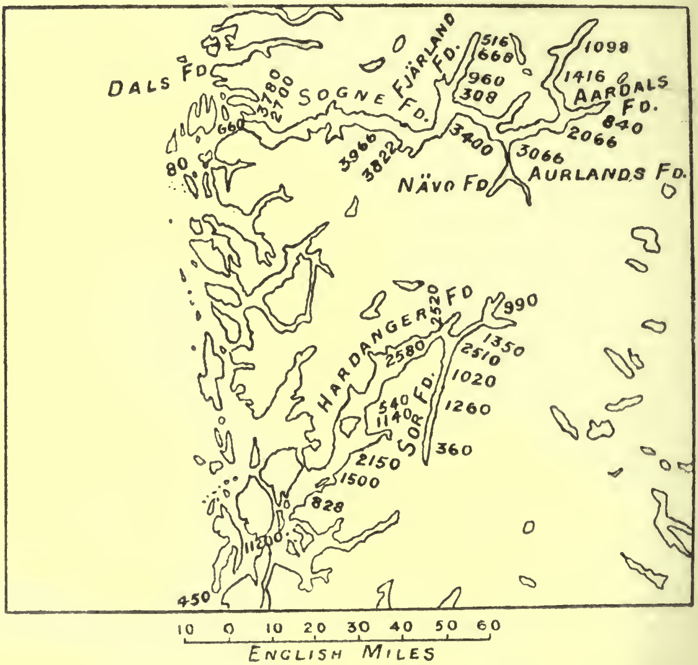


FIG. 15.—SKETCH-MAP OF THE SOGNE AND HARDANGER FIORDS.
Showing their courses and variations in depth (depths in ft.).

Farther south, Hardanger Fiord and Bukken Fiord trend south-westerly. At the southern extremity of Norway the valleys run southward ; thence, following the coast north-eastward, the fiords at Laurvik trend south-eastward ; and, though the Christiania Fiord lies north and south, some of its branches and the lakes to the north of it trend from north-north-west to south-south-east.

3. The Representative Fiords of South-western Norway

The typical fiords of Norway are those that penetrate the highlands of the south-western part of the country. Among the most famous examples are the Hardanger Fiord, Sogne Fiord, Nord Fiord, and Geiranjer Fiord, and it is to them we should turn to learn the essential characteristics of a fiord.

The country beside these fiords includes some of the parts of Norway which are geographically and geologically the best known. The nature of the fiords has been frequently discussed. Prof. W. M. Davis has stated the case for the glacial origin of the Hardanger Fiord. Prof. Reusch, in a valuable memoir, has described the evidence for their pre-glacial age. An excellent bibliography has been compiled by Kolderup and Monckton (**1912**, pp. 55–60).

The Sogne Fiord

The Sogne Fiord is perhaps the most representative of all the Norwegian fiords, and is the deepest fiord in Europe. It is the longest fiord in Norway, being 112 miles long; it is on an average four miles wide, and its greatest depth is about 4,000 ft. Its scenery is wilder, bolder, and more barren than that of the other long fiords of southern Norway.

The general direction of the fiord is east and west. The outer part of the fiord lies for fifty miles a little north of the 61st parallel, and its course includes three slight bends. The upper part of the fiord is more crooked, and it receives six main tributary fiords, which join it at high angles; and they give the plan of the fiord some resemblance to that of a river and its tributaries. Owing to the depth to which the side-valleys have been cut, there are fewer waterfalls than on the Hardanger Fiord.

Sogne Sjö, the entrance to Sogne Fiord, passes between many islands, of which the greatest length is north and

FIG. 16.—THE MOUTH OF THE SOGNE FIORD.
Showing the fiord-valleys in the Sulen Islands transverse to the main fiord.

south, and the valleys and the narrow fiord-straits between them trend in the same direction (Fig. 16). The hills rise to about 1,000 ft.; they have well-rounded forms, and are elongated north and south, at right angles to the length of the fiord. The average rainfall amounts to eighty inches a year, and, as the climate is mild, even in winter, any level land is fertile and the lower slopes are well wooded.

Within the fiord the elevation of the land soon increases, for the fiord penetrates into the highest area in Norway; the scenery grows bolder and wilder, the course becomes straighter and the sides are steeper, rising on each side in nearly parallel walls. Above the height of about 2,000 ft. the slopes become gentle, and the country is

Photo by H. W. Monckton.

FIG. 1.—ESSE FIORD, A TRIBUTARY OF THE SOGNE FIORD,
Showing its steep, straight wall, like one arm of a V. (*Vide* p. 79.)

Photo by H. W. Monckton.

FIG. 2.—ESSE FIORD,
Showing a preglacial platform and a V-shaped valley. (*Vide* p. 88.)

a widespread level plateau which has been interrupted by the formation of the fiord-valleys (Pl. II. Fig. 1). Some peaks rise from the plateau to the height of 3,000 ft., and some of the highest bear glaciers and snow-fields. Still farther inland the walls become still steeper (Pl. III. Fig. 1. and Pl. V. Fig. 1). The northern wall of the fiord slopes down at an angle of 28½° and the southern wall 34°, and the walls continue downward to the depth of about 4,000 ft. below sea-level.[1] From the top of the fiord-walls the land rises more gradually to mountains, some of which attain to the height of 4,500 ft. At Vik, fifty miles from the mouth, the fiord bends to the north at a right angle; and this reach, six miles long, is in line with Fjärlands Fiord (Pl. V. Fig. 1), which extends for sixteen miles, between precipitous walls and mountains 5,800 ft. high, to the Jostedalsbrä, the largest glacier in Europe.

The main fiord continues east-south-east for thirteen miles, through fertile country, and then, after two sharp and almost rectangular turns, the Aurlands-Fiord joins from the south. This fiord has extreme fiord characteristics; it is straight and very narrow, being nineteen miles long, and usually a little less than one mile wide; it is bounded by precipitous walls 3,000 to 4,000 feet high. The Naerö Fiord branches from the Aurlands Fiord to the south-west, and is described as the grandest of all the branches of the Sogne Fiord, and one of the most impressive fiords in Norway. It is usually 1,000 yards wide, but in places only 200 yards wide; the mountains beside it rise to over 5,000 ft., and cliffs 1,000 ft. high, streaked with small waterfalls, rise so abruptly from the water that there is rarely room even for a cottage on the water-side. The wall is recorded by Dinse (**1894**, p. 212) as rising at angles of 53°, and he calls it the steepest fiord-wall in Europe.

[1] The angles of the slope are those given by Dinse (**1894**, p. 228). The maximum depth recorded on the Admiralty Chart No. 2,304 is 661 fathoms, or 3,966 ft.

The easternmost branch of the Sogne Fiord is the Aardals Fiord, with its waterfall, the Vettisfos, of some 700 ft. high. The Aardals Fiord ends at Aardal, whence a fiord-like valley with a long narrow lake, the Aardals Vand, continues inland, to a series of high-level lakes.

The Hardanger Fiord

The Hardanger Fiord, to the south of Bergen, is the second longest of the Norwegian fiords, and is often regarded as the most beautiful. The inner fiord is sixty-two miles long, but the whole length, including the straits which lead to it, is one hundred miles. Its width is somewhat irregular, ranging from three to eight miles, while some of the branches are narrower and more regular. The scenery is, as a rule, less bold than that of the Sogne Fiord. The slopes are often gentle, and they are in places forest-clad; the general aspect is more wooded and more fertile than the country along the Sogne Fiord (Pl. IV. Fig. 1.)

Through Bömmel Fiord (lat. 59½° N.) the Hardanger Fiord reaches the sea one hundred miles south of the entrance to the Sogne Fiord. Here the coast trends south-eastward, and many of the fiord-straits through the island "Skjaergaard" extend from north-north-west to south-south-east. The main trend of the fiord is north-eastward. The outer part runs inland to about north-north-east. It then bends due northward past the island Varaldsö, while the Moranger Fiord continues nearly along the line of the main fiord. The middle section of the Hardanger Fiord consists of a series of basins varying in width from one and a half to five miles. It turns north-eastward and this line is continued by the narrow Graven Fiord, when the main fiord makes a sudden bend to the east-south-east. This reach of the main fiord ends in a T-shaped junction.

The southern arm, the famous Sŏr Fiord, is the largest well-developed trough-valley in Norway. It is twenty-

Photo by H. W. Monckton.

FIG. I.—HARDANGER FIORD LOOKING UP THE FIORD FROM VIKEN,
Showing the level-topped ridges, which are remains of the old plateau-surface. (*Vide* p. 87.)

Photo by H. W. Monckton.

FIG. 2.—FJÄRLANDS FIORD,
Looking from the head of the fiord and showing the succession of truncated spurs. (*Vide* p. 79.)

five miles long, and from one and a quarter miles to only a few hundred yards wide. Its walls are bare and straight, and the whole aspect of the fiord is that of a vast cleft cut through the mountains regardless of the structure of the rocks. The walls rise steeply. According to Vibe the slope from the fiord to the Thorsnut above Odde is 20° 39′ for the height of 5,194 ft. (1,583 m.) in about two and three-quarter miles (4·2 km.); along parts of the fiord there is an average slope, according to the Norwegian Survey-maps, of 30° to the height of 4,000 ft. Above this level the ground spreads out as a plateau, on which one peak rises to 5,060 ft.

The other arm of the Hardanger Fiord is the Ejd Fiord; it has a slightly curved course, which is at first east-north-eastward and then due east. Ejd Fiord also is bounded by precipitous cliffs. Its tributary, Ose Fiord, leads north-north-eastward and continues the curved line of the Sör and outer Ejd Fiords.

The depths of the Hardanger Fiord are less extreme than those of the Sogne. The maximum depth is 2,550 ft., and the fiord is divided into two main basins by a rise of its floor.

The most striking difference between the Hardanger and Sogne Fiords is that the former is less regular in width and its walls are often less precipitous, though Sör Fiord looks as much like an artificial trench as any part of the Sogne Fiord.

The Hardanger Fiord has a less well-developed series of tributaries, and accordingly many of the streams which discharge into it leap over the cliffs in high waterfalls, for which the Hardanger Fiord is famous. They are doubtless very impressive during the melting of the snow in spring.

The outer part of the Hardanger Fiord is through an archipelago in which the islands are larger and the network of channels more regular than those off the mouth of the Sogne Fiord.

The general plan of the Sogne Fiord resembles that of a river with a long main trunk and a number of tributary branches. The plan of the Hardanger Fiord, on the other hand, is more like a network of cracks in a slab of glass or stone. Some of the cracks are not open below sea-level, so that the network is only complete when the land-valleys are taken into consideration as well as the submerged valleys.

1. *The Bukken Fiord*

The Bukken Fiord, or Stavanger Fiord (Fig. 17), may be taken as the third representative of the fiords in western Norway. It is a broad basin rather than a narrow channel, though its boundaries are somewhat indefinite, owing to its innumerable islands and its irregular coasts. Its basin is about twenty-two miles wide at the mouth and twenty-five miles long. Bukken Fiord is, therefore, rather a bay than a fiord. From this bay a series of true fiords project both into the islands and the mainland. The main fiords trend from about west-south-west to east-north-east, and, including the valleys occupied by lakes, there are five main lines with this trend. They are (1) Lyse Fiord to the south; (2) Aardals Fiord, continued by the Upper Tysdals Vand, while the Lower Tysdals Vand and Bjoreim Vand are on a parallel line a little south of Aardals Fiord; (3) Hjösen Fiord; (4) the line including Yrke Fiord, Vinde Fiord, and Hyls Fiord; and (5) while farther to the north on the same trend are the Aakre Fiord and some other parallel fiord-straits in the Hardanger basin.

The fiords of the second series in the Bukken group cross the members of the first group at approximately right angles. The most conspicuous of this group, the Sandejd Fiord, continued by the Ombö Fiord, crosses the line of Yrke and Vinde Fiords, so that those form a cruciform group.

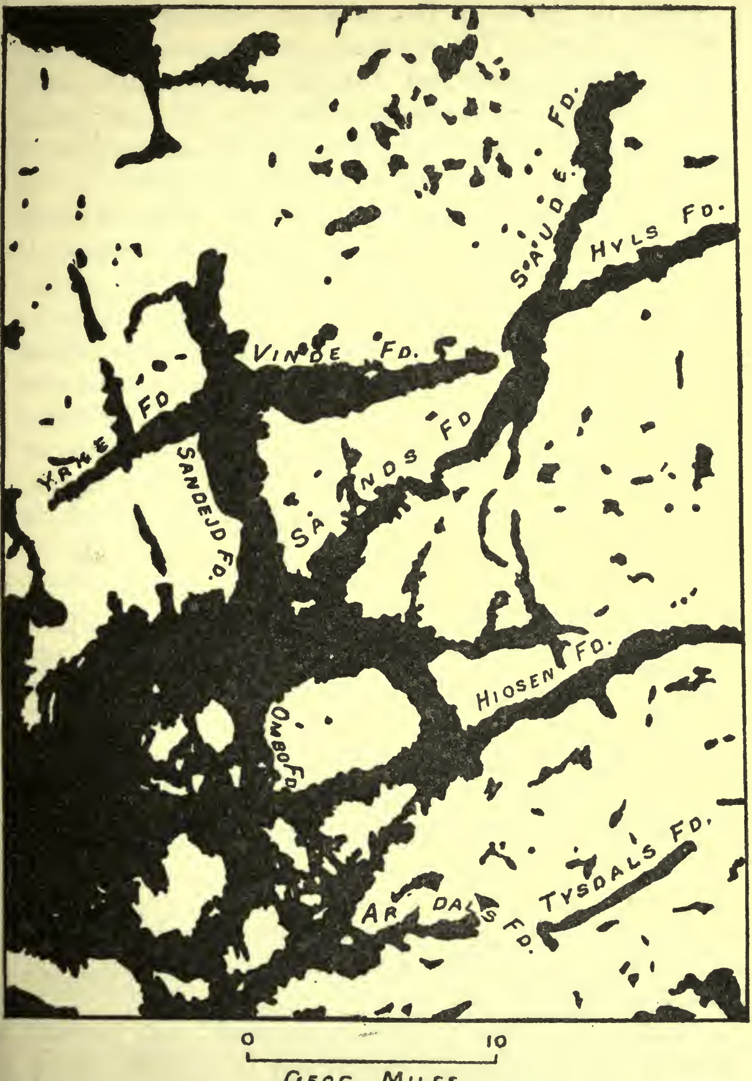


FIG. 17.—SKETCH-MAP OF BUKKEN FIORD AND ITS BRANCHES.

The third series trends in the northern part of the area from north-north-east to south-south-west, and farther to the south the direction becomes north-east and south-west. The most conspicuous member of this group is the Sands Fjord. Suledals Vand has the same general direction, though one reach is deflected to an east-south-east and west-north-west course, where it enters the line of the Vinde and Hyls Fiords.

The most remarkable member of the Bukken group is Lyse Fiord, which has been often quoted as the example of a rock-basin with a shallow threshold at its mouth. The chart by Vibe (**1860**, pl. 1) has been frequently reprinted and shows that, whereas the basin has depths of 229 Norwegian fathoms[1] the outlet is a narrow passage with the depths of 48 and 51 Norwegian fathoms at the mouth, and apparently of only 11 fathoms at one point within. Lyse Fiord is a trough-valley slightly curved in direction. Vibe (**1860**, p. 4) describes it as follows:

"This narrow fiord is bounded, with few exceptions, by vertical or overhanging rock-walls which rise immediately from the surface of the water to 3,000 ft. and higher. The whole may be regarded as an immense crack (*Borst*) or rent (*Spalte*) in the mountain masses, a rent which continues deep below the sea, for in many places the sounding-line shows a depth of not less than 1,400 ft."

Peschel (**1878**, p. 20) characterises the Lyse Fiord as "the sharpest, deepest, and most regular incision in the Norwegian coast."

Bukken Fiord has no definite threshold, and its most striking characteristic is the regular intersection of the fiords, which cross one another like a net-work of cracks and not like branches of an ordinary river-system or of a series of glacier-valleys.

[1] The Norwegian fathom is 5·82 ft.

4. The Depths of the South-western Fiords

The Hardanger Fiord is one of the Norwegian fiords which is deeper than the sea to which it opens. It has a deep inland basin which shallows seaward, as the floor of the sea is much higher than that of the fiord; but it has no fiord-threshold across the entrance, unless the whole platform between the Norwegian coast and the Norwegian Channel be regarded as such.[1] The upper branches of the Hardanger Fiord increase fairly regularly in depth from their inner ends. Thus the Sör Fiord attains the depth of 1,260 ft. about half-way down the fiord; thence it shallows to 1,020 ft., and then deepens again to 2,310 ft. at its junction with the Ejd Fiord; that fiord and the Ose Fiord both appear to deepen steadily to their junction with the Sör Fiord. From this point the main Hardanger Fiord continues to deepen until, in the wide basin known as Samlen, its bed, according to the Admiralty Chart No. 2,304, is 2,550 ft. deep. It then shallows steadily until, near the island of Varaldsö, the depth is apparently only 540 ft.; farther south, and at its junction with Mauranger Fiord, the depth is 2,130 ft. Still nearer the sea, it shallows to the depth of 828 ft. before its junction with the fiord-strait of Langeneren, and, with one or two slight variations in depth, the floor rises till the depth is 720 ft. at its mouth in Bömmelen Fiord, off which the sea is still shallower, with depths of only from 400 to 500 ft.

The Sogne Fiord attains an even greater depth[2] than the Hardanger Fiord. Its upper branches deepen fairly steadily, though there are one or two minor variations

[1] The depths of the Norwegian fiords are less well-known than those of the Scottish lochs, because in most cases there is only a single line of soundings down the middle of the fiord, which may not be the deepest part of the channel.

[2] According to the list of depths of the Norwegian fiords given by Helland (**1872**, p. 557), the maximum depth of the Hardanger Fiord is 791 metres, and that of the Sogne 1,244 metres, or 4,082 feet.

which might be explained by fuller soundings. The main channel is deeper than the branches.

Thus the Fjärlands Fiord increases in depth from 516 ft. near its inner end to 660 ft., 960 ft., and 1,308 ft. near its mouth, opposite which the Sogne Fiord has a depth of 3,400 ft. Hence, if the Sogne Fiord were drained, the Fjärlands Fiord and other branches would be left as hanging valleys upon its sides.

The deepest point on the Sogne Fiord is to the west of the sharp bend at Vik, and, as the bottom of the fiord is there about 4,000 ft. deep, it is lower than most of the floor of the Atlantic Ocean near the Norwegian coast, though the northern part of the Norwegian Channel is deeper. The slope, however, by which the floor of the fiord sinks to this great depth is very slight. Dinse (**1894**, p. 226) calculated the slope downward from the head of the fiord as the inappreciable angle of only 39 minutes. The floor rises westward at an angle of 1° 2′, till, at the southern bend of the outer part of the fiord, it is 2,700 ft. deep. It then deepens again to 3,780 ft. and shallows to 660 ft. at its mouth. The sea-bed immediately off the mouth of the Sogne Fiord has a depth of 480 ft.

Sogne Fiord consists, therefore, mainly of one deep basin with a small secondary basin near its mouth. Its greatest depth is about half-way up the fiord.

5. The Origin of the South-western Fiords

Owing to the steepness of the fiord-walls and the depth of the valleys the first impression gained from a steamer is that the fiord districts are intensely rugged and mountainous. The typical fiords, however, intersect a plateau-land which was formerly a level, unbroken plain. This plain sloped evenly westward to the sea, but its surface has been deeply dissected by valleys in consequence of the increased power given to the rivers, either by the uplift of the land or the steepening of the western slope by the sinking of the land to the west of Norway. The remains of the ancient plain, which Reusch (**1901**, No. 1, p. 133) calls the "palæic" surface of Norway, are still widespread and conspicuous. They can often be recognised from the fiords, but are best seen in wide views across the highlands (Pl. II. Fig. 1. and Pl. IV.). Reusch has shown the influence of this ancient plain on the scenery by a number of instructive sketches

FIG. 18.—THE DISTRIBUTION OF THE PREGLACIAL SHORE LEDGES (MARKED BY THICKENED LINES) IN THE INNER PART OF THE HARDANGER FIORD (AFTER REUSCH).

(**1901**, No. 1, p. 137 for the Sogne and plate opposite p. 193 for the Hardanger). And he shows its extension across south-western Norway by a map (p. 134).[1]

This ancient land-surface was certainly preglacial, and its dissection by the deep valleys, which are now

[1] Around Bergen is a lower plain which is also preglacial (Reusch, **1894**, p. 349). That the surface of Norway is a dissected plain had been previously pointed out, as by Kjerulf (**1880**, pp. 328–9) and by Penck (**1894**).

occupied by the fiords, was also preglacial. The Hardanger Fiord is bordered by platforms which are the remains of the floor of a preglacial valley (Reusch, **1901**, No. 1, pp. 255–6). The Sogne Valley is also preglacial, for Reusch has shown that near Fröningen, east of the junction with the Aurlands Fiord, the glacier only occupied the valley to the height of about 2,300 ft., while the upper thousand feet retain the old unglaciated surface. Moreover, some of the side-valleys are narrow and V-shaped, and were not glacier-cut (Pl. III. Fig. 2). Yet their floors are as low as the present sea-level. Similarly Reusch has shown that some of the tributaries of the Aurlands Fiord had been excavated nearly to their present depth in preglacial times (**1901**, No. 1, p. 139).

Reusch therefore claims, and the evidence seems convincing, that "a side-valley, and consequently also a main valley, surely existed before the ice did its work. The glaciers enlarged the main valley and partly destroyed the side-valleys, but they cannot be said to have made the main valley."

The Naerö valley, a branch of the Aurlands Fiord and one of the most famous valleys in Norway, is also preglacial in age; its floor at Stalheim is part of an old valley which drained south-westward to Lake Opheims, instead of north-eastward as at present. The deep gorge below Stalheim is a young trench cut on the floor of an ancient valley.[1]

The evidence seems overwhelming that the fiord-valleys were mainly preglacial.[2] Though they have been

[1] As another example of the preglacial age of the main valleys in Norway, reference may be made to Rekstad's memoir on Söndhordland, in which he shows that the main valleys, which trend from about south-west to north-east, are preglacial, while gaps between these valleys have been cut by streams in the last stage of the ice-age (Rekstad, **1908**). Richter (**1896**, p. 179) also accepts the valleys as preglacial.

[2] According to Prof. Davis, however, the fiords are practically glacial in age, as they were previously only narrow canyons (*vide* p. 444). Hansen (**1894**, p. 364) has advocated the formation of the fiords in "early glacial or interglacial times" on the ground that

modified by the glaciers that once flowed down them, they were not made by glacial action. Some of them are normal valleys of erosion, and, like the Sogne Fiord, have the plan of an ordinary river-system. Reusch truly concludes (**1901**, No. 1, p. 242) that "a great Sogne River and its side-streams have eroded the fiord and its many arms in the palæic surface during a long and eventful history." [1] In other cases the valleys have been eroded along lines of weakness, which are generally due to earth-movements and fractures. Occasionally they have been worn out along bands of soft rock. Thus according to Kolderup (**1912**, p. 30) the longer fiords, near Bergen, are "typical erosion-valleys and erosion-fiords excavated along the lines of least resistance, these lines being parallel to the direction of the strata." But, even with these, he adds, "old thrust-planes, too, may perhaps partly have decided their direction." The coincidence between the trend of these fiords and the strike of the rocks is, however, quite exceptional. Kolderup observes that it is "such as is found in few other parts of Norway" (**1912**, p. 28) and the intersecting cross-fiords Kolderup attributes to erosion along sunken strips of country or along systems of fractures.[2] Kolderup illustrates this conclusion by reference to the Sör Fiord of Bergen (not the

the ice could not have advanced beyond their heads. His view is apparently that, if the fiords were preglacial, they would have been occupied by the sea, which would have dissolved the ice and prevented it passing beyond a line joining the fiord-heads. The evidence from Greenland and the claim that glaciers can corrode basins below sea-level by replacing the water (*vide* p. 450) are opposed to Hansen's view.

[1] According to Rekstad, the Sogne Fiord system includes two series of valleys : one, an older series, trending north and south, and a younger series trending east and west (**1910**, No. 1, p. 46).

[2] Reusch has also described the dependence of the main sounds and fiords of this district on the direction of the folds and of the cross-fiords on the joints which intersect the folds almost at right angles (**1901**, No. 3, p. 105). In 1902 he referred to the coincidence of the faults and fiords around Bergen (**1902**, p. 108).

branch of the Hardanger Fiord with the same name) and the Samnanger Fiord, along which he has proved the occurrence of earth-movements. "The whole form of the Sör Fiord," he remarks (p. 31), "is really so peculiar that it is hard not to believe that old fractures, and possibly also trough-depressions, have decided the direction of the eroding forces." The adjacent country beside the inner Oster Fiord is also greatly fractured, and Kolderup says that "we soon realise that they [the fractures] were the main factors in defining the land-mass." Some of the movements he assigns to a post-glacial date. Kolderup therefore recognises for the Bergen district that the chief fiords were determined by preglacial movements, although "some valleys, and possibly also smaller fiords, were formed entirely by glacial erosion" (**1912**, p. 32).

The plan of the Hardanger Fiord system resembles a network of cracks rather than that of an ordinary river-system, and it affords exceptionally clear evidence of the fractures which determined its position and distribution. Thus the Sör Fiord and the valley at its head are in a remarkably straight line; and Reusch observes that running water by itself does not make such rectilinear valleys (**1901**, No. 1, p. 257). "The water," he says, "must have followed a structural line in the earth's crust; there has probably been a system of joints"; and he quotes evidence of its secondary valleys "following lines of weakness that can hardly be anything but fissures." Similarly the valley which leads from the Ejd Fiord, the easternmost branch of the Hardanger Fiord, to the famous waterfall Vöringfos, has a trench on its floor from Tveite to Maabo, which Reusch explains as a cleft on the bottom of a preglacial valley. Reusch has shown that the topography around the Vöringfos has been determined by a series of fissures, which are very well displayed. He infers, from his study of these fissure-started valleys, that "the part the fissures play in the region in question is that of guiding and helping both water and glacier erosion (by plucking of blocks)." [1]

The agreement between the sounds and fiords at the mouth of the Hardanger Fiord with the tectonic lines was shown in Reusch's memoir and map published in 1890.

The refracturing of Norway in recent geological times was probably caused by its great oscillation in level. The old land-surface was doubtless formed in early Kainozoic times, when Norway stood 2,000 ft. lower than its present level. The country was subsequently uplifted at a date for which there is no certain evidence; but, judging from the general geological history of north-western Europe, it was probably in the late Miocene or early Pliocene. This uplift must have been accompanied by fresh movements on the old fracture-lines and the gaping of old joints into open clefts. Their exposed surfaces were then weakened by weathering, and they were widened into the fiord-valleys by rain and rivers. The country sank again during the glacial epoch, and after the melting of the ice the land rose again. The uplift did not affect the whole country uniformly; it was a differential, or tilting movement, which occasioned fresh dislocations on the old fractures.[2] The interior was elevated more than the coast; and, as the glacial uplift and subsidence were part of one wave-like movement, it is probable that the interior had previously sunk more than the coastal districts. The greater depth of the inner parts of the fiords may be explained by this greater oscillation of the interior.[3]

[1] Reusch also shows that the Rjukanfos in Telemark, which has been described as the grandest waterfall in Europe, has developed on a fissure, illustrating the widespread influence of fractures on the topography of Norway (**1901**, No. 1, pp. 214–17).

[2] According to Rekstad the uplift on part of the Sogne Fiord was in seven successive steps (**1910**, No. 1, p. 46).

[3] The extension of this differential movement and the greater oscillation of the interior of Scandinavia has been demonstrated for northern Sweden by Prof. Högbom (**1904**); and the tilting near Tromsö has been proved by Helland (**1900**, pp. 29, 30).

Norway is, in fact, a plateau-land which has been twice refractured in recent times. The fracture-systems determined the position of the valleys, but their aspect was largely modified by the subsequent glaciation. The glaciers gave the main valleys their trough-shaped form by wearing away the spurs, while the removal of the lower ends of the tributaries left them as hanging valleys. The influence was not limited to mere abrasion. Large masses of rock were torn away, and this plucking was most effective where the rocks were most jointed and rifted.

The whole of the truncation of the spurs and mouths of the side-valleys is not to be attributed to the ice. Much of it was doubtless due to the streams which so often flow on each side of the lower end of a glacier. Though Reusch accepts the argument from hanging glaciers as proof of great glacial erosion, he remarks that "it is probably more correct to regard it [fiord formation] as a result of interglacial water erosion, alternating several times with glacier erosion" (**1901**, No. 1, p. 240). The effect of the glaciers has often been surprisingly small. Reusch has called attention to the insignificant traces of the glaciers on the higher parts of the high fells of Norway. "One at first thinks that no traces of ice-action are to be found" (**1901**, No. 2, p. 232), though occasional boulders show that the whole region was covered by an ice-sheet. In the valleys a relatively small amount of widening may give rise to a great apparent deepening of a valley. Thus, if a glacier flow down a narrow, sinuous, V-shaped gorge which has been cut by a river, the removal of the spurs would convert the gorge into a trough-shaped valley; and this change may be completed without any actual deepening of the valley. It will have been "over-deepened" (*vide* p. 410), in reference to its tributaries without any actual deepening. The Naerö Valley shows how great a change may be made in the aspect of a valley by slight rock-abrasion (Fig. 19). It is a narrow gorge

Photo by H. W. Monckton.

FIG. 1.—FJÄRLANDS FIORD.

Head of the fiord at low-water, showing its continuation as a V-shaped valley. (*Vide* p. 79.)

Photo by H. W. Monckton.

FIG. 2.—BOUIN VALLEY

In which the feet of the spurs have not been removed, and show normal denudation-curves.

 (*Vide* p. 92.)

with the stumps of its spurs remaining.[1] A comparatively slight planing of the spurs would produce a trough-valley, the whole of which might be attributed to glacial action; whereas the ice would merely have smoothed the sides of a river-cut gorge. The frequent failure of a glacial occupation to remove from valleys the features due to their formation by rivers has been illustrated by

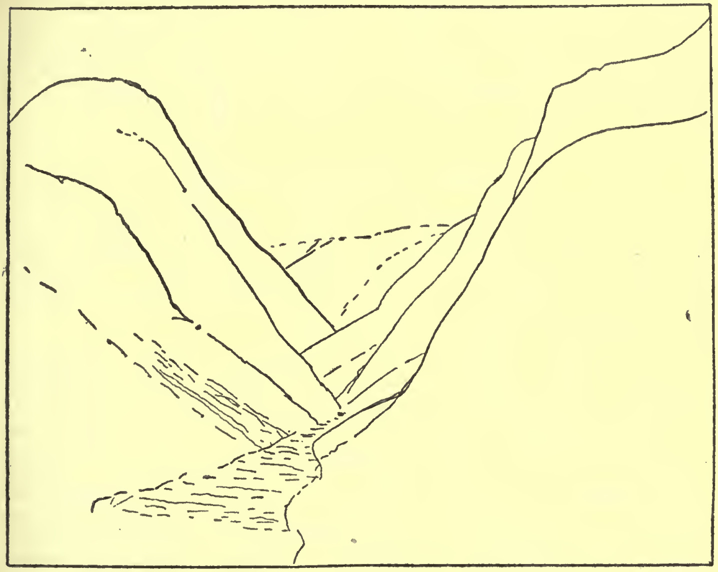


FIG. 19.—OUTLINE OF THE NAERÖDAL FROM STALHEIM.
Showing the overlapping valleys; slight glacial erosion of these spurs would give the valley the aspect of a trough-valley.

Reusch from the Turtegrö Valley. This valley descends from east to west into the Fortun Valley at the head of the Lyster Fiord, the north-eastern branch of the Sogne Fiord. It is a straight trough, most of which has a U-shaped section due to the glacier that once flowed down it. The ice has, however, in places failed to modify the river-cut cleft on the floor of the valley. The cleft is

[1] The overlapping profiles of the two sides of the gorge are shown *e.g.* in a photograph by Rekstad (**1910**, No. 1, fig. 4, p. 24).

regarded by Reusch as in part preglacial, as he says that it "seems too large to have been entirely made since the ice-age." The floor of this valley projects at its western end as a rock-bastion, 650 ft. high, into the main valley; "this," says Reusch (**1901**, No. 1, p. 247), "is a remarkable fact, not easy to explain." A possible explanation is that the Turtegrö Glacier flowed over the rock at this point, and thus protected it from abrasion by the glacier in the main valley. The rock-wall on either side of the Turtegrö Valley was meanwhile being worn backward, leaving its protected floor as a projecting bastion.

6. The Christiania Fiord

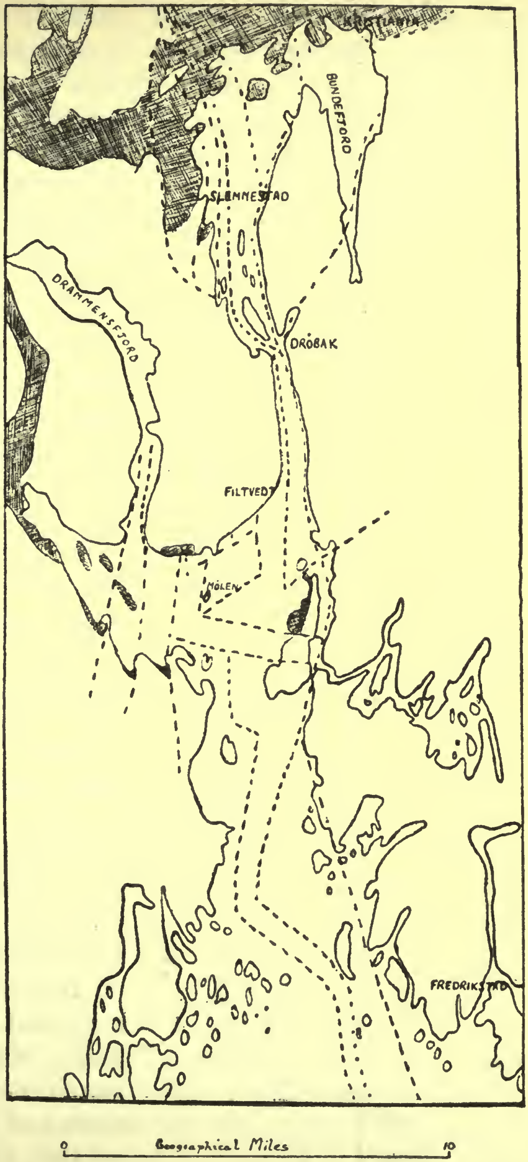
The Christiania Fiord requires special notice from its political and historic importance. It is the best known of those in southern Norway, and it occurs in a district of exceptional geological interest.

The nature of the fiord has been very carefully investigated. Its origin was ascribed by Kjerulf (1884) to the numerous dislocations and fractures which he found along it. Helland (**1882**, p. 185, etc.) admitted the existence of faults along the fiord; but he regarded them as having played no essential part in its formation, which he assigned to glacial erosion. He apparently regarded the coincidence of fiord and fault as accidental.

Professor Brögger (**1886**, p. 100) has adopted an intermediate position; he recognises that the direction and shape of the fiord were determined by faults, but he attributes the fiord, as we see it to-day, to glacial erosion.

The Christiania Fiord consists of three main parts. Its outer end is somewhat funnel-shaped, though both shores are very indented, and it differs from ordinary fiords by the presence of many small islets which extend almost to the middle of the fiord. At the northern end of this outer section is a wide basin which runs east and west at right angles to the main direction of the Christiania

Fiord; from the western end of this basin the Drammen Fiord runs northward through a great mass of post-Silurian granite, and then bends westward until at its northern end near Drammen it extends east and west. The main Christiania Fiord continues northward parallel to the lower part of the Drammen Fiord, through the Dröbak Channel, which is the narrowest and most picturesque part of the fiord. Its



— — — Faults.
Palæozoic Rocks.

Fg 20.—Sketch-map of Christiania Fiord (after Brögger).
Showing its coincidence with faults.

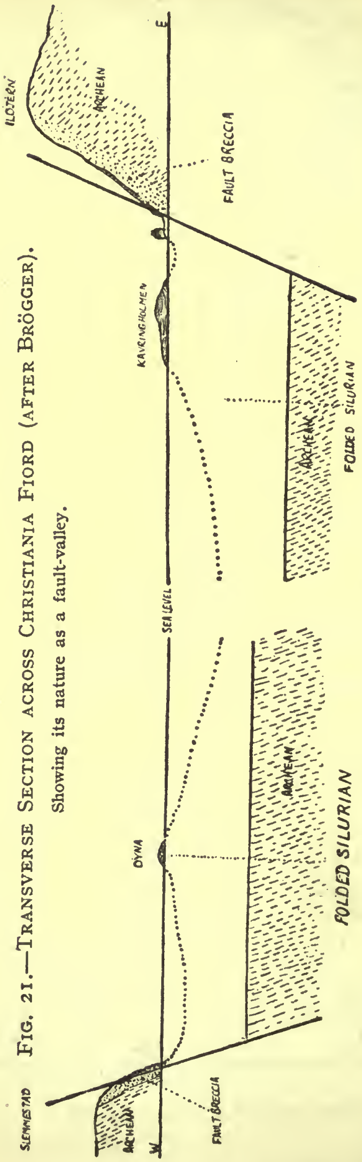


FIG. 21.—TRANSVERSE SECTION ACROSS CHRISTIANIA FIORD (AFTER BRÖGGER).
Showing its nature as a fault-valley.

walls are high, straight, and spurless, the waterway is deep and unbroken by islands, and this channel has the characteristics of a normal fiord. The Dröbak Channel expands at its northern end into the inner Christiania Fiord—a wide, lake-like basin with gently sloping shores ; a narrow passage leads eastward into another land-locked basin, Bundefjord, upon the northern shore of which stands the city of Christiania.

There is convincing evidence that Christiania Fiord occupies an irregular band which has been lowered by a series of faults. The evidence for the faults is conspicuous. Thus the shores of both the inner part of the Christiania Fiord and of the Bundefjord are composed of Archean rocks ; whereas the numerous islands in both of them and some of those in the outer fiord are composed of much younger rocks which are

Palæozoic and mainly Silurian. These younger rocks are part of a sheet which once extended across the country above the Archean rocks, which now form most of the hills beside the fiord. The low level of the Silurian rocks proves that they have been dropped by earth-movements, which Kjerulf and Brögger have shown to be faults. Brögger's map of the fiord shows that the borders of the fiord coincide throughout with lines of ancient dislocations. Thus the main fiord (see Fig. 21) consists of a band of Silurian rocks, which has been faulted down into the Archean foundation. Sheets of crushed rock [1] remain in places on the walls of the fiord as further evidence of these dislocations. The faults have clearly determined the course of the fiord. Where the faults run north and south, so does the fiord; and where slabs of rock have been lowered by east and west faults the fiord is crossed by the basin which runs east and west past the island of Molen. The bent, deep,

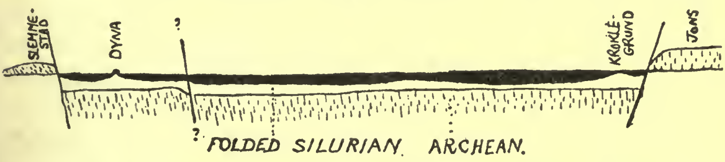


FIG. 22.—LONGITUDINAL SECTION ALONG CHRISTIANIA FIORD (AFTER BRÖGGER).

Showing the relations between the depth of the fiord and faults. The solid black represents the water in the fiord.

island-free channel up the outer part of the fiord is also bounded by fault-lines, and Brögger's section (Fig. 22) along the fiord shows, that its greatest depths occur where the faults have dropped the rocks deepest, and that the variations in depth and the thresholds generally coincide with the faults that cross the fiord. He states that "the deepest part of the fiord on a north and south line occurs over the most deeply sunken slab of rock." [2]

[1] These crush-breccias have been described in detail by Brögger (1886, pp. 104–142).

[2] Brögger, 1886, p. 187.

The walls of the long, narrow Dröbak Channel coincide, according to Brögger, with two great fault-lines. These faults themselves were first formed by movements of great geological antiquity; but, as Brögger himself states,[1] movements have taken place repeatedly along the old fault-lines, and it is probable that these movements along the old fault-planes have continued to recent times. In most parts of the district denudation has destroyed the cliffs directly made by the earth-movements. Brögger has, however, clearly shown their dominant influence on the development of the fiord. He states that faults have unquestionably decided the most important orographic lines of the fiord. "If," says Brögger, "we draw the greater faults on a map it becomes manifest that some of the most essential orographic lines of the district coincide with the greater fault-lines."[2] Brögger, however, points out that the formation of the fiord[3] belongs to two stages—first, the fault-movements which lowered the bands or blocks which now form the floor of the fiord; and, secondly, the moulding of the country by the denuding agents to which the present topography is mainly due. Brögger maintains that the influence of faulting has been indirect, and that the fiord as we see it is due to glacial erosion; but his own sections show the close dependence of the present topography on the fault-lines, which coincide with the edges of many of the deeper basins and the thresholds. The glacial erosion moulded a topography due to dislocations, and the glaciers were not able to level the irregularities made by the earth-movements. Glacial activity has its greatest opportunity of effective erosion where a stream of ice impinges on a projecting mass of rock; but in the Christiania Fiord the ice did not remove such rocks, but flowed over them into the preglacial depressions.

The coincidence between the down-faulted bands of

[1] Brögger, **1886**, p. 155.
[2] *Ibid.* p. 209.
[3] *Ibid.* p. 175.

FIG. 23.—MAP OF THE TVER-LANDET PENINSULA, A LIMESTONE THRESHOLD (AFTER J. REKSTAD, 1910 (2)).
Black is limestone.

Silurian rocks with the fiord-valley may suggest that the Christiania Fiord is mainly due to the readiness with which these comparatively weak rocks were removed by denudation. The course of the fiords is, however, so often independent of the strength of the rocks that their occasional agreement is a mere coincidence. Thus the Salten Fiord lies in an area of Archean rocks and Silurian limestones which strike obliquely across the fiord. A peninsula which projects from the northern shore almost completely separates the fiord from its inland continuation, the Skjerstadt Fiord (Fig. 23). This peninsula consists mainly of limestone, while the adjacent basins have been excavated in granite and mica-schists (Rekstad, 1910).

The Christiania Fiord certainly occupies the site of an old rift-valley and was therefore caused by faults, and, though the rocks on its floor are softer than those on the adjacent highlands, erosion has been less effective along it than on the higher ground. For the Silurian rocks are the fragments of a continuous sheet once spread across the whole country. They have been completely removed by denudation from the high ground, and yet great slabs of them have been left on the floor of the fiord.

The fiord-valley can only be attributed to glacial erosion on the assumption that, after the faults had ceased, the whole country was planed down to one level surface, and that the glaciers flowed over this level plain and formed the present fiord by wearing away the bands of soft rock.

It seems, however, very improbable that the country was such a plain at the beginning of the glacial period. Even if, at any previous period, the area had been worn down to a peneplane, this would have been eroded into valleys in preglacial times. The re-erosion of the area can only have followed an uplift, which produced many small faults and clefts in the rocks (see Fig. 24); and there is evidence that faults have taken place in recent times along the ancient fault-lines.[1] The most probable explanation of the topography of Christiania Fiord appears to be that the country was uplifted in Miocene and Pliocene times, that faults took place along the old fault-lines, and that the combined influence of faulting and denudation renewed the old valley. Where, moreover, the erosion has been most effective the fiord has lost its fiord-like character. In the outer and inner parts of the fiord the faults are mostly below the water and the evidence for them is inferred; but in these two areas the Christiania Fiord is really a fiard. They differ from typical fiords in their rounded shores, the low relief of much of the surrounding country, and the numerous islands which are scattered over the surface of these

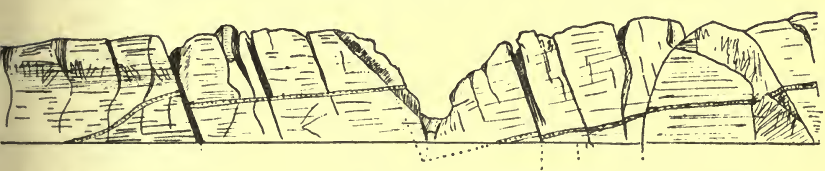


FIG. 24.—SKETCH IN THE LANGESUND DISTRICT (AFTER BRÖGGER).
Showing dislocations along parallel tension-clefts.

lake-like expansions. But where erosion has done least to wear back the walls and to conceal the faults, as along the Dröbak Channel, the fiord remains a fiord.

The evidence of the Christiania Fiord has been considered at length because it has been so well investigated. The other fiords of southern Norway show the same phenomena and were no doubt caused in the same way. Thus Brögger's description of the area around Langesund and Skien, some 50 miles west of Christiania, shows that the fiord-valleys there are also developed along a series of fractures, of which a network is especially well shown near Brevik (**1884**, pp. 302–8).

[1] An interesting instance of these small postglacial faults is described by Brögger; a pothole in an apatite mine near Langesund has been cut across by a fault and the halves slightly displaced (**1884**, p. 399). See also Brögger, **1886**, p. 155.

The adjacent Ekern See has been described by Kjerulf (**1881**) as a basin which cannot have been made by ordinary processes of valley-erosion. It is a typical fiord-like basin; one end is in granite and the other in Silurian rocks. Its surface is 62 ft. above sea-level, and its floor sinks 453 ft. below. It is not on any river-course, and Kjerulf is emphatic that it was not formed by erosion (p. 8).

7. The Fiord-network near Trondhjem

To the north of the area of the south-western fiords the Norwegian coast makes a sudden turn and runs from south-west to north-east. This part of the coast, from Aalesund to Trondhjem, is indented by a net-work of fiords.

The course of the coast is here only slightly oblique to the grain of the country. Fiords are well developed both along and across the strike of the rocks, and form a reticular series; the cross-fiords run south-south-east across the grain of the country, and give off branches trending east-north-east and west-south-west. Near the coast the east-north-east branches from neighbouring fiords unite and form straits parallel to the coast. Hence the land is broken up into a network of rectangular islands. The fiords in this district are an especially well-developed example of reticular fiords.

This district includes the Geiranger Fiord, famous for the steepness of its high walls, and the Romsdal Fiord, of which a good chart has been given by Sandler (**1890**) in illustration of his theory of the origin of fiord-terraces. Information regarding the Romsdal fiords is also given by Helland (**1897**).

Farther to the north the coast is intersected by a series of typical fiords, which repeat the features of the south-western fiords on a smaller scale. Salten Fiord, one of the most important, is well known from the monograph of Vogt. Much information regarding the fiords of this district is given by O. Nordenskjöld (**1900**, pp. 162–82), who, though a warm advocate of the glacial origin of fiords, admits that the great West Fiord may be tectonic and due to a sinking which also made the fiord-like Norwegian Channel. Some of the smaller fiords in the Lofoten Islands have been described by Helland (**1897**, pp. 92–100).

The fiords of north-western Norway have many characteristics which are inconsistent with their glacial origin, and Dr. Sjögren in 1896 showed that their orientation in the Sulitelma district was due to the influence of the vertical joints or diaclases (*vide* p. 392). (**1896**, p. 376.)

8. The Arctic Rias of Norway

The last group of fiords in Norway includes those on the northern coasts. The shore of the northern province, Finmark, is indented by a series of widely-open, funnel-shaped gulfs, one of which, the Varanger Fiord, runs along the junction between the Gaisa formation and the older crystalline Archean rocks and has some small fiords on its southern shore (Fig. 25). Others, such as Tana Fiord, Laxa Fiord, and Porsanger Fiord, are almost at right angles to the trend of the Gaisa Formation. These four great gulfs agree in their topographic characters and must be regarded as essentially of the same nature; but they are not typical fiords, for they are less regular in width and tend to be funnel-shaped. These fiords deepen seaward, as is shown by the accompanying figures of the Tana Fiord and the Varanger Fiord. Dr. Otto Nordenskjöld (**1900**, p. 193) claims the occurrence of a threshold in the front of the Varanger Fiord. The sea certainly becomes shallower at some distance from the mouth of the fiord, but the charts show no threshold comparable to that of the typical fiords.

Dal's geological map of the Varanger district (**1900**) suggests that the north-western shore of the Varanger Fiord is determined by a fault-line; for the continuation of this line inland lies along the junction of the crystalline rocks with the younger sandstones.

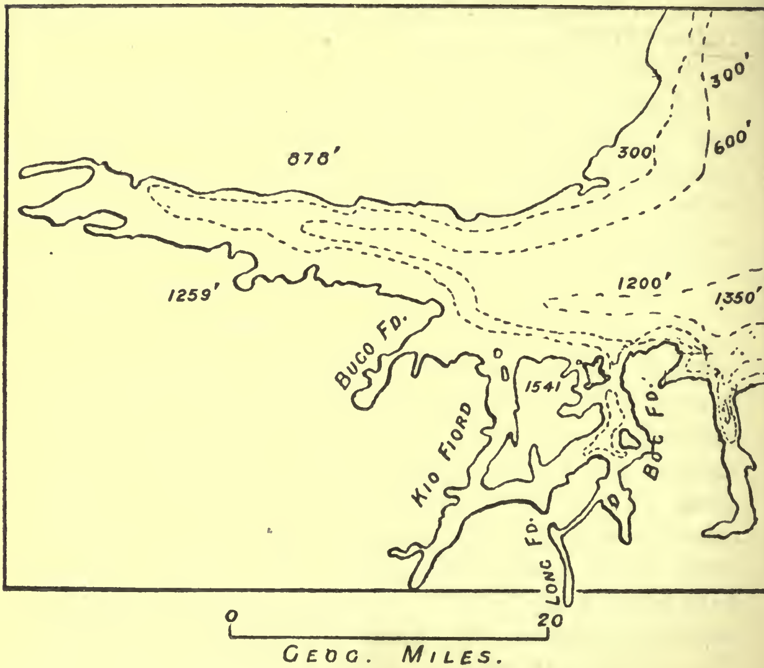


FIG. 25.—SKETCH-MAP OF THE VARANGER FIORD.

A drowned rift-valley with a group of cleft-formed fiords on its southern side.

The special characters of these northern fiords is perhaps due in part to the lower elevation of the district in which they occur. Thus the official work on Norway (**1900**, p. 17) remarks that "when the high-land ceases in Finmark, the fiords, too, acquire another character. They become broader and shallower, less typically formed basins in the loose schist, beds indeed, for less active and less concentrated glacier-streams, because here, in the low plateau country, there were not originally such deep canyons to determine the course of the glaciers, as on the western slope of the mountains" (p. 17).

This explanation is, however, inadequate. Where the land is low in south-eastern Norway the inlets have the character of fiards. The arms of the sea in Finmark are not fiards, from which they differ even more strongly than they do from fiords. As this change in the character of fiords may be seen along all the main continental coasts on approaching the Arctic Ocean, it must have a widespread cause; its nature will be considered later.

These four northern fiords are probably old river-estuaries: the Tana Fiord now receives the Tana River which drains an extensive basin. The Varanger Fiord was probably the estuary of the Upper Tana which has now been diverted northwards. From their funnel-shaped form, their gentle slopes, irregular outlines, and absence of fiord-thresholds, these great arms of the sea are essentially rias.

This group of rias ends to the west at the North Cape and thence the Norwegian coast trends south-westward to the Lofoten Isles. This coast is intersected by many fiords, and is fringed by a belt of islands. The prevalent direction of the fiords is at first north and south, with shorter reaches running east and west; fiord straits, also running east and west, cut off parts of the land as islands. Following the coast to the south-west, the fiords lying east and west gradually increase in size and number. After passing Tromsö the trend in the fiords from north-east to south-west becomes more important, as many of the fiords occupy strike-valleys; the most conspicuous members of the fiord-system are here the fiord-straits that run parallel to the coast. From 70° N. to 64° N., *i.e.* from Tromsö past the Lofoten Islands to Trondhjem, the coast is concordant in structure, and it is characterised by the second chief group of Norwegian fiords.

The largest arm of the sea in this area is the Vest Fiord, which separates the Lofoten Islands from the mainland; and, like most of the fiord-straits of this area, Vest Fiord trends from south-west to north-east; it contracts north-eastward, and, bending round to the east, runs far inland as the Ofoten Fiord, from the head of which a valley continues eastward into Sweden and curves round to the south-east along the line of the great lake of Tornea Träsk. The Vest Fiord, in its position and characters, is similar to the Minch, in Scotland, which separates the Hebrides from the mainland. Owing to its great width, its funnel-shaped entrance, and its passages northward, it is not a typical fiord, though many true fiords pass off from it on the one side into the Lofoten Islands, and on the other into the mainland. To the south of the Lofoten Islands the trend from south-west to north-east becomes less frequent, though this direction is still seen in the Salten Fiord, and farther south in Thosen Fiord, the main part of Aar Fiord, and Lingen Fiord. The main fiords of this area, such as Vefsen, Vel and Namsen Fiords, run inland either to east or south-east, across the strike of the rocks. The oldest and widest valleys appear to be those at right angles to the coast; but there is a well-marked tendency for the fiords to take up courses parallel to the strike of the rocks. The longest fiord in this part of the country is the well-timbered Ranen Fiord, which leads to the iron-ore mines of Dundersdal; and it trends to 18° north of east, and is therefore oblique to the coast. Farther south, about Namsos, the fiords are either short, wide channels at right angles to the coast or long, narrow fiords parallel to it.

9. The Geological Relations of the Fiords

Scandinavia consists geologically of one vast block of very ancient rocks of which Finland also is part.

With the exception of small patches of later deposits in the southern corner of Sweden and on the Lofoten Islands, and of the recent glacial and post-glacial deposits, Scandinavia consists entirely of Archean and early Palæozoic rocks. Some rocks have been assigned to the Carboniferous, but this determination is doubtful. Scandinavia consists essentially of Archean rocks, which are divided into a lower series of gneisses and schists, and an upper series of comparatively unaltered sediments, including sandstones and quartzites. Both series have been invaded by vast masses of granites and other igneous rocks. The Archean foundation is covered in places by Cambrian, Ordovician, and Silurian rocks and some Old Red Sandstone; though some large areas referred to the Silurian may ultimately prove to be of pre-Cambrian age.

Owing to the extreme antiquity of its constituent rocks, the grain of Scandinavia is somewhat irregular. In the far north, in the province of Finmark, the strike of the rocks is generally from east-north-east to west-south-west, as is indicated by the range of the great sheet of pre-Cambrian sandstones, the "Gaisa System," from Varanger Fiord to the western coast near the Lofoten Islands.

South of the latitude of about 69° N., the main trend of the rocks is from north-north-east to south-south-west, but the same trend occurs farther north in the older Archean rocks to the south of the "Gaisa System." This south-south-westerly trend is the most important in Scandinavia. The coast between the latitudes of about 70° N. and 65° N. is, though very irregular, on the whole a concordant coast. At about 65° the strike turns more westward and becomes west-south-westerly. The coast at first projects westward in accordance with the change in strike, and from the neighbourhood of Trondhjem to Aalesund the strike of the rocks and the trend of the coast-line are nearly parallel; that part of the coast is therefore a concordant coast; but the structure is discordant all along the south-western coast from lat. 62½° N. to Stavanger in 59° N., and thence to the southern point of Norway, Cape Lindesnäs.

From the southern cape to Christiania the coast is approximately parallel to the trend of the rocks. Christiania Fiord runs inland almost due northward and is oblique to the strike of the adjacent rocks; and the coast from Christiania Fiord southward to the Swedish frontier and along south-western Sweden to Gothenburg is again a discordant coast.

The terms "discordant" and "concordant" are not very appropriate to Scandinavia, as, owing to the complexity and variability of the ancient rocks and the absence of the more recent stratified deposits the grain is often obscure. The strike of the foliation in the ancient crystalline rocks has often no connection with the geographical structure. Nevertheless, speaking generally, the coasts from the Lofoten Islands to the neighbourhood of Trondhjem and Aalesund, and that from Christiania south-westward to Christiansand may be regarded as concordant coasts, and the outer coast of southern Norway as discordant.

According, therefore, to von Richthofen's definition the Geiranger Fiord would be a true fiord, while the Hardanger Fiord and the Sogne Fiords, though usually regarded as the most beautiful and typical of Scandinavian fiords, would have to be regarded as rias, as they open on discordant and transverse coasts, and most of the Hardanger Fiord runs parallel to the grain of the country. The separation of fiords and rias by their relation to the grain of the land is quite impracticable in Scandinavia.

There is no constant relation between the fiords and the geological structure of the districts around them. The country intersected by the fiord network between Trondhjem and Aalesund consists mainly of parallel bands of gneiss and granite with some Silurian rocks. The fiord-straits and the fiords parallel or nearly parallel to them lie along the strike of these rocks, which is crossed by the main fiords approximately at right angles. As the Silurian rocks, which in the interior are at a high level, occur along the coast of Hitterö at sea-level, the coastal belt has clearly subsided in reference to the interior.

The entrance to Sogne Fiord lies between the islands of Old Red Sandstone; the main fiord, as far inland as the great bend of Vik, cuts obliquely across the strike of a broad belt of Archean gneisses and schists, with one belt of granite. Most of the upper branches of the Sogne Fiord are in a belt of Silurian and Ordovician rocks, and the tendency of the branches to run from north-east to south-west shows the influence of the grain of the country on the course of the valleys. The main fiord, however, continues to cross the strike of the rocks obliquely, and some of the branches cut across it at right angles.

Hardanger Fiord, on the other hand, is a strike-valley. The rocks upon its north-western side are mainly Silurian and those on its south-eastern side are Archean gneisses and granite.

Sör Fiord appears to cross the grain of the gneisses somewhat obliquely and finally ends in an area of granite, while the innermost part of the Hardanger Fiord is also in a wide mass of granite. Many of the islands at the mouth of the Hardanger Fiord are of Silurian beds, which occur at the same level as the much older Archean rocks. The Hardanger Fiord clearly lies along a line, where the rocks to the north-west have been lowered from the height of the interior plateau to sea-level.

The main basin of the Bukken or Stavanger Fiord appears to be also along a strike-valley. A broad belt of Silurian rocks there reaches the sea and forms the islands and peninsula of Stavanger. The members of the cruciform group of fiords on the northern side of the

Bukken Fiord cross the Silurian rocks obliquely; and the Sandejd Fiord, the stem of the cross, lies along a valley which continues northward across land and sea for more than sixty miles. The geological evidence is unmistakable that this area has sunk deeply, as was clearly recognised by Kjerulf.

An excellent illustration of the fact that fiords are independent of the distribution of hard and soft rocks is given in a geological map of the Tosen Fiord by Rekstad (**1910**, No. 3). This fiord is a long, narrow trough which trends from north-east to south-west. Its present outlet to the sea is at right angles to its main course, at about half-way along the full length of the fiord. Most of this fiord is in an area of granite, but it leaves this rock and cuts obliquely across a band of limestone, hornblende-schist, and gabbro, without any deviation in its course. Its present entrance through Bindals Fiord and a former connection with the sea from its western end into Aarset Fiord also show that the course of the fiord is independent of the grain of the country.

Kjerulf (**1880**, p. 329) has called attention to fiord-basins which have been excavated in the hardest rocks of the neighbourhood, a fact consistent with their formation along fractures but not with their glacial erosion.

10. The Fiords and the Structural Lines of Norway

The fiords of south-western Norway have therefore no direct relation to the geological structure of the country. The structural grain of Scandinavia and the trend of its rocks date from periods which are primeval when compared with the formation of the fiords. The plan of their distribution is, however, directly connected with the geographical relief of the country. Norway is essentially a plateau. Visitors, who sail up its fiords and have only vistas of mountains between the precipitous walls of the trough-valleys, may fail to recognise the resemblance to a plateau. The country is often regarded as exceptionally rugged and mountainous. If, however, the country be surveyed from the mountain summits it is at once recognised as an old plateau, which has been dissected by the formation of the fiords and valleys. Cook's *Guide to Norway* (1904, pp. 17–18) truly describes its structure when it says that—

> "The whole country consists of one immense mountain plateau, intersected in the east by great valleys and in the west by deep fjords and bays. The tops of the mountains are mostly rounded, giving the whole country the predominating character of an undulating plateau, in which the fjords and valleys only appear like narrow fissures. . . .
>
> "Having noted the general configuration of Norway, which appears like a vast table-land with an elevation of from 2,000 to 4,000 feet, . . . it will be perceived that the roads traversing the country must necessarily follow the valleys and mountain passes" (*Norway*, 1904, p. 26).

The main plateau of south-western Norway is bounded by steep slopes, the course of which is parallel to many important fiords and valleys. This fact was clearly expressed by Kjerulf in his *Coup d'Œil sur les traits dominants du relief de la Norvège*" (1878) [1] and in several memoirs. He pointed out that the coasts, fiords, lakes, and valleys of south-western Norway occur along straight lines which may be arranged in seventeen groups; and the intersection of these valleys divides the country into a series of angular blocks. He classified these lines as follows, with the initials used on Fig. 26:

1. *Lines with a north-easterly strike.*
   K. Tr. The fiord-straits parallel to the coast between Trondhjem and Aalesund.

[1] See *e.g.* 1879 and 1880, pp. 329–334.

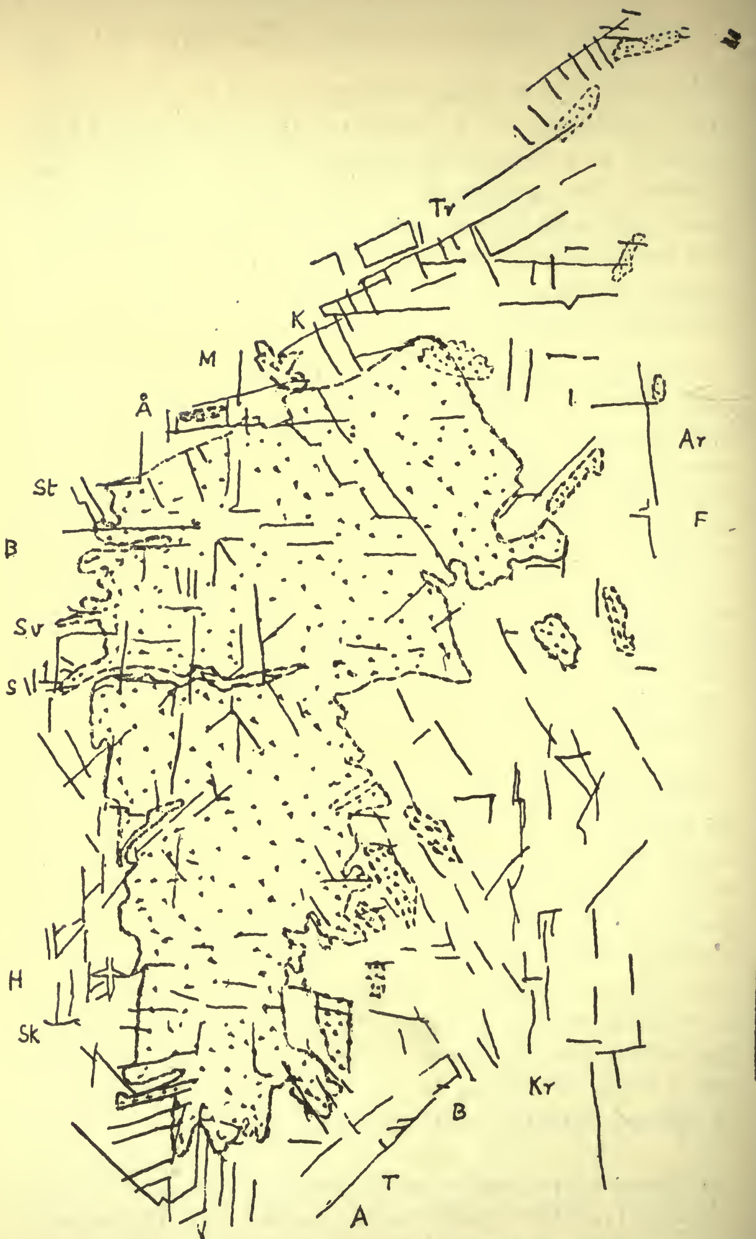


FIG. 26.—PLAN OF THE FIORDS AND VALLEYS OF SOUTH-WESTERN NORWAY (AFTER KJERULF).

The areas marked by dots are highlands bounded by steep sides.

H. Ar. The Hardanger Line.
A. T. The Arendal coast.

2. *Easterly strike.*
K. The Sälbu Line, south of Trondhjem.
B. F. Nord Fiord.
S. Sogne Fiord.
Sk. B. Bandags Fiord, south of the mouth of the Hardanger Fiord, and Risör Fiord near Christiania.

3. *South-easterly strike.*
M. Romsdal.
Aa. Kr. Ekern.
St. B. Stat.
T. Fyrris and Höle Fiord.

4. *Southerly strike.*
Ar. F. Kjölen Fiord.
Tr. Kr. Christiania Fiord.
M. L. Lindesnäs.
Aa. Sk. Gands Fiord.
S. Sulen Line.

The intersection of these four series of lines divides the country into angular blocks which are well shown on the shaded relief-maps of Norway.

The geographical importance of Kjerulf's fracture-lines has been recently reaffirmed by Sederholm, who regards them as mainly of Miocene age (**1911**, pp. 33–7), with minor post-glacial movements. He has extended the area affected by these fractures to Finland, and shown that many of the Finnish fiard-like lakes lie along them (Sederholm, **1911**, pp. 42–4 and map *Les Lignes de Fracture dans la Fennoscandia*).

The Scandinavian area which underwent the greatest oscillation in glacial and post-glacial times was along the Swedish coast of the Gulf of Bothnia between Sundsvall and Umea. Thence the movements gradually diminished until they ceased along a line which lay off the coasts of Norway and Lapland, crossed the mouth of the White Sea, traversed Russia to the east of St. Petersburg and Riga, skirted the northern coast of Germany, and then turned northward across Denmark and passed near the south-western point of Norway. Many of the fracture-lines are radial from the area of maximum movement, which might suggest that the fractures followed by the fiords are of glacial or post-glacial date. In some parts of the Scandinavian peninsula, however, as in the fiord-network near Trondhjem, the main lines are concentric with the lines of equal movement instead of being transverse to them; and, as Sederholm remarks (**1911**, p. 45), if these abundant fractures were of such recent date Scandinavia would not enjoy its present general immunity from violent earthquakes. The dislocations are probably due to Miocene and Pliocene movements, and those of post-glacial times are of secondary importance, except in a few special areas, where earthquake shocks are not uncommon.

Angular networks of valleys are hardly the natural result of ice-erosion. The ice, in a country which is covered with a vast ice-sheet, would flow outward from the region of largest snowfall toward the lower land. The line of the ice-shed need not coincide with the present watershed, and in Scandinavia it lay far to the east of the watershed. The ice flowed westward over Norway to the Atlantic and south-eastward down the Swedish slope to the Baltic. The ice during one stage both of its advance and decay would no doubt have occurred as valley-glaciers, which would have modified the valleys. But there seems no reason why an ice-sheet or a system of valley-glaciers should have cut out a series of intersecting cross-valleys, many of which would have lain at right angles to the main advance of the ice.

Kjerulf insists that the coincidence of the fiord-valleys with a system of fracture-lines explains the great depth of the fiords. He says (**1879**, p. 143): "If a land be cut into pieces and then raised together, it is clear that the floors of the fractured (*eingeborstenen*) fissures would not correspond throughout with the gradient of the present running water, but would lie sometimes higher and sometimes deeper." He therefore regards the deep hollows as of tectonic origin, though the ice that once flowed into them has smoothed their slopes.

Kjerulf (**1879**, p. 145) clearly explained that the Bukken or Stavanger Fiord was not due to erosion, but to subsidence. For the Silurian beds occur at sea-level on the islands and can be seen as a dark wall above the gneisses and granites on the mountains to the east. The Silurian beds on the islands have been lowered along a fracture, which Kjerulf describes as "a line running north and south from Vikedal to Hjelmeland." He stated that Dahll "authenticated the occurrence of this bed in the east of Hjelmeland above the granite masses 2,000 ft. higher, but on the islands it plunges into the sea." The position of the Silurian rocks on the islands can only be explained by earth-movements, as can be judged from Kjerulf's apt comparison to a submerged house. A house with its roof just rising above a sheet of water cannot have been lowered by erosion, which would have removed the roof and exposed the lower floors. Similarly, the occurrence at sea-level in the fiords of Silurian beds, which cover the gneisses and granites on the neighbouring mountains, proves either the subsidence of the fiords or the uplift of the adjacent areas.

Many of the Norwegian fractures are very ancient, and it has been suggested, as by Brigham (**1906**, p. 338), that any valleys formed by earth-movements would long since have disappeared. There is, however, abundant evidence that the great oscillations of Scandinavia in recent times were attended by the irregular tilting and refaulting of the country. Thus Hansen has called attention to evidence in favour of the earth-movements being still in progress in some parts of Scandinavia ; he considers that the land in the upper part of Lake Wener is being upraised about eight inches a century, and that the coast of parts of Norway may have emerged 65 ft. during the last 2,000 or 3,000 years.

The extensive fracturing and dislocation of the Norwegian coast in recent geological times are well established, and it is now generally recognised that the topography is to a large extent due to these earth-movements.

"The Norwegian coast," says Prof. Hobbs (**1912**, p. 229), "was long ago shown to be a complexly faulted region, and these larger divisions of the relief-pattern, instead of being explained as a consequence solely of selective weathering, must be regarded as largely due to fault displacements. . . . Yet, whether due to displacements or to the more numerous joints, all belong to the same composite system of fractures expressed in the relief."

11. Summary of the Norwegian Evidence as to the Essential Characteristics of Fiords

After the previous summary of the distribution of the Norwegian fiords and a description of a few representative examples, we may consider what are the main characteristics which separate fiords from other types of drowned valleys. The walls of fiords are their most conspicuous and characteristic feature. In the typical fiords the walls are high and steep. The highest sea-cliff in Europe, Hornelen, 2,940 ft. in height, is on one of the fiord-straits and steep cliffs 3,000 and 4,000 ft. high are found along some of the inland fiords. The walls moreover are not carved by deep gullies. The sides of the most typical fiords are flat and unbroken for considerable distances. Hence the term "wall" is the most appropriate to apply to them, in contradistinction to the sides of ordinary valleys. The streams which rise on the level uplands beside the fiords frequently descend as waterfalls over these walls, instead of as cataracts down lateral gorges, which have been formed by the cutting backward of the cliff along the stream-beds. In many cases these waterfalls are so recent in origin that their face is almost flush with the general wall.

Another striking feature of fiord-walls is that they are often sub-parallel, so that the fiords are often uniform in width for considerable distances. The general course of a fiord-valley is straight rather than curved. They are sometimes slightly sinuous, but as a rule the bends are at sharp angles, and the reaches of the fiords are straight. In contrast to the sinuosity of river-valleys, fiords are dominated by straight lines and sharp angles.

The branching of fiords is also characteristic. Instead of the tributaries joining the main fiord at gentle angles, which point seaward, they join at high angles and often at right angles. Whereas the typical plan of a river-system is a tree-like arrangement of bifurcating branches, the tributaries of a fiord-valley form a network which breaks up the country into angular blocks.

The floors of the tributaries of fiords often stand above the level of the main valley. They therefore occur as hanging valleys, whereas in rivers the tributaries are generally cut down to the level of the main valley.

The floors of fiords are usually fairly flat, so that a section across a fiord is rather trough-shaped. The flatness of the floor in the Norwegian fiords is probably exaggerated by the fewness of the soundings. If soundings were taken more closely and at lines across the fiords, the bottom would very likely be found to be less regular than is shown by the present data.

The typical Norwegian fiords are surprisingly deep. The deepest parts in the typical fiords of south-western Norway lie about half-way along their length. The fiord, therefore, consists of a very deep basin, the outer rim of which no doubt in many cases consists of rock. The fiord-basins are probably of four distinct types: (1) simple rock-basins in which the fiord is separated from a deep sea by a comparatively narrow rock-threshold; (2) simple basins which are bounded by a wide tract of comparatively shallow sea; (3) compound basins due to more than one rise and fall of the floor of the fiord; (4) valleys which have been converted into basins by the deposition of a bar of sediment.

Such are the characteristics of the typical fiords. It is fiords with these features that rise to one's mind when pleasant voyages in the Norwegian waters come back to the memory. The scenes on the fiords that appear most vivid are probably those of high, dark, bare cliffs rising above a narrow channel of smooth dark water, and perhaps the only sign of human occupation a low log-hut on a narrow strip of green meadow alongside the beach or on a small patch beside the mouth of a stream.

It is important, however, to remember that these characteristics are by no means always present. They occur in the fiords where, owing to the hardness of the rocks and to various protecting agencies, the valleys have been but little widened by the ordinary processes of denudation and therefore still retain the characters of young valleys. Many of the fiords, however, coincide in places with old valleys, of which the walls have been cut back to gentler slopes, and on their floors are wide tracts of fertile meadow-land and forests. Visitors to the western parts of the Sogne Fiord are often disappointed by the lack of grandeur in the scenery due to the comparatively gentle slopes. The popularity of the Hardanger Fiord largely depends upon the fertility of the level ground beside it and upon its well-wooded banks. Fiords, after contracting to narrow, rock-bound gorges, often widen out again into broad basins, which approximate in contours to the ordinary types of weather-worn river-valleys.

The hardness of the Norwegian rocks and the protection afforded by a mantle of snow and ice, during part of the period since the formation of these fiord-clefts, have preserved the valleys in the forms of geographical youth. It is upon those fiords which have retained their steep spurless walls and deep island-free channels, that the geographical conception of a fiord is based.

CHAPTER V

THE FIARDS OF SWEDEN AND FÖHRDEN OF SCHLESWIG

A. THE SWEDISH FIARDS

It may not be because this tranquil hour,
  Brightening elsewhere to beauty scenes more grand,
  Here lights with milder beam a lowlier strand,
And that yon sea, like a tired warrior,
For quiet joy hath laid aside his power.

AUBREY DE VERE.

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1. Resemblance to Norway.—2. The Fiords of Bohusland.—3. The Fiards of south-eastern Sweden.

1. RESEMBLANCE TO NORWAY

SWEDEN, though so closely adjacent to Norway, is not a fiord-land. The two countries are essentially one in geological history and structure; for Sweden, like Norway, consists of a foundation of Archean rocks covered with some Lower Palæozoic sediments. Both countries have undergone the same severe glaciation. In both the coasts are greatly indented and fringed by a belt of islands, which in Sweden is known as the Skärgård. But Norway is a high plateau with a steep broken descent to the Atlantic, whereas Sweden has a long gradual slope eastward to the Baltic. Hence Sweden has a wide coast-land at a comparatively low level, and the coastal types of the two countries are very different. The inlets on the Swedish coast are shorter and shallower than those of Norway. It has, in fact, few fiords, but many fiards, In the interior there are many great lakes, but they are not fiord-lakes, though often long and narrow; for they usually lie in depressions on river-valleys and have low or gently sloping shores. The two great lakes of southern Sweden occupy tectonic basins. Lake Wetter is the more fiord-like, as it is long, deep, and proportionately narrow, and lies between steep parallel banks; its surface is 289 ft. above sea-level, and its maximum depth is 390 ft.[1]; so that its floor goes 101 ft. below sea-level. It also has the north-north-east to south-south-west trend, which is so important throughout the fiord area of north-western Europe, and is approximately parallel to the Gulf of Bothnia, to the whole length of Scandinavia, and to some of the chief geographical lines in Scotland. Lake Wetter is, however, a tectonic lake-basin, and occupies a rift-valley between two sub-parallel faults. Though doubtless modified by glacial erosion, the lake-basin was not due to this process. Glacial action in Sweden appears to have had on the whole a levelling effect, for the ice has worn down the ridges more than it deepened the basins between them.

2. The Fiords of Bohusland

The Swedish fiords are confined to the province of Bohusland (Gothenburg) near the Norwegian frontier, on the eastern side of the Skager Rak. Several inlets there are accepted by Dr. Otto Nordenskjöld (**1900**, p. 194) as true fiords, and he describes them as the representatives of his class of fiords outside mountain regions. Gullmar Fiord is 19 miles long by from ½ to 1¼ miles wide; it has a maximum depth of 466 ft. and a threshold at its mouth by which its depth there is reduced to 256 ft. Farther south is Kolje Fiord with By Fiord, which is

[1] Lake Wener, though three times as large, has the maximum depth of only 292 ft.

equally narrow but longer, and has a maximum depth of 187 ft., while its outlet through a strait parallel to the coast is only 20 ft. deep. From these measurements it will be seen that these fiords have well-developed thresholds.

The geological structure of Gullmar-fiord and its neighbourhood has been described by Axel Lindström (**1902**, pp. 3–4), who has briefly referred to the geographical characters of the inlets. He describes the Gullmar Fiord as 20 km. long and from 2 to 3 km. wide. He shows that the granites of the neighbourhood are traversed by conspicuous parallel-jointing, which he illustrates by a sketch of the shore of Stockvik (Lindström, **1902**, p. 34, fig. 2).

Baron de Geer (**1891**, pp. 298–9) has called attention to the connection between the fiords and lakes of Bohusland, with the fissures of the area, of which there are two conspicuous systems; the members of one system trend along the fiords from 40° to 60° east of north, while those of the other system trend from 10° to 20° west of north, approximately parallel to the coast. He instances Ide Fiord, the Bullarsjö, Dynekillens, and the inner parts of Strömsvattnets as examples of fiords and lakes formed along these fissures. He suggests (Geer, **1891**, p. 299), moreover, that the coast-fissures are older than those along the fiords.

The inlets along this part of the coast of Sweden are also described as fiords by Svedmark (**1902**, p. 4) in his description of the geological structure of the country around Fjellbacke. He quotes some as fiords, but their place-names, as Sannäsfjärden and Jordfjorden, designate some as fiards and others as fiords. They are less well developed farther south near Gothenburg and in that area, while some are known as fiords, such as Elfsborgsfjorden and Elfvefjorden; "Lökebergskil, with its continuation in Elgöfjärden," is accepted as a fiard (Blomberg, **1902**, p. 8).

3. The Fiards of South-eastern Sweden

The most striking irregularities of the Swedish coast are on the shore of the Baltic between Stockholm and Karlskrona. The coast is very jagged and fringed with a belt of rocks and islets. The inlets are, however, not true fiords; for the land is low, its slopes are gentle, and the inlets belong to the subdivision of fiords known as fiards. Von Richthofen explained the characters of fiords as partly due to the absence of marine abrasion; yet the Baltic inlets are not fiords, although its waters are quiet and almost tideless. The coast is beaten by heavy seas in storms, but it is not exposed to the ceaseless backward and forward scour of the tide.

The harbour of Karlskrona illustrates one of the types of fiards.[1] The town of Karlskrona is on the end of an irregular peninsula that projects southward into a wide bay, which is separated from the Baltic by peninsulas at the sides and a chain of islands in front. Karlskrona Bay is divided into three main parts, known as the Utö Fiard to the west, Stor Fiard, and Östra Fiard to the east. The country around Karlskrona consists of Archean schists and gneisses invaded by younger granites. The strike of the gneisses in the country to the west of Karlskrona is generally from north-west to south-east, and this trend continues through Karlskrona to the islands on the south-east. To the north-east of the town the strike in the Archean rocks bends round till it becomes east and west. Eastward from Karlskrona the coast takes a sharp bend to the north, at the beginning of the Kalmar Sund; and the coast is formed by a band of Cambrian sandstones and conglomerates with the strike parallel to the shore. The coast near Karlskrona is therefore transverse, as it cuts across the grain of the

[1] The geological structure of the coast around Karlskrona and thence westward past other fiards to Karlshamn is described in a monograph by Blomberg (**1900**).

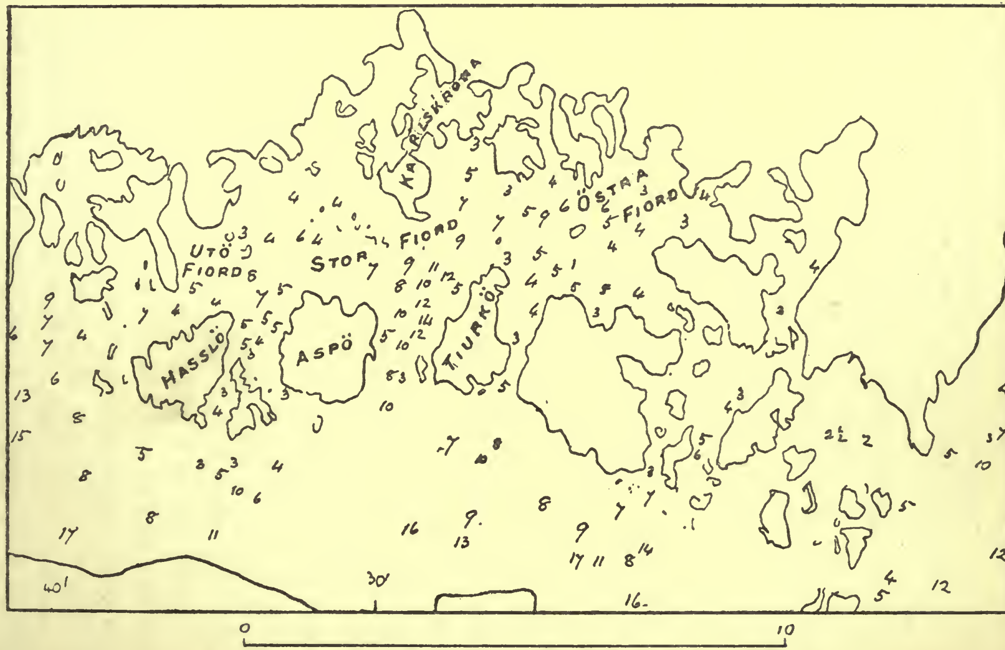

FIG. 27.—THE FIARDS OF KARLSKRONA.

Depths in fathoms. From Admiralty Chart, Sheet I., Sweden, 1910.

country. The irregular form of the harbour is clearly due to the land having had an undulating slope southward; a sheet of glacier-ice doubtless flowed down this slope and etched it by the removal of the weak weathered rocks and thus formed many irregular depressions. When this land sank these hollows were filled by the sea, and thus formed the Karlskrona Fiards. The variations in depth of the Karlskrona Fiards is shown on Fig. 27, reduced from the Admiralty Chart.[1] The west, or Utö Fiard, has a maximum depth of 48 ft., and its outlets on the two sides of the island of Hasslö have no more than 24 and 18 ft. Stor Fiard has a very irregular bottom; its greatest depth is 84 ft., which is near its mouth, where there is a bar with no more than 48 ft. The Östra Fiard has a maximum depth of 54 ft., and its outlets have thresholds of no more than 18 ft.[2]

A more fiord-like group of fiards may be illustrated by those in the neighbourhood of Vestervik, which I had the privilege of visiting in 1906 with Prof. Högbom, Dr. J. Gunnar Andersson, and Prof. H. Bäckstrom. Gamleby-viken is a long inlet with the sides nearly parallel and with a narrow outlet at Vestervik (Fig. 28). Its depth[3] near its inner end is 216 ft.; it shallows to a passage of 54 ft., deepens again to a long narrow basin with depths of 84 and 90 ft., and then has a narrow outlet, only 48 ft. or perhaps less in depth opposite Vestervik. Then follows another irregular and wide basin of 66 ft., and a final outlet with the depth of 48 ft. Gamleby-viken is, then, a compound basin with well-marked thresholds.

The next inlet to the north is Gudinge Fiard, a broad

[1] The Coast of Sweden, Sheet I., November 1910.

[2] The geological structure of the country around Karlskrona is shown on the map of the Sveriges Geologiska Undersökning, Ser. A 1, a, Bladet 5, 1905.

[3] The following depths are taken from the Swedish topographic map (Scale 1 to 100,000; Sheet 37, Vestervik). The geology is shown on the map of the Sveriges Geol. Unders. map, 1 to 50,000, Bladet Loftahammar, Ser. A a. No. 127, 1904, and Västervik, Ser. A. a. No. 137, 1907.

basin, with its mouth nearly closed by islands. The greatest depth marked in the fiard is 132 ft.; 150 ft. occurs in the entrance-passage; this, however, shallows to between 30 and 42 ft. at the outer end. Proceeding northward along the coast there are fiards which, though very variable in form and depth, are in general parallel to one another and oblique to the main line of the coast;

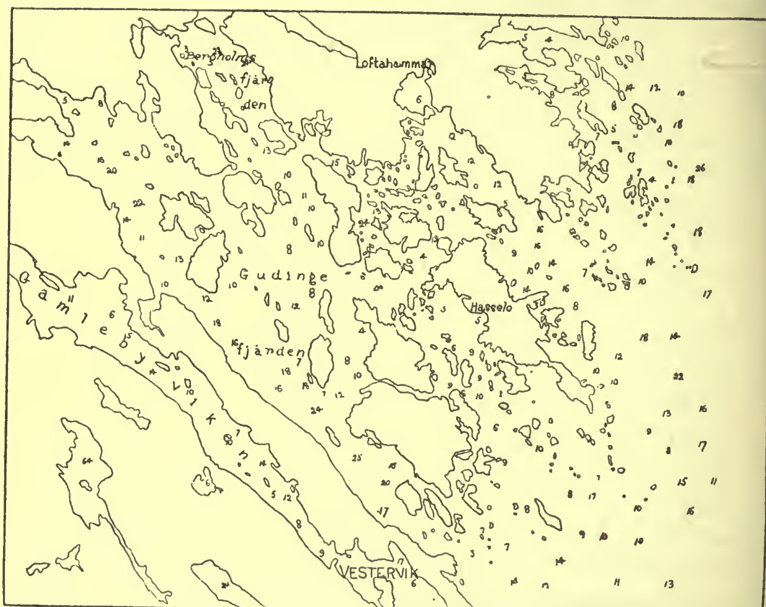

FIG. 28.—MAP OF THE FIARD COAST NEAR VESTERVIK, SWEDEN.
Scale 10 geogr. miles to 1 in. (depths in fathoms).

and they have basins separated from the Baltic by well-developed thresholds.

The resemblances of these inlets to fiords is increased by the network of channels, the frequent arrangement of the islands in regular lines, and their often angular outlines. The Vestervik Fiards, including Gamlebyviken, therefore have some points of agreement with fiords; but they are true fiards, as their shore-lines are usually curved, the outlines of the country are well rounded, straight lines are exceptional, and the slopes are gentle. Inland these fiard-valleys are occupied by lakes, in similar basins, of which the margins are above sea-level.

The land around the fiards is all low. The highest point near Vestervik is only 125 ft. above sea-level. The ridges between the fiards were doubtless formerly higher, but the passage of ice across them has left the country with a low, rounded relief, and a scenery characterised by the succession of low, level-topped ridges with well-rounded wooded sides and valleys with innumerable lakes and inlets.

The rocks around Vestervik are all of Archean age; they include altered sediments, schists, and gneisses, into which the Vestervik granite has intruded. The strike of the rocks is from north-west to south-east, so that the parallelism recognisable in the fiards and the islands is an expression of the grain of the land. The fiards occupy strike-valleys.

The coast-line in this part of Sweden runs north and south, so that it is oblique to the grain of the country. There is no direct trace of the influence of earth-movements in the geography of this district. The whole country has been worn down to a low level by prolonged denudation. The passage of the ice across it swept away all the loose material and left the hills as low rock-ridges separated by valleys; later, the subsidence of the country under the inflowing Baltic drowned the lower ends of these valleys and thus formed the fiards.

The distinction between fiords and fiards is not always maintained in practice even for the typical fiard areas of south-eastern Sweden, for Gavelin (**1904**, pp. 3–4) describes the inlets near Loftahammar as fiords, although the local place-names call them fiards, such as Gudingefjärden, Bergholmsfjärden. Gavelin gives interesting evidence of the gaping of the rocks in this district by joints, one of which at Smågö has been filled up by sandstone, and thus formed a sandstone dyke. (**1904**, p. 62, fig. 11.)

B. THE FÖHRDEN OF THE SOUTH-WESTERN BALTIC

Her walls have no granite for girder,
  No fortalice fronting her stands;
But reefs the bloodguiltiest of murder
  Are less than the banks of her sands.

A. C. SWINBURNE.

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1. Föhrden.—2. Geology of the Schleswig Peninsula.—3. Diversion of the Drainage.—4. Super-position of the Föhrden on Older Valleys.—5. Distinction between Föhrden and Fiords.

1. FÖHRDEN

THE use of the term "fiord" has been extended to include the inlets on the eastern coast of Schleswig-Holstein in northern Germany and to the arms of the sea on the mainland of Denmark. One of them, the Limm Fiord, is now a strait across the Danish peninsula, as a storm in 1825 broke through the land between it and the North Sea (Jordan, **1903**, p. 59). In Denmark these inlets are called "fiords," while in Schleswig they are known as "föhrden," and according to various authorities, especially Hubbard (**1901**, p. 337) and Werth,[1] they are to be regarded as a variety of fiord. The best-known and most typical föhrden are the three southernmost members of the series—the Kiel Föhrde, Eckenförde, and the long inlet known as the Schlei, which have all been described and discussed by Haas (**1888**).

The characteristics of the northern föhrden and the inlets which represent them in eastern Denmark, such

[1] Werth indeed regards föhrden as synonymous with fiards (**1909**, p. 355).

as the Limm Fiord, Mariager Fiord, Randers Fiord, etc. (Fig. 29), have been summarised in a table by Jordan (**1903**, pp. 51–7); he has also given detailed measurements of the coasts of Denmark and Schleswig (pp. 18–47). The strikingly different character of the western coast of Schleswig can be appreciated from the description of Haage (**1899**) (cp. Fig. 29).

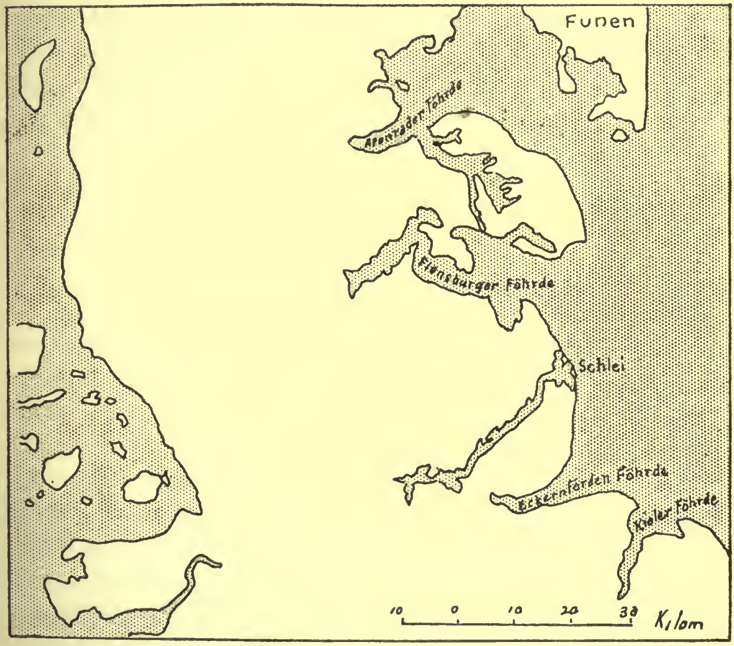

Fig. 29.—Sketch-map of the Föhrden of Schleswig.

2. Geology of the Schleswig Peninsula

The foundation of the peninsula of Schleswig-Holstein consists mainly of rocks belonging to periods between the Cretaceous and the Miocene.[1] These older rocks are almost entirely covered by a mantle of drifts, which

[1] *E.g.* Lepsius, Geol. Karte deut. Reichs. 1,500,000, Sheet I. Schleswig, 1894.

consists mostly of glacial deposits, and, according to Haas, varies from 260 ft. to 425 ft. in thickness. The level of the whole country is comparatively low. The greatest height, known as the Huttener Berge, 348 ft. high, is a hump on a moraine and the other chief elevations such as a mound 230 ft. high north of the mouth of the Eckenförde and another 173 ft. high in the interior, are also hummocks of drift. The older rocks are mainly below sea-level, above which the land consists of glacial drifts. These deposits, according to the generally accepted view, were laid down during two distinct glaciations, which allowed an interval of time sufficiently long for the ice to disappear completely.

3. Diversion of the Drainage

The present watershed lies along the eastern side of the country, and the main drainage is westward into the North Sea. In the inter-glacial and probably earlier times the drainage was north-eastward to the Baltic. Haas remarks that the direction of this earlier drainage is still unexplained; but he suggests that it may have been due to the rivers having been diverted to the Baltic by an ice-sheet which lay to the north-west of Schleswig and lasted much later than the Baltic ice to the north-east. Accordingly the Baltic Sea was ice-free, while the adjacent part of the North Sea was still ice-covered; so the rivers all flowed to the Baltic and cut out channels which are now the föhrden. Once again the country was covered by an ice-sheet, and on its retreat it disappeared first to the west, so that the rivers took their present courses and flowed westward to the North Sea. Hence the föhrden, on the complete withdrawal of the ice, were left empty and no longer acted as the main river channels (Haas, **1888**, pp. 30–31).

4. Superposition of the Föhrden on Older Valleys

According to Haas the general topography immediately before the first glaciation was much the same as it is at present. The old valleys occupied the position of the present depressions, for the sheet of drift only softened, but did not completely obliterate, the earlier topography. The föhrden themselves, therefore, tended to occur along the older valleys; and, according to Haas, they were excavated by the combined action of the inter-glacial streams, the sea, and the ice-sheet.

According to other authors the föhrden are younger than Haas thought, and were formed by the later glaciation. Olbricht, it is true, regarded the föhrden as old trough-valleys altered by the younger glaciers, but his view has been rejected by most subsequent authorities. Thus Gagel (**1909**, p. 236) describes the föhrden as excavated during the later glacial period and probably by water from the melting ice, and he considers that they were most likely formed as sub-glacial channels. He admits that this conclusion is not consistent with all the evidence, but he believes that no final solution of the föhrden problem is yet possible (Gagel, **1909**, p. 235). Gagel describes the Untertrave as a typical föhrde and says that it is in no way a simple drowned river-valley, but is undoubtedly a channel eroded by water from the melted ice flowing in a reverse direction to the present fall of the valleys.

Jordan (**1903**, p. 7) also assigned the föhrden to the later glaciation of Schleswig, and he regarded them as having been at "first only inter-glacial stream-beds" (p. 8).

The history of the föhrden is therefore that of the successive diversions of a river-system in an area of soft young beds. They are abandoned river-channels, probably along the courses of still older valleys. According to Haas's view they are beheaded estuaries, which, owing to the obstruction of a former ice-dam, have lost the rivers that entered them. If the rivers had continued to discharge into the föhrden the valleys would have been altered in shape owing to the silting of the channels and the erosion of the banks ; but because of the diversion of the rivers the föhrden have remained long and narrow, and include some basins deeper than the outlets, for though little sediment has been carried into them from the land, their mouths have been blocked by shoals. Moreover, the Baltic being an almost tideless sea, these parallel-sided channels have not been worn by tidal scour into the triangular or funnel-shaped form of ordinary estuaries.

The thresholds at the mouths of the föhrden are merely alluvial bars, and they are only occasionally present. They occur at the entrance to both the Schlei and Mariager Fiord: for the Schlei is 14 ft. deep at its entrance and 50 ft. within. The Mariager Fiord, which is 25 miles long, has a narrow, shallow channel at its mouth ; the eastern part varies in depth from 18 to 30 ft., while the western or inner part includes a broader basin, which is 120 ft. deep (Jordan, **1903**, pp. 51, 52, and chart opposite p. 64). Randers Fiord and Apenrader Föhrde are about as deep at the entrance as within. Horsens Fiord, Vejle Fiord, Kolding Fiord, Haderslebener Föhrde, Flensburger Föhrde, Eckernförde, and the Kiel Föhrde are all deepest at the mouth, and so they have no thresholds.

5. Distinction between Föhrden and Fiords

Von Richthofen selected the coast of the south-western Baltic as the typical Cimbrian coast,[1] which he asserted

[1] Von Richthofen regarded the Arctic Archipelago of America as of the Cimbrian type, but it appears to have an essentially distinct structure.

was due to the submergence of reticular, branched, elongated valleys, whose origin is connected with glacial action on a lowland beside an inland sea. He points out that the forms of these inlets would have been very different, if the sea which they enter had had strong tides and wave-action. According to this view the föhrden should not be regarded as a variety of fiords. They agree with fiords only in characters of secondary importance. According to Jordan (**1903**, pp. 60–62), fiords and föhrden agree in many of their dimensions and proportions, in being groupal, and, according to him, in both dating from glacial times. He restricted fiords to high coasts and föhrden to low, hilly land, and he observed that föhrden are free from islands. Further resemblances are that they do not serve as estuaries, and that, owing to shoals, some of them are separated from the sea by thresholds.

But the föhrden differ from fiords as they occur in low country and are valleys cut through soft beds. Föhrden resemble fiords in plan as they happen to have been protected from silting because their rivers have been diverted, and from widening by erosion because no strong currents have swept down the valleys.

CHAPTER VI

THE FIORDS OF ICELAND

All the folk in Alftafiord
Boasted of their island grand ;
Saying in a single word,
" Iceland is the finest land
That the sun
Doth shine upon."

LONGFELLOW.

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1 Contrast with Norway.—2. Its Fiords partly Sunk-lands.—3. The True Fiords.—4. Submarine Trenches continuing the South-eastern Fiords.—5. Geological History.—6. The Fiords Pre-glacial Valleys in a Volcanic Plateau.

1. CONTRAST WITH NORWAY

THE volcanic island of Iceland stands on a shallow submerged ridge which connects Greenland with Scotland. Its coast is riven by fiords. " Deep narrow fiords penetrate inwards from every direction, but in largest number from the north-west," says Thoroddsen (**1899**, p. 267). " The fiords," he continues, " are shut in by dark walls of basalt, which in many places rise perpendicularly, or with a very slight inclination, straight from the sea, to an elevation of 2,000 to 2,500 ft." The Icelandic fiords have many of the features of the typical fiords of Norway. Yet Iceland differs geologically from Norway in all essential features. Scandinavia is a very ancient land, and is built mainly of Archean rocks and has no remains of recent volcanic action. Iceland, on the other hand, is a very young land. It contains no ancient rocks ; it is almost exclusively built up of volcanic materials

FIG. 30.—SKETCH-MAP OF ICELAND.
Showing its fiords and their deeps (depths in ft.).

erupted in geologically modern times, and it is still the scene of intense volcanic activity. The only important point of agreement in structure between Norway and Iceland is that they are both plateau-lands which have been greatly dissected.

The physical geography and volcanic history of Iceland are best known from the elaborate researches of Dr. Thorwald Thoroddsen, and most of the following chapter is based on the monograph (1905–6) in which he summarised the results of his life's work, and on the paper which he contributed to the *Geographical Journal* in 1899.

The area of Iceland is 40,450 square miles, and is therefore larger than Ireland by nearly a third. It consists in the main of a volcanic plateau from 1600 to 3,000 ft. high, above which some smaller plateaus rise to the height of from 4,500 to 6,500 ft. The coast is indented by a series of wide bays, funnel-shaped gulfs, and narrow fiords which, as in Norway, are all called fiords, but with the Icelandic spelling, fjördr.

There are two broad, open bays upon the western coast; three long, tapering gulfs and several wide bays on the northern coast; and a series of small fiords in the south-eastern coast. The most important of the fiords are those on the western and especially the north-western coast. The southern coast is mostly even and unbroken; it is described as "destitute of harbours, all the fiords having been gradually filled up by the detritus carried down by the glacial torrents" (Thoroddsen, **1899**, p. 481).

2. Fiords partly Sunk-lands

The two great western bays are known as Breidi Fjördr and Faxa Fjördr, and they are marked on the Admiralty Charts as Brede Bay and Faxe Bay. These two fiords belong to the class represented in Norway by

Bukken Fiord. They are both sunk-lands, for, according to Thoroddsen, they were both formed by the foundering of blocks of land beneath the sea. They are each surrounded by a series of concentric fractures.

3. The True Fiords

Narrow fiords run inland from both of these wide bays. Borgar Fiord and Hval Fiord, the two chief fiords

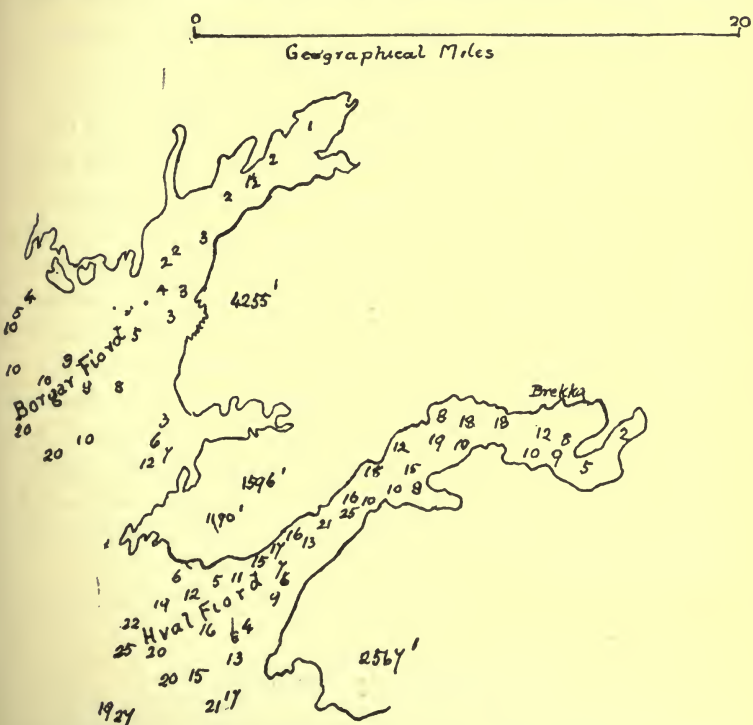

FIG. 31.—TWO FIORDS OFF THE SUNK-LAND OF FAXA FIORD.
There is a threshold to Hval Fiord, but not to Borgar Fiord.

opening into Faxa Fiord, are illustrated by Fig. 31, copied from the British Admiralty Chart. Borgar Fiord has a rather tapering form. It is shallow and increases regularly in depth into the outer bay. Hval

Fiord, on the other hand, has more regular and parallel sides. It deepens for the upper two-thirds of its length to an extreme depth of 150 ft. It then shallows to its entrance, where in one section of the channel the deepest part is probably about 90 or 96 ft.

The fiords on the north-western peninsula include ten main and several small fiords. They are connected, according to Thoroddsen, with a series of concentric fractures.

The deepest fiord, according to Thoroddsen, is 623 ft. deep.

The fiords on the eastern coast of Iceland are short and simple. Along the northern part of this coast they trend to the north-east; farther south they lie east and west; as the coast farther on bends round towards the south-west and the trend of the fiords keeps at right angles to the coast, they therefore open to the south-east. Mio Fiord and Beru Fiord (Fig. 30) are typical examples of this series. Mio Fiord has a tapering form and deepens with fair regularity from its head to its mouth; it therefore resembles a ria. Beru Fiord has somewhat irregular shore-lines, though its sides are often almost parallel; it has a well-marked threshold, for its depth, at two-thirds of the length up the fiord, is 252 ft., and the depth of the passage at the mouth appears to be as low as 60 ft.

4. Submarine Trenches

The south-eastern fiords are continued by submarine trenches, which extend seaward for about thirty miles as valleys on the sea-bed (Fig. 30); they make deep notches on the edge of the hundred-fathom plateau. The chief of these trenches are marked on the Admiralty Charts and named the Beru Fiord Deep, Loons Deep, Horne Fiord Deep, Jökulsaa Deep, and Skeidaraa Deep.

5. Geological History

The ages of the rocks associated with the Icelandic fiords have been approximately determined by some fossil plants found in layers interbedded with the lavas; but there is still some uncertainty as to the exact date of these fossils. The oldest lavas were discharged in Lower Kainozoic times, and were contemporary with those of the north-western islands of Scotland and the Antrim plateau in Ireland. The foundation of the whole island consists of lavas, which accumulated to the thickness of from 10,000 to 12,000 ft. The eruptions built up a series of vast lava-plateaus. Iceland was then united to Greenland and the British Isles. This great land was broken up by a series of subsidences. Iceland remained for a while connected with Greenland and Scotland; but further subsidences at the end of the Miocene period converted Iceland into an island. The subsidences continued through the Pliocene [1] and fresh volcanic eruptions took place along the fracture-lines. The land was reduced in area and great valleys in it were carved by rivers. At the end of the Pliocene the land was standing at the height of 820 ft. above its present level. The eastern fiords were probably excavated by erosion at this time; and the lower parts of these fiord-valleys formed the five "deeps," or submarine fiords in the submerged platform along the south-eastern coast.

6. The Fiords Preglacial

The sunk-lands of Faxa and Breidi Bays were both due to subsidences which began, according to Thoroddsen, at the end of the Miocene. Faxa Bay is younger; its formation started in the Pliocene, and its subsidence

[1] Dr. Helgi Pjetursson has shown that the Icelandic marine Pliocene beds at Tjörnes prove that the Pliocene period in Iceland was a time of volcanic quiescence and of slow subsidence (**1906**, pp. 712–14). According to him, some of the events usually referred to the Pliocene happened in the Pleistocene.

is probably still in progress; but, according to Thoroddsen, "The broad bays of Breidifjord and Faxafloi were both formed prior to the glacial epoch" (**1899**, p. 493). The main fractures which formed the fiords of western and north-western Iceland were probably due to the continuation of the subsidences through the Pliocene. In Pleistocene times the land sank till it was 330 feet below its present level; and on the retreat of the ice the land was uplifted, with a long pause in the elevation, when the sea was 130 ft. above its present level.

The connection of the fiords with the earth-movements was recognised by the earlier writers who described the fiords. Thoroddsen quotes Midda in 1833, Zirkel in 1860, and Keilhack in 1866 as attributing the fiords to tectonic causes. In 1865 the view of their formation by glacial erosion was suggested by Paijkull, and this theory was strongly supported by Helland in 1881. Some of the authors who are inclined to this view recognise that glacial erosion only enlarged older valleys. According to Johnstrupp in 1876, these preglacial valleys were due to rivers. Most later authors have, however, considered that the valleys were excavated along fractures; this conclusion was adopted by Thoroddsen (**1905**, p. 79), and by H. G. Ferguson, who described the district of Faxafloi and Hval Fiord, and represented these fiords as partly due to glacial action, and as "in part due themselves to faults" (**1906**, p. 124).

Dr. Pjetursson and the late W. von Knebel, who lost his life while exploring a cauldron lake in central Iceland in 1907, both lay stress on the importance of erosion by water during the inter-glacial periods, of which, according to von Knebel, there were two or probably three (**1905**, p. 541).

The whole of Iceland was no doubt once covered with an ice-sheet, according to Thoroddsen, over 3,000 feet thick. The direction of the ice-movement, however, did not fully agree with the trend of the fiords; for "the striations," says Thoroddsen, "without exception, all radiate outwards from the centre of the island towards the coasts" (**1899**, p. 493). The main valleys, moreover, were preglacial. Thoroddsen was emphatic that the Icelandic fiords date from Pliocene times; and he declared, "On the whole my geological investigations prove that the general structure and contour-lines of Iceland were in all respects essentially the same before the Glacial epoch that they are to-day." This conclusion is confirmed by the later observations of Pjetursson and von Knebel.

The Icelandic fiords are, therefore, a series of preglacial valleys, of which those in eastern and south-eastern Iceland may be due to ordinary erosion by Pliocene rivers; but those in the western part of the country are connected with a series of fractures, which were caused by the uplift in Pliocene times of a wide volcanic plateau.

CHAPTER VII

The Lochs of Scotland and the Faroe Islands

Toward each creek and headland of that shore,
The long-loved lineaments they may see nevermore.

. . . . .

White castellated isles leagues far away,
Headlands and reefs and paps whose fretted stone
Breasted the sucking whirlpool's clamorous moan,
Grew incandescent o'er the wind-flogged sea
Scaled over with whitening scum as struck with leprosy.

Mathilde Blind.

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1. Contrast between Eastern and Western Scotland

The most striking feature in the map of Scotland is the contrast between the eastern and the western coasts. The eastern shore extends in long, even lines and only a very few small islands rise above the sea before it. The western coast is indented by a complex series of gulfs known as lochs, and is fringed by the archipelago of the Western Isles. The western half of Scotland also contains many long, narrow lakes, the fresh-water lochs, which are so intimately connected with the sea-lochs that they clearly have the same origin. It is, in fact, not easy on a map to distinguish between the fresh-water and salt-water lochs; for some of them, like Loch Etive, are connected with the sea by a small tidal channel, and others, like Loch Maree, are separated from it by a narrow bar of land traversed by a non-tidal river. Some of the fresh-water lochs are, moreover, deeper than the sea-lochs. Thus the bed of Loch Morar is 995 ft. below sea-level, and is deeper than any part of the Atlantic within 100 miles of the Scottish mainland. Loch Lomond sinks in one place 599 ft. below sea-level; therefore its bed also lies deeper than any part of the adjacent seas.

The fresh-water lochs are almost entirely restricted to western Scotland, for Lochs Tummel, Freuchie, and Turret in the Southern Highlands, and Lochs Muich, Eunach, and Avon in the eastern Grampians are the chief long, narrow lakes to the east of the fourth meridian. The absence of fiord-like lochs from eastern Scotland is doubtless due to the same cause as its comparatively unbroken shore.

2. The Eastern Firths

The eastern coast of Scotland, instead of being penetrated by a maze of lochs, has only a few inlets, of which the chief are six firths—Dornoch Firth, Cromarty Firth, Beauly Firth, Moray Firth, Firth of Tay, and Firth of Forth. These firths are each large arms of the sea; most of them expand seaward, and are thus funnel-shaped; the two exceptions to this rule are the Firth of Tay, which is somewhat constricted near its mouth, and Cromarty Firth, to which the present entrance is through a gap on its eastern side; but the firth no doubt originally

FIG. 32.—MAP OF SCOTLAND.

Showing the distribution of narrow, fiord-like lochs and of those with floors below sea-level (depths below sea-level in ft.).

continued north-eastward and opened seaward east of Tarbatness, and it then had the normal funnel shape. The firths, moreover, usually deepen seaward, though the Firth of Forth is deepest at the narrow part crossed by the Forth Bridge, and the Firth of Tay shallows somewhat to its mouth. The firths, finally, are approximately parallel to the grain of the country, and each acts as the estuary of a considerable river.

Hence, from this combination of characters, the Scottish firths belong to Richthofen's class of rias. They are the estuaries of the rivers which discharge on the eastern coast of Scotland, and consist of the lower parts of river-valleys which have been drowned through the subsidence of the land.

The only other arms of the sea called firths in Scotland are the Pentland Firth, which is the Strait between the Orkney Islands and eastern Caithness, the Firth of Lorn, which is the outer part of Loch Linnhe, and the wide, irregular basin of the Firth of Clyde.

3. The Sea-lochs confined to the Highlands and to the Old Rocks

The Scottish lochs are restricted to the older rocks. Scotland is composed geologically of three main divisions. The Highlands include all Scotland to the north of a line from the mouth of the Clyde to the eastern coast near Stonehaven. The country to the north of this line consists of a foundation of Archean rocks covered in some places by sheets of Old Red Sandstone and in others by occasional patches of various sedimentary rocks which have been protected by geographical accidents, and here and there the Archean foundation has been broken through by various igneous rocks. The Highlands end abruptly to the south against the Highland Boundary Fault, which divides them from the Midland Valley of Scotland. This valley includes the belt of Scotland from the Highland Boundary Fault on the north to a southern series of faults, which extend from Girvan on the Ayrshire coast to the North Sea near Dunbar. The typical rocks of the Midland Valley are Old Red Sandstone and various representatives of the Carboniferous and Permian systems. To the south of the Midland Valley is the third division of Scotland—the Southern Uplands. This division has a foundation of Ordovician rocks, which disappear to the south beneath the Silurian rocks; these are covered in places by sheets of Old Red Sandstone, of Carboniferous deposits, and of New Red Sandstones, of both Permian and Triassic age.

The lochs of Scotland are practically confined to the Archean rocks of the Highlands. There are a few small lochs on the Old Red Sandstones of Caithness; Loch Ness, one of the series used by the Caledonian Canal, is partly bounded by Old Red Sandstone; some small lochs occur on the igneous rocks associated with the Old Red Sandstone of western Argyll. Sea-lochs indent the coasts of the volcanic areas of Skye and Mull; but, with the exception of a few relatively unimportant, long, narrow lochs, such as Loch Doon and Loch Ken, on the harder rocks of the Southern Uplands, and some round lochs, like Loch Leven and the Lake of Menteith in the Midland Valley of Scotland, the Scottish lochs are confined to those parts of the Highlands where ancient crystalline rocks either form the surface or occur as the foundation, and are developed only on the western half of the country.

The Scottish lochs offer especially favourable opportunities for the study of their mode of origin, for they have been surveyed with exceptional thoroughness. Dinse (**1894**, p. 220) remarked in 1894 that the Scottish sea-lochs were the best examples for study, as they had been so well sounded; and since then the *Bathymetric Survey of the Scottish Lochs under the Direction of Sir*

John Murray and Mr. Lawrence Pullar has supplied even fuller data regarding the freshwater lochs.

4. The Lochs in Rock-basins

The origin of the basins of the Scottish lochs has been much disputed. According to one view they are valleys which have been obstructed at the lower end, so that the water collected behind the barrier and formed a lake. According to the alternative view they are basins which have been excavated in solid rock by land-ice.

The discussion was at first mainly concerned with the question whether the loch-basins are completely surrounded by rock or are old valleys dammed across by embankments. Professor James Geikie devotes two chapters of his *Great Ice Age* to the origin of the rock-basins in Scotland. He insists that many of them are true rock-basins, and not mere basins caused in the valleys by moraines. In this conclusion there can be no doubt that Professor Geikie is correct, though occasional lochs are due to banks of sediment deposited across valleys. Prof. Geikie (**1894**, p. 218) concludes that, with the unimportant exception of rivers just below a waterfall, ice is the only agent which can erode rock-basins. He holds that the Scottish loch-basins cannot be explained as due to faults, and he adopts the extreme position that "no single instance has yet been adduced, either at home or abroad, where a fault could be demonstrated to be the proximate cause of a lake hollow." He also shows that the explanation advanced for some Swiss lake-basins, which have been explained as due to earth-movements having tilted the valleys, and upraised the lower ends, to form lake-dams, is inapplicable in Scotland, owing to the very complex series of uplifts that would be required. It is probable that the process may account for some of the Scottish lake-basins, though it is difficult to regard it as the cause of them all. By rejecting in turn the other available explanations, Prof. Geikie concludes that the Scottish rock-basins must have been excavated by ice.

5. Thresholds often Absent

One argument which has had great weight in support of the glacial origin of Scottish rock-basins is that founded on their greatest depth being often at their inner ends, whereas most ordinary estuaries are deepest at their seaward ends. Many of the fiord- and loch-basins are shovel-shaped, owing to this shallowing at the lower end. This feature is, however, by no means always present. The subsequent enumeration of the Scottish fiords shows how many of them have no threshold. The proportion of the fresh-water lochs which are deepest at their inner ends is shown in the following table, which has been compiled by Mr. A. Stevens from Murray and Pullar's *Bathymetric Survey.*

Number of lochs which consist of simple basins	226
Number of simple basins deepest at upper end	83
Number of simple basins deepest in the middle	59
Number of simple basins deepest at lower end	84
Number of lochs which consist of compound basins	108
Number of lochs excluded on account of irregularity of outline	97
Number of lochs excluded on account of breadth nearly as great as length	103
Number of lochs excluded on account of artificial origin (these have nearly all a dam at the lower end at which they are deepest)	8

Number excluded on account of difficulty in determining outlet, etc.	20
Total excluded	228
Total included	334
Total number of lakes included in survey	562

Hence of the lakes with simple basins as many have their greatest depth at the outer as at the inner end.

6. The Lochs regarded as Fiords or as an Intermediate Type

The general character of the Scottish sea-lochs has led to their general identification as fiords. They have been thus accepted by Dana in **1849**, Robert Brown (**1869**, p. 121), Brögger (**1886**, p. 99), and Sir Archibald Geikie (**1901**, p. 481), who knows these lochs so well. He describes the lochs that open into the estuary of the Clyde as good examples of fiords, and he especially mentions Loch Long as a fiord. Goodchild (**1896**, p. 9) called Loch Long "that fine example of a Scottish fiord"; and Dr. H. R. Mill, in his well-known memoir on the Firth of Clyde, refers to its tributary lochs as "fiord-like inlets." Dinse (**1894**, p. 247) declares that the bays of Scotland are as typical fiords as those of Norway; and, according to Prof. Herbertson (**1910**, p. 39), "the sea-lochs of West Scotland are typical fiords."

Von Richthofen, however (**1886**, pp. 301, 304), defined the Scottish lochs as a type intermediate between fiords and rias. This conclusion necessarily followed from his definition limiting fiords to concordant, or, as he expressed it, longitudinal coasts; and it is only occasionally, as from Skye to Cape Wrath, that the coast of western Scotland is concordant. The northern shore of the estuary of the Clyde from Dumbarton to the west of

Bute is also approximately concordant, and thus the lower parts of Loch Long and Loch Fyne would be true fiords; but the rest of the western coast of Scotland, from Skye to Kintyre, has its grain oblique to the coast-line, and the inlets would, according to Richthofen's definition, be rias rather than fiords.

Such arms of the sea as Loch Sunart, Loch Nevis, Loch Swin, and Loch Linnhe cannot, however, be easily separated from the other lochs; and the general characters of the lochs of western Scotland have led most authorities to regard them as fiords.[1]

7. Their Fiord Characteristics

(*a*) *Shape.*—Their fiord-like character is shown in the first place by their shape and dimensions. Many of them are long and narrow. Loch Long is sixteen miles long, and for eleven miles the average width is half a mile; upper Loch Fyne is twenty-one miles long by about one mile wide; west Loch Tarbert is ten miles long by half a mile wide; Loch Swin is nine miles long by about three-quarters of a mile broad; Loch Sunart is twenty miles long by an average of about three-quarters of a mile wide; Little Loch Broom is nine miles long by about three-quarters of a mile broad; Upper Loch Broom is nine miles long by three-fifths of a mile wide; and Loch Glencoul and its continuation Loch Cairnbawn are eight miles long by half a mile wide. Hence several of the sea-lochs of Scotland have a ratio of breadth to length of 1 to over 20, which, according to Dinse and O. Nordenskjöld, is well within the proportions of true fiords. Thus Dinse (**1894**, p. 210) estimates the usual ratio of breadth to length as between 1 to 10 and 1 to 20, though occasionally as much as 1 to 40.[1]

[1] Some of the sea-lochs, however, are fiards and not fiords; Loch Assynt may be cited as an example of a fresh-water loch of the fiard type.

(*b*) *Parallel Sides.*—Secondly, the sides of the loch are usually parallel or subparallel, as in Loch Ness, Loch Linnhe, Loch Eil, Loch Fyne, and Loch Long; and this feature is still more marked in many of the fresh-water lochs.

(*c*) *Regularity of Direction.*—Thirdly, the Scottish lochs, like the members of the typical fiord-regions elsewhere, are remarkably regular in direction.

(*d*) *Thresholds.*—The fourth feature is the existence of a fiord-threshold, which is, however, not always present.[1] Thus, taking the chief fiords in order around western Scotland from Cape Wrath [2] southward, the first, Loch Inchard, deepens to 198 ft. at a point near its mouth, where the floor rapidly rises to only 114 ft. deep. Loch Laxford, the next to the south, is an irregular fiord-like inlet. Its depth increases seaward from 6 ft. at its head to 48, 54, 96, 150, 240 ft. It then shallows to 120 ft. at the mouth and deepens to 228 ft. and to 276 ft. just off the mouth. Loch Glencoul consists of two upper basins—Loch Glendhu and Loch Glencoul, of which the latter has a maximum depth of 168 ft. After the junction of the two branches the passage is blocked by some rocky islands with only narrow, shallow passages between them, after which it continues as Loch Cairn-bawn (or Cairn-bahn) and the depth increases to 204 and 366 ft. and then shallows at the outlet to under 180 ft. Loch Inver has no definite threshold; its depth increases rather steadily from its upper end to 138 ft. at the mouth; an island lies a little distance off its mouth, and the passage to the north of the island shallows to 102 ft. and the depth of the southern passage apparently in one place decreases slightly, but a passage out of over 120 ft. is marked on Bartholomew's *Atlas of Scotland*.

Loch Broom [3] consists of an upper basin with a maxi-

[1] About one in five of the lochs have no threshold.

[2] Admiralty Charts: Cape Wrath to Flannan Isles, No. 2,386, 1908.

[3] Admiralty Charts; Scotland, West Coast, Sheet IV. 1909, No. 2,475.

mum depth of 156 ft. which is separated by a threshold only 66 ft. deep from the middle basin near Ullapool. This middle Loch Broom descends with some regularity to a depth of 264 ft. near the mouth. The depth at its mouth is 222 ft. and thence the broad outer loch has depths going down to 366, 432, and 468 ft. There is no threshold to the outer loch except for a slight shallowing of the outlet from both the Lochs Broom and Gruinard Bay, between the peninsula of Rudha Mor and the Summer Isles.

Little Loch Broom has its greatest depth of 342 ft. at about its central point. The channel at its mouth has only a depth of 156 ft.

Loch Ewe has a very irregular shape. Its maximum internal depth is 186 ft., while its mouth is only 108 ft. deep.

The Gairloch, though a short loch, has a more regular form with parallel sides. The depth increases from 120 to 162, 180, 204, and 276 ft. at its mouth and thence continues outward down to 390 ft. so that it has no threshold.

Upper Loch Torridon is a basin in one place 270 ft. deep; the strait or kyle which leads to outer Loch Torridon has a depth of only 60 ft.; beyond this threshold the depths are irregular, but that of 522 ft. at its mouth is greater than at any point within the loch.

The outer Loch Carron, with its northern arm, Loch Kishorn, increases fairly regularly in depth to 798 ft. in the Inner Sound. Upper Loch Carron is, however, a basin with a depth of 360 ft. near its mouth, which is in places only 36 ft. deep.

Loch Duich, although short, is one of the most fiord-like of Scottish lochs, because of its high and regular walls; it attains its maximum depth, 366 ft., almost at the middle point, and a threshold of only 66 ft. separates it from Loch Alsh. Loch Alsh is a basin in one place 348 ft. deep, and is separated from the Inner Sound by a channel, the Kyle of Loch Alsh, only from 42 to 72 ft. deep, and from the Sound of Sleat by Kyle Rhea, which has a depth of as low as 48 and 54 ft.

Loch Hourn has an upper basin, Loch Hourn-Beg, that has a maximum depth of 108 ft. It is separated from Loch Hourn by a narrow passage with a depth of only 42 ft. The deepest point of Loch Hourn is 468 ft. at about its middle point; while the Sleat across the entrance to Loch Hourn has a maximum depth of only 342 ft.

Loch Nevis has an inner basin 96 ft. deep, which is connected by a narrow shallow strait with the outer loch, that deepens seaward to a depth of 324 ft. at the narrowest point of its mouth; thence the channel shallows to 60 ft., while the floor of the Sleat opposite its mouth descends to 438 ft.

Loch Ailort has a basin 96 ft. deep, while its island-strewn entrance is only 18 ft. deep.

Loch Sunart has a narrow inner basin with a depth of 306 ft.; a passage only 18 ft. deep leads to the outer basin, which increases outward to a depth of 348 ft. The entrance is barred by some islands; and the main channel past Charma Island has a depth of 180 ft. Loch Sunart opens into the upper part of the Sound of Mull, where, between Ardmore Point and Stron Beg, is a depth of 594 ft., beyond which there is a band less than 240 ft. deep from Ardnamurchan Point to the north-eastern point of Mull.

On the western coast of Mull[1] are the two well-marked lochs, Loch na Keal and Loch Scridain. The latter deepens regularly seaward except that there is a rise across its mouth, so that the western outer end of the mouth is 54 ft. shallower than its inner end.

Loch Linnhe increases in depth seaward up to 660 ft. near its junction with the Sound of Mull. This deep is cut off by a shallow between Lismore Island and the

[1] Admiralty Charts: Scotland, West Coast, Sheet III. 1907.

coast of Mull, south of Duart Point; after this shallow part there are three separate patches in the Firth of Lorn each over 600 ft. deep. Then, at the mouth of the Firth, the depth on the line between the northern end of Colonsay and the coast of Jura descends to less than 120 ft.; and from northern Colonsay to the south-western point of Mull the passage is less than 300 ft. deep.

Loch Etive is one of the Scottish lochs most often described owing to its well-marked threshold; it consists of two basins, an upper one, which is parallel to Loch Linnhe and increases in depth fairly regularly from its upper end to 456 ft., before it shoals rapidly to 42 ft. at the narrow strait, which leads to the outer Loch Etive; this part trends approximately east and west, and is transverse to the grain of the country and has a maximum depth of 186 ft. and discharges through Connel Sound with a maximum depth of only 72 ft.

Loch Eil, a branch of Loch Linnhe, has a regular parallel-sided basin with a maximum depth of 222 ft., and is connected with Loch Linnhe by a narrow passage less than 24 ft. deep.

Loch Leven, also a tributary of Loch Linnhe, consists of two basins, of which the outer one opposite Ballachulish has a maximum depth of 186 ft. and discharges through a narrow channel, 18 ft. deep, known as Peter Strait.

Loch Melfort is an irregularly shaped basin with a maximum depth of 180 ft. near its mouth; though its outlet to Seil Sound is only 96 ft. deep. Seil Sound has a depth of 240 ft., whereas its outlet through Shuna Sound has depths of less than about 120 ft.

Loch Craignish, except for some slight irregularities, deepens steadily seaward and has no threshold.

Loch Swin, a long, narrow loch, parallel to the Sound of Jura, has a maximum depth near its head of 132 ft., but most of the loch is comparatively shallow, and it has a long threshold across its narrow mouth only 54 ft. deep.

Loch Killisport has a somewhat tapering form, and increases in depth seaward; its maximum depth, 138 ft., is at its entrance.

West Loch Tarbert, for most of its length, is very shallow. It has a depth of 48 ft. at its mouth, with 78 ft. at one point within.

Loch Indail, on the southern coast of Islay, increases in depth steadily outward and has no threshold.

Loch Fyne has a somewhat irregular basin; its upper part near Inveraray has depths of 384 ft., which increase to 462 ft. opposite Strachur, and to 492 ft. near Newton; it then shallows, and from Cladich to Otter Bay the deepest line varies from 204 ft. down to 138 ft. After its junction with Loch Gilp, Loch Fyne deepens again to 534 ft., and a little beyond East Tarbert reaches a depth of 624 ft.

Loch Striven increases steadily in depth from its head to 240 ft. about a mile north of its mouth, where the depth is only 210 ft.

Loch Long has two basins, an inner basin 180 ft. deep separated by a slight rise from an outer basin over 240 ft. deep, which again has a slight threshold between it and the Firth of Clyde.

Campbeltown Loch,[1] in Kintyre, has an inner basin with a depth of 66 ft. separated by a bank of 48 ft. from the outer loch, with a depth of 132 ft. outside it, and the sea-floor deepens slightly into the Firth of Clyde.

The Firth of Clyde has maximum depths of 534 ft. at a point in Kilbrennan Sound, and of 552 ft. three miles north-east of Brodick, in Arran; farther south the depth decreases, and one line from the Mull of Kintyre to Corsewall Point in Wigtown does not go deeper than

[1] Admiralty Charts: Irish Channel, Sheet I. No. 1,825 a, 1909.

East to west lines. I-I-I-I-I North to south lines.
North-east to south-west lines. - - - - North-west to south-east lines.

FIG. 33.—CHIEF GEOGRAPHICAL LINES IN SCOTLAND.

180 ft. The North Channel outside the Firth of Clyde has a long central depression, which has a maximum depth of 894 ft.

8. The Lochs arranged as a Broken Network

The most important feature in the Scottish lochs is their regularity of arrangement, as displayed by their frequent parallelism and the intersection of the branches at regular and usually at right angles. The lochs are arranged on the plan of a broken network. The most conspicuous geographical lines run from north-east to south-west, and this set is traversed by a transverse series trending at right angles to the first, from north-west to south-east. The network has, however, been somewhat strained, so that in places the directions approach more to north and south and to east and west. Occasionally the series intersect at angles of approximately 45°, as at the bend of Loch Etive.

The lines from north-east to south-west include the main coast-lines of Scotland as along eastern Caithness and Sutherland, the western shore of Moray Firth, from Tarbatness to Beauly Firth; and the main east coast from Buchan Ness, near Peterhead, to the mouth of the Firth of Tay.

On the western coast are the north-western coast of Lewis, the line of the north-western coast of Skye, the south-eastern part of Skye, the Sound of Sleat, and upper Loch Carron. This series also includes the lochs of the Great Glen and many of the best-known lochs of the south-western Highlands. The variations in the trend of this series of lochs is shown in the following list :

Loch Eriboll	35°
Loch Naver (main middle reach) . .	50°
Loch Choire	40°
Upper Loch Carron	40°
Sound of Sleat	40°
Loch Shiel (upper part) . . .	50°
Loch Sundart (middle reach) . .	50°
Loch Ness	40°

Loch Lochy	40°
Loch Linnhe	40°
Loch Laggan	50°
Loch nah Earba	38°
Loch Ericht	42°
Loch Ossian	55°
Loch Tay (middle reach)	35°
Upper Loch Etive	35°
Loch Laydoch (Laidon)	42°
Loch Awe	42°
Loch Lyon	50°
Upper Loch Fyne	42°
Loch Long	36°
Sound of Jura	30°
Loch Indaal (Andail) (Islay)	35°
Loch Craignish	30°
Loch Swin	30°
Loch Killisport	35°
West Loch Tarbert	42°

The directions are not always exactly from north-east to south-west, as they vary from 30° to 50° east of north; and they are linked by others, such as Loch Ossian, with a trend of 55,° to those which are still farther from the meridian.

The second important series of lines trends from north-west to south-east. The only important coast-lines in this direction are the south-western coast of Skye, the Sound of Mull, and the course of the shore of the Firth of Clyde from the entrance of Loch Fyne to Troon in Ayrshire. There are, however, many important lochs and valleys with this trend. Thus on the north-western coast there are:

Loch Inchard—inner end (the outer end bends more to west)	120°
Loch Laxford	120°

Loch Cairnbawn and Loch Glencoul	120°
Loch More	120°
Loch Assynt	120°
Loch Broom	135°
Little Loch Broom	120°
Loch Ewe	150°
Loch na Shiellag	135°
Loch Fada	135°
Loch Maree	135°
Loch Shin	135°
Loch Snizort (Skye)	150°
Loch Dunvegan (Skye)	150°
Loch Duich	135°
Middle Loch Hourn	135°
Middle Loch Nevis	135°
Sound of Mull	125°
Loch Frisa (Mull)	135°
Loch Ba (Mull)	115°
Gare Loch	155°
Loch Goil	160°
Loch Seaforth (Lewis)	158°

Some of the lochs have a trend approximately north and south; this groups includes:

Loch Hope	Sound of Islay
Loch Loyal	Lower Loch Fyne
Inner Sound	Loch Striven
Sound of Raasay	Loch Lomond
Loch Slavin (Skye)	Kilbrennan Sound

The only important stretches of coast with this trend are those of North and South Uist and along western Ross from Rudh Be to Applecross. At right angles to the northern and southern group are a series of coasts and lochs, which trend east and west; the chief coasts with this direction are the northern shore of Sutherland and

Caithness and the coast of Elgin, Banff, and Aberdeen. This trend also occurs in various sea-lochs along the western coast and among the Western Isles, such as Lochs Erisort and Shell in Lewis, Loch Eport in North Uist, Lochs Eynort and Boisdale in South Uist, the Gairloch, Upper Loch Torridon, Loch Alsh, the outer and inner ends of Lochs Hourn and Nevis, outer Loch Ailort, western Loch Shiel, Loch Moidart, and Loch Sunart. There are many important freshwater lochs with this trend, including, in order from north to south:

- Loch Naver
- Loch Fannich
- Loch Rosque
- Loch Morar
- Lochs Mullardoch and Lungard in Glen Cannich
- Loch Clunie in Glen Moriston
- Loch Quoich
- Loch Garry
- Loch Arkaig
- Loch Eil
- Loch Leven (Lochaber)
- Lower Loch Etive
- Loch Rannoch
- Loch Tummel
- Loch Earn
- Loch Voil

The lochs of Scotland have, therefore, a striking regularity in arrangement which is obvious on the most casual inspection of a map. The lochs and the valleys in which they occur form a network. The direction of its lines are not constant through the country. The main lines radiate from an area which is in the neighbourhood of the volcanic plateau of Antrim. The transverse lines necessarily also vary in direction, as they tend to keep perpendicular to the main lines.

9. Their Relations to Geological Structure and Former River-systems

These lines have no constant relations to either the geological structure or the ancient river-system of the country. The old river-system of the Scottish Highlands includes two series of rivers; the rivers of the older series flow across the geological grain of the country, and they are known as "consequent" rivers,[1] because their direction is a direct consequence of the original slope of the ground. The rivers of the second series, run along the grain of the country approximately at right angles to the first; they flow through valleys which have been excavated along bands of soft rock, and the harder bands rise as ridges between them. The second series are known as "subsequent" rivers,[1] as their valleys were excavated subsequently to the consequent valleys. At first sight it appears tempting to regard all the Scottish rivers and lochs that trend from north-west to south-east as parts of an original consequent series, and the valleys at right angles to them as subsequent valleys worn out along weaker bands of rock. There are many coincidences with this arrangement. Thus Loch Shin, Loch Broom, Loch Goil, Loch Gare, Loch Eck and the Holy Loch, Lochs Striven and Ridden, and the Kyles of Bute—all agree in direction with the course of the old consequent valleys. Upper Loch Fyne, the lochs in Knapdale (West Argyll), and the Sound of Jura occur along bands of soft rock; and they are normal strike or subsequent valleys. Others, such as the middle part of Loch Tay, Loch Lyon, Loch Linnhe, Loch Lochy, and Loch Ness, lie along fault-planes.

In the valuable summary of the relations of the Scottish lochs to the geological structure of Scotland by Drs. Peach and Horne (**1910**), they point out many coincidences between the direction of the fresh-water lochs with the grain of the country and with important lines of earth-movement. Nevertheless, in many cases the Scottish valleys and lochs are not coincident with directions that would be expected from the geological structure. Many lochs are parallel or at right angles to the strike; but others cross it obliquely. The divergence is especially

[1] Both of these terms are due to Prof. W. M. Davis.

significant when the lochs and the grain of the country intersect at a slight angle.

Hence, though the coincidences are sufficient to tempt one at first to regard the loch-network as a direct expression of the geological structure of Scotland, there are too many differences for this explanation to be satisfactory and complete. The geological grain of the Scottish Highlands was impressed upon it in very ancient geological times. It dates partly from Archean and partly from Palæozoic times. The loch-system, on the other hand, is geologically modern; and though the loch-system has been modified by the older structure and bent into conformity with it, the two developed independently.

10. Relation to Glacial Movement

Neither can the plan of the loch-system be explained by glacial erosion.

There are three fundamental features in which the loch-system does not agree with the arrangement that might be expected if the loch-valleys were due to ice-action. Firstly, eastern Scotland was as thoroughly glaciated as western Scotland. In fact the main ice-shed in glacial times lay far to the east of the existing watershed. Thus Loch Rannoch, though on the eastern side of the present watershed, was on the western side of the ice-shed, so that the ice was probably thickest in central Scotland and the eastern half of the country was as intensely attacked by ice as the western. If ice-erosion could dig out fiords, we should expect to find them at least as well developed in eastern Scotland as in western, since in many parts of the country the eastern rocks are softer than those to the west.

Secondly, the rarity of lochs in Scotland outside the Highlands. The Midland Valley and the Southern Uplands both underwent intense glaciation. The Midland Valley is quite, and the Southern Uplands almost, free from long, narrow lochs. There are a few, such as Loch Doon, and Loch Ken. Loch Doon is probably a true rock-basin, but most of the others are only flooded parts of river-valleys which have been dammed up by alluvial deposits and moraines. If the loch-basins were simply due to ice, more might reasonably be expected in the glaciated Southern Uplands, as well as in many of the glaciated but lake-less parts of England.

Thirdly, there is the frequent inconsistency between the shape of the lochs and the position of the deepest hollows with the direction of the ice-movement.

The general direction of the ice-movement in Scotland is shown in a map by Sir Archibald Geikie (**1901**, pl. iv., opposite p. 306), which, though diagrammatic and open to revision in details, is generally accepted as on the whole correct. This map represents the ice as having often flowed across the lochs, instead of along them, as would have been the case if the lochs had been worn out by the ice. Thus in the northern Highlands Loch Watten, in Caithness, is crossed at an angle of 45° degrees by the arrow indicating the ice-flow. Loch Naver, in Sutherland, is almost at right angles to the movement of the ice across it, and Loch Eriboll was crossed obliquely by the glaciers from the district around Ben Loyal and Ben Hope. Farther south, on the western coast, Loch Kishorn lies transverse to the direction of the ice-flow from the Highlands to the west of Mam Soul. The ice-streams from the same district are represented by Sir Archibald Geikie as having crossed obliquely over the Inner Sound, overridden the Sound of Raasay, and passed over or parallel to northern Skye, and finally crossed Lewis at right angles to the direction of some of its lochs, such as Loch Erisort, Loch Shell, Loch Resort, and Loch Langabhat, and also the Eye Peninsula.

Similarly, the ice which came from Ardnamurchan and Morven crossed almost at right angles to Loch Teacuis, the southern branch of Loch Sunart, and also across the Sound of Mull and Loch Frisa. The ice from Loch Fyne flowed across Knapdale (Jamieson, **1862**, p. 177). The ice from southern Argyll crossed the Sound of Jura obliquely, and some of that from Arran flowed westward right over Kintyre and passed at right angles over Loch Andail in Islay. A map of the ice-movement in Colonsay recently published by Wright and Bailey (in Craig, **1911**, p. 61) shows that, though the ice flowed along some of the wider valleys, its direction was usually transverse to the trend of the lochs.

Many of the smaller lochs also lay across the direction of the ice-movements. This fact was pointed out by Grant Wilson for Loch Earn, which trends east and west; yet the ice flowed across it to the east-south-east (**1888**, p. 257).

The independence of the fiord-valleys and land-forms upon the movements of the glaciers is well illustrated by the Orkney, Shetland, and Faroe Islands. The glaciation of these three archipelagoes was described by Helland in 1879. The Faroes are intersected by many straits, fiords, and fiord-valleys, and the general trend of these depressions is from north-north-west to south-south-east. The Faroes were glaciated by ice of local origin, and its course was naturally in the main parallel to the valleys (Helland, **1879**, pl. xx.). The preglacial age of the Faroe valleys has been shown in the memoirs on the glacial geology of the islands by Prof. J. Geikie, and by Grossman and Lomas. Although Prof. Geikie claimed that glacial erosion in the Faroes had been considerable (**1883**, p. 260), he regarded the fiord-valleys as preglacial, and attributed them to "the usual atmospheric agents, aided by the subsequent erosive powers of glacier-ice" (p. 257). Grossman and Lomas are emphatic on this question. "We do not believe," they say, "that the fiords and valleys were scooped out by the ice. We have shown in the foregoing that the ice did little more than modify pre-existing valleys" (Grossman and Lomas, **1895**, p. 14).

The evidence of the Orkney and Shetland Islands is quite inconsistent with the glacial origin of the fiords and valleys. Both archipelagoes were glaciated by ice which was formed elsewhere and flowed right across them. Prof. J. Geikie's map of the glaciation of the Shetlands (see Fig. 2) shows that the main geographical lines and the chief lochs run north and south, at right angles to the flow of the ice (**1894**, pl. 1). Helland's map had shown this fact in **1879** for both groups of islands, as it represents the main ice-movement in the Orkneys as from south-east to north-west, while the Shetlands were crossed by ice coming from the north-east and going to the north-west. In both cases the ice rode across hill and valley regardless of the shape of the land.

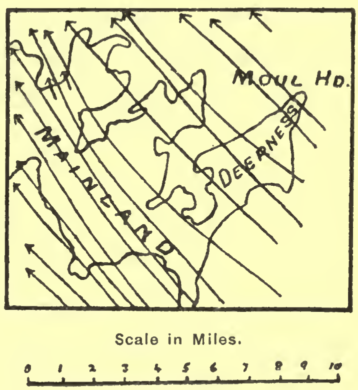

FIG. 34.—DIRECTION OF ICE-MOVEMENT IN ORKNEYS (AFTER PEACH AND HORNE).

Helland's conclusions have been further confirmed by Messrs. Peach and Horne (**1880**). They proved that the ice passed across the Orkneys in a north-westerly direction, and that its course was almost entirely independent of the topography of the country. For example, as shown by Fig. 34, the eastern part of Mainland (the largest island of the group) projects north-eastwards in a series of peninsulas, such as Deerness; the ice passed over these peninsulas almost at right angles, and throughout the Orkneys the trend of the ridges and valleys is quite independent of the path of the ice. The main topography is in fact preglacial.

II. "DEFLECTION-BASINS"

An explanation of the divergence between the trend of the lochs and the direction of the ice-flow has been suggested by Prof. Geikie (**1894**, p. 242). He calls basins which are elongated across the direction of the ice-movement "deflection-basins"; he attributes them to erosion by the lower layers of ice, which, being obstructed by a rise in the ground beneath, flow in an undertow or undercurrent in a different direction from the main ice-sheet. He considers that the upper layers of ice would continue to flow onward, while the lower layers were deflected along old valleys and deepened them into basins at right angles to the main advance of the ice. He applies this principle sometimes on a very large scale. There is, for example, a deep depression in the bed of the North Channel, which is at right angles to the ice-movement from the Firth of Clyde; Prof. Geikie explains this deep trough as a deflection-basin produced by the lower layers of Scottish ice being forced north-north-westward or south-eastward parallel to the Irish coast. Again, the deep channel in the Great Minch and the Little Minch, on the eastern side of the Outer Hebrides, is explained as a deflection-basin due to the lower ice being blocked in its westward advance by the islands of Lewis and Uist.

It is quite true that in a river the current on the bottom may be diverted by a boulder, and thus the water, for the width of the obstacle, may move at right angles to the main flow of the river; but the excavation of deflection-basins by the lower layer of ice seems most doubtful; for, though the ice might be deflected by a cliff, it seems improbable that a gentle slope should cause the lower layers of an ice-sheet to flow at right angles to the movement of the upper layers. Messrs. Wright and Bailey have pointed out the absence of any definite evidence of such deflection of the lower ice; they remark that the ice should have been diverted not only below sea-level but also above it, and the different directions of the upper and lower ice should be recognisable from the striæ (in Craig, **1911**, pp. 58–9). Wright and Bailey, however, attribute these basins to glacial erosion, and explain the course of the ice by the obstruction of islands to the west.

Recent opinion regarding the behaviour of thick sheets of ice has been well expressed by Mr. E. C. Andrews (**1909**) in his paper on glaciers as gravity-streams; and the analogy between the flow of rivers and of ice is so close that it seems reasonable to infer that ice in deep hollows would remain practically stagnant and have but slight power of digging into fresh, hard rock. Mr. Andrews insists that, where valleys widen, the corrosive effect of the ice diminishes, and that ice-streams are most effective as denuding agents, where a contraction in a valley causes the ice-stream to flow most quickly. His paper attributes deep hollows and thresholds to variations in the excavating power of a glacier, due to changes in its rate of flow.

There are many valleys in Scotland which illustrate the results of ice having filled a depression at right angles to the main ice-movement. Thus Glencroe, a tributary to Loch Long, lay across the ice-flow. The upper part of the glen, when seen from the opposite side of Loch Long, appears as a trough-shaped valley with smooth, spurless sides. If the lower part of the glen were filled with water so that only the trough-shaped part were seen, Glencroe would become a fiord. The lower part of the glen is, however, a narrow, sinuous gorge, and spurs project from both sides, so that one cannot see far up the glen. The spurs from the two sides overlap, and that part of the glen has the character of a typical river-cut gorge. This lower part of the glen appears to be preglacial in age, but was not moulded by ice because it was occupied by almost stagnant ice, while the upper part of Glencroe and Loch Long were being widened by the ice that flowed freely along them.

The main southern tributary to Glen Douglas on the western side of Loch Lomond shows the same characters. This district was at one time glaciated by ice, which came from the mountains around Ben Arthur and flowed south-eastward across the valley of Loch Long into Loch Lomond. The ice flowed across Doune Hill, glaciated and smoothed its north-western slopes, and gave a typical ice-worn form to Glen Douglas, Glen Mallochan, and Glen Luss. But the valley which passes between Doune Hill and Mid Hill to Glen Douglas is a deep, curved gorge, which was apparently filled with stagnant ice and was thus protected from ice-erosion, except during the advance and retreat of the ice.

The Great Minch, Irish Channel, and the other deflection-basins are parallel to important structural lines. Mackinder has suggested that the Great Minch and the Little Minch occupy a submarine rift valley; and this view appears the most probable explanation. Similarly, the erosion of the deep depression of the North Channel by ice, which had failed to cut its way through the "Great Plateau" across the mouth of the Firth of Clyde appears to involve greater difficulties than the explanation of this "deep" as a subsidence beside the volcanic plateau of north-eastern Ireland.

12. Lochs with Floors below Sea-level

The distribution of the Scottish lake-basins which sink below sea-level also indicates for them a tectonic rather than glacial origin. These lakes and their depths below sea-level are enumerated in the following list, and the distribution of some is shown on Fig. 32. None of them occur in the intensely glaciated eastern Grampians or Southern Uplands.

LOCHS WHOSE BASINS EXTEND BELOW SEA-LEVEL IN ORDER OF DEPTH BELOW SEA-LEVEL; DEPTHS IN FEET

Loch.	Maximum Depth.	Surface-level (above Sea-level).	Depth below Sea-level.
1. Morar	1,017	30	987
2. Ness	754	53	701
3. Lomond	623	24	599
4. Lochy	531	94	437
5. Shiel	420	11	409
6. Maree	367	30	337
7. Arkaig	359	139	220
8. Hope	187	13	174
9. Awe (Etive Basin)	307	118	189
10. More (Laxford)	316	128	188
11. Suainabhal	219	37	182
12. Tay	508	349	159
13. Katrine	495	364	131
14. Ba (Mull)	144	41	103
15. Arienas	116	31	85
16. a'Bhaid Daraich	121	49	72
17. Eck	139	67	72
18. Nell	115	49	66
19. Dubh (Ailort)	153	103	50
20. Owskeich	153	About 100	About 50
21. Oich	154	106	48
22. Seil	91	55	36
23. Spiggie	41	4	37
24. Tingwall	60	28	32
25. Kernsary	93	68	25
26. Snarravoe	29	5	24
27. Eilt	119	96	23
28. Menteith	77	55	22
29. Achilty	119	99	20
30. Cliff	21	6	15
31. Strom	13	1	12
32. Doire nam Mart	48	37	11
33. Skebacleit (Lewis)	44	35	9
34. Brow	6	—	6
35. Kilcheran	60	55	5
36. Stocsavat	40	36	4
37. Fad	38	35	3
38. Ard	107	105	2

In North Uist and Benbecula there are forty-five lochs of irregular form near sea-level, whose basins extend to various depths below sea-level, down to 42 ft. Similarly, there are ten irregular low-lying lochs in Shetland extending down to a maximum of 50 ft.

Three of the basins sink more than 500 ft. below sea-level. The deepest is Loch Morar, on the bed of which there is a depression which sinks 987 ft. beneath sea-level. This remarkable hollow has not been adequately explained. It can hardly be part of a river-valley, as the sea-floor does not reach that depth for a distance of more than 100 miles west of the Scottish coast. Loch Morar lies in one of a series of parallel valleys which extend east and west; they probably coincide with dislocations which are intersected by another series parallel to the Great Glen. The two series must cross at an angle of about fifty-five degrees. The great depth of part of Loch Morar may be due to excavation of decayed rock around the intersection of two of the major dislocations of this district; but the deep hollow may have been drilled by pot-holes, for it occurs opposite a low gap which leads northward to Loch Nevis and the expansion of the glacier over this low ground probably caused the formation of crevasses, which would have been kept constantly open at about the same position, and been used by the glacier-streams for the formation of numerous pot-holes.

The second deepest Scottish lake-basin is Loch Ness; it lies along the important fault which extends through the Great Glen. Loch Lochy is in the same glen, and has the fourth deepest lake-floor. Loch Maree, the floor of which sinks 337 ft. below sea-level, also lies along a well-known fault. The deepest part of Loch Tay occurs where the loch coincides in direction with the Loch Tay fault. Loch Shiel and Loch Awe both lie in valleys parallel to the Great Glen, and are also on lines of dislocation.

Loch Lomond, which has the third deepest floor, lies along a great fault, and Kinahan (**1875**, p. 216) described it, I think correctly, as excavated by various denuding agents "along lines laid out by faults or other shrinkage fissures."

The deep Scottish lochs, therefore, all coincide with important lines of earth-movements, and as the glaciers, though equally well developed, and apparently equally vigorous, did not excavate deep lake-basins where they did not find such lines of weakness, it appears reasonable to conclude that the earth-movements were at least as necessary for their formation as glaciers.

It has been suggested that the lines of ice-flow shown on the general maps of Scottish glaciation indicate the directions of movement only during the maximum glaciation, and that the lochs were excavated at the beginning and end of the period, when the ice would have moved in valley-glaciers along the lochs. But this view would imply that the ice, at the time of its maximum development, had no fiord-excavating power, and that many of the great fiords and loch-basins were cut during the retreat of the ice by dwindling valley-glaciers, which the advocates of glacial erosion generally admit had comparatively small powers of excavation; for it is often insisted that the power of ice has been under-estimated, owing to observations on the comparatively small glaciers of Switzerland.

13. The Age of the Fiord-valleys

It is, therefore, important to consider the age at which the loch-basins were formed; for if they existed before the maximum glaciation, and if ice had great powers of erosion, then the trough-valleys which lay across the path of the ice should have at least been widened into broad basins.

The evidence seems conclusive that the valleys in which the lochs lie were preglacial in origin. Thus Prof. James Geikie (**1894**, pp. 236–7) clearly applies glacial erosion only to the rock-basins and not to the valleys in which they lie. "Our mountain-valleys," he says, "were in existence long before the ice period, and many of them doubtless headed in cirques, before any glacier appeared in our country."

That the lochs belong to a date which is geologically recent is generally recognised. Thus Sir Archibald Geikie (**1901**, p. 256) says: "Under any circumstances, it is quite certain that the lakes must be of recent geological date." Their precise age, however, is somewhat uncertain, owing to the unfortunate gap in the geological record of Scotland between the close of the eruptions which built up the volcanic masses of the Western Isles and the beginning of the glaciation. The volcanic eruptions happened in the Lower Kainozoic; they were either wholly Eocene or perhaps partly Oligocene. Their date is indicated by the fossil plants associated with the volcanic rocks. The lochs were certainly formed later than the eruptions, for the volcanic rocks are cut through by the lochs in Skye and Mull. Outside the volcanic area the lochs are also shown to be post-volcanic; for those dykes of igneous rocks which to the north-west of Glasgow trend from north-west to south-east were no doubt injected during the volcanic period. Some of these dykes are cut across by the lochs, as by Loch Fyne; and the evidence at the intersection clearly shows that the lochs were formed long after the solidification of the igneous rocks.

The loch-valleys were doubtless cut during Pliocene times by the dissection of the plateau, the remains of which, at the level of about one thousand feet, form one of the most conspicuous features in the structure of western Scotland.

14. Relation of the Lochs to the Earth-movements in North-western Europe

In the absence of direct evidence as to the geology of Scotland in the long interval between the volcanic and the glacial periods, we are dependent for information as to its intervening history on physiographic considerations. At the period of the volcanic eruptions Scotland was part of a vast land which extended north-westward past the Faroe Islands and Iceland to Greenland. As the same flora lived in all these countries, they were probably continuous. At the close of the volcanic period Scotland was a plateau with a long slope downward to the south-east. This plateau was cut up by earth-movements of two main sets. The first set was no doubt connected with the subsidences which formed the basin of the North Atlantic Ocean; they probably began during the volcanic period, but continued after the eruptions had ceased; and these subsidences separated Iceland from Greenland and Scotland.

The second movements came from the south; they were the northernmost of the waves of folding, which formed the mountains of the Alpine System across Central Europe.

The foundering of the North Atlantic basin left the British Isles on a submerged platform which extends for from 30 to 100 miles westward. The depth of this platform is less than one hundred fathoms. From its edge the sea-floor slopes rapidly downward to the deep basin of the North Atlantic with the depth of over 1,000 fathoms. This steep slope lies about 100 miles west of the western coast of Scotland. The part of it known as the Vidal Bank has a trend parallel to the main north-east to south-west geographical lines in Scotland, such as the south-eastern coast of Caithness and Sutherland, the main eastern coast of Scotland, and the line of the Caledonian Canal.

The parallelism of these geographical features and those of the border of the Atlantic basin to parts of the Norwegian coast suggests that they are due to some common cause.

The North Atlantic basin ends to the north against a comparatively narrow bank which extends north-westward through the Faroes to Iceland. Its main direction is from north-west to south-east, parallel to the Loch Broom series of lines in Scotland. The east and west lines, such as those of the northern coast of Scotland and the eastern and western coast to the east of the Moray Firth, can also be traced far afield; for it marks the northern termination of the Rockall Bank, three hundred miles westward in the Atlantic. These east and west lines, like the axis of the Weald in the south-east of England, are probably connected with the Alpine movements.

The result of the earth-movements was to break up the old river-system of Scotland into two main groups. The ancient rivers which rose on the north-western plateau probably flowed originally south-eastward across Scotland into the North Sea. The fault along the Great Glen lowered the country to the north-west of it, and so separated the upper parts of the rivers from their lower courses. The rivers of south-eastern Scotland were therefore beheaded and thenceforward were limited to the south-eastern side of the Great Glen. The north-western rivers still continued to flow south-eastward into the Great Glen and doubtless joined two rivers, one of which discharged north-eastward through Loch Ness, and the other south-westward through what is now Loch Linnhe. How far the north-western Highlands were lowered there is no evidence; and it is possible that the Great Glen sank below sea-level, and Loch Eil, Loch Arkaig, and Loch Garry may have been converted into estuaries opening into a long, narrow strait.

The rivers on the south-eastern side of the Great Glen, such as the Spey and the Leven, are comparatively young. They collected the drainage from the north-western face of the Grampians after the formation of the Great Glen. The subsidence of the

Great Glen was no doubt due to renewed movements on a much older fault-line. Earth-movements, probably about the same time, and also along old faults, re-formed the Midland Valley of Scotland. The floor of this valley is a tract of land that was sunk between the Highland Boundary Fault on the north and the Southern Boundary Faults on the south; and the subsidence was sufficiently rapid for the fault-walls to have remained for a time as cliffs; and thus the valley was a rift-valley, as was suggested by Mr. Mackinder [1] and subsequently confirmed by Mr. E. B. Bailey.[2]

Before the formation of the Midland Valley southern Scotland was drained by a series of rivers, which rose on the Southern Highlands and probably flowed south-eastward across the site of the Midland Valley and over the Southern Uplands to the North Sea. A river then rose near Ben Cruachan and flowed south-eastward along the present course of Glen Aray, Loch Eck, and the Holy Loch; a tributary crossed upper Loch Fyne and the site of Hell's Glen into Loch Goil and the Gareloch. The united river continued south-eastward along the present course of the Clyde into the basin of the Tweed. The formation of the Midland Valley broke up this river-system. The Clyde, the lower Tay, and the Forth were developed along the Midland Valley, and the lower ends of the older rivers were limited to the southern slopes of the Southern Uplands.

The Great Glen and the Midland Valley are tectonic valleys, and they were certainly preglacial. The coincidences between the directions of the Scottish lochs, of the earth-movements, and of the borders of the North Atlantic basin indicate that the loch-valleys of Scotland were formed about the same time as the Great Glen

[1] H. J. Mackinder, *Britain and the British Seas*, 1902, p. 68.

[2] In "The Geology of East Lothian," *Mem. Geol. Surv. Scotland*, 1910, p. 10.

and the Midland Valley. The clefts which determined the position and trend of the lochs probably date from Pliocene times, and the loch-valleys themselves were preglacial. The ice flowed into the valleys formed along these clefts, and enlarged them by the removal of all loose debris and rotten rock; but the valleys themselves were there before the ice entered them.

CHAPTER VIII

THE FIORD-LIKE INLETS OF ENGLAND AND IRELAND

Northward, the headlands of a rocky coast
Are white with surf—while southward, broad and blue,
The Shannon rolls, in tranquil majesty,
Into the billows of the boundless sea.

E. G. A. Holmes.

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1. No existing English Fiords.—2. The Lakes of the Lake District.—3. Relics of Ancient Fiords in Cornwall.—4. The Irish Rias and Fiards.—5. Their Preglacial Shores.

1. No Existing English Fiords

Most of the English coast is moderately irregular and indented, yet there are but few inlets which have any claim to be considered as fiords. Along the eastern coast the great commercial estuaries of the Tyne, the Tees, the Humber, and the Thames are long and narrow, and some have deep channels behind a shallower threshold; but these estuaries are ordinary drowned river-mouths with alluvial shoals deposited where the fresh water joins the sea. The absence of fiords from the western coast is more remarkable owing to the harder nature of the rocks there.

2. The Lakes of the Lake District

The Lake District of Cumberland and Westmoreland includes several long, narrow lakes and some of their walls, such as that of Wastwater, are steep, straight, and spurless. If the Lake District were submerged to the depth of 400 ft. all the chief lakes except Ulleswater and Hawes Water would be connected with the sea, and thus form a group of radial fiords. Ulleswater would be joined to the sea by a submergence of 500 ft., and Hawes Water by one of 700 ft. The drowning of the western lakes would leave them as comparatively shallow fiords. In Windermere, Wastwater, and Lake Coniston the floors descend below sea-level for 89, 58, and 41 ft. respectively. These Cumberland lakes have been claimed as occupying glacially eroded lake-basins; but Dr. J. E. Marr **(1895)** showed that the evidence for this conclusion is inadequate in regard to many of the tarns. They occupy moraine-blocked hollows and not basins cut out of solid rock. The present outlet from the tarn may be across a sill of rock, as the overflow is now through a gap, which was originally on the side of the valley, the main channel having been filled with sediments. Nevertheless, if "the Lake District" were standing at a lower level, and these lakes were arms of the sea, whether rock-basins or not, they could fairly be regarded as fiords. They are, however, fresh-water lakes, and the adjacent coasts are free from fiord-like inlets.

3. Ancient Cornish Fiords

The most fiord-like gulfs in England are on the coast of Cornwall and south Devon. The most important are Carrick Roads, the estuary of the River Fal and its tributaries (Fig. 35), the Fowey River, Plymouth Sound, with the estuary of the Tamar, and the estuary of the Salcombe River. They resemble fiords in their long and narrow proportions, their approximately parallel sides, their parallelism in direction, and their angular branching. They differ, however, from fiords in all the consequences of the low level of the adjacent country, and, as their banks usually have gentle slopes, they are fiards rather than fiords. They deepen gradually seaward, so they are

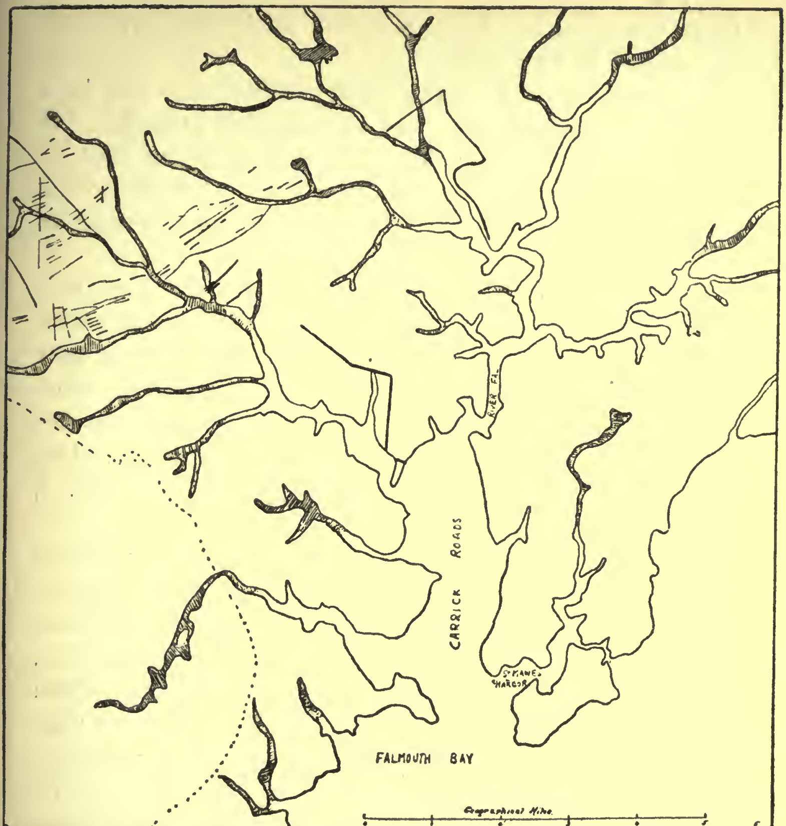

FIG. 35.—MAP OF FALMOUTH HAVEN AND ITS BRANCHES.
A fiord that has been worn into a fiard.

not rock-basins now, whatever they may once have been.

Silt is being deposited in most of these harbours so rapidly that any deep rock-basin within them would long since have been filled up. According to Messrs. Hill and MacAlister (**1906**, p. 101), at one point in Falmouth Haven the channel has silted up 10 ft. since the Admiralty Survey of 1698; and Restronguet Pool was dry in 1855 where it had been 42 ft. deep at low-water in 1698. They quote information that the amount of silt being brought into Falmouth Haven would, every forty-three years, form a layer one foot thick over the whole haven and its branches.

The lower valley of the Fowey River also lies in a north and south trough with right-angled branches. It is marked on the Geological Survey Map (Sheet 347), as parallel to two important faults, 1½ and 2¼ miles to the west; and its east and west tributaries are parallel to the faults from Fowey eastward to Lanlivet Bay.

The Hamoaze, the channel which joins the Tamar to Plymouth Sound, also occurs along a north-north-west to south-south-east fault, and it lies, like the lower part of the Tamar, in a fairly deep, steep-sided trough. Further up its course, the Tamar River becomes sinuous and meandering; but the Hamoaze is straight, and it receives its main tributary, the St. Germans, or Lynher River, nearly at right angles.

The valleys and inlets of southern Cornwall and south-western Devon are arranged on three main directions—north to south, east to west, and from north-north-west to south-south-east. According to Mr. Hill (**1906**, p. 102), these three prevalent directions are common to the whole district; but in the eastern part of the area, the most conspicuous valleys vary in trend from north-east to north-north-east and thus approximate to the strike of the slates and the Upper Palæozoic fractures. Near Truro and Falmouth the main valleys run north and south, and have no relation to the general strike of the rocks.

The valleys of the third group, trending from north-north-west to south-south-east, coincide with Kainozoic fractures. Thus Restronguet Creek apparently lies along the north-west to south-east fault, which, to the north-east of Redruth, brings the Falmouth and Portscatho Series against the Mylor Series. The Truro River near Truro appears to lie along a north-north-west to south-south-east fracture. The coincidence of the faults and the valleys is seldom actually shown. Mr. Hill (**1906**, p. 102) states regarding the valleys that " the straightness of some of them, and in other cases their parallelism, suggests that their course has frequently been determined by lines of dislocation, or well-marked joints. Moreover, two valleys divided by a ridge are often in perfect alignment, as if their course had been determined by a single line of fissure." Mr. Hill (**1906**, p. 87) assigns the later faults to the early Kainozoic and the formation of the valleys to the later Pliocene (p. 101). They were doubtless formed at some time in the Pliocene, as they were carved in a plateau, 700 or 800 ft. above sea-level, the existence of which in western Devon and eastern Cornwall in Miocene times has been proved by the work of the Geological Survey. (Reid and others, **1911**, p. 1.)

The evidence as to the age of the faults along which the valleys were excavated is very indefinite. They may themselves date from the middle Kainozoic, and the development of the existing valley-system may have begun after their formation.

The Cornish inlets differ from rias by their general uniformity in width, their angular branching, and their regularity in direction. In these respects they resemble fiords, but, owing to the slight elevation of the neighbouring country and the gentle gradients of their banks, they belong to the group of fiards. It is therefore interesting to note that they, the most fiord-like inlets in England, occur in an area where there is no evidence of glacial action. The recent geological survey of Cornwall, according to Mr. Hill (**1906**, p. 93), "failed to detect any indication of glacial phenomena." "Nowhere," he adds, "on the coast of Cornwall is there evidence of glacial action," though he recognises that the climate would once have been Arctic, owing to the proximity of the ice-field that covered the land to the north.

Opposite these Cornish inlets in Brittany on the southern coast of the English Channel there are several gulfs which have the same general characters and history, and have been repeatedly claimed as fiords (*vide* Chap. IX.).

4. The Irish Rias and "Fiards"

In Ireland there is a series of fiord-like inlets along the western and southern coasts. The existing names of two of them are derived from their having been called fiords by the Danes. For, according to C. Blackie,[1] the suffix "ford" in both Waterford and Wexford is a rendering of "fiord." Wexford was the Danish Weisfiord, the western fiord, and Waterford is derived from Vadrefiord, the fordable part of the bay.

Waterford and Youghal Harbour, both on the southern coast, are long and narrow, of uniform width, and in plan resemble fiords; but they are only drowned river-mouths, and are rias.

The four bays on the south-western coast of Ireland, viz. Dingle Bay, Kenmare River, Bantry Bay, and Dunmanus Bay, are long, funnel-shaped gulfs. Their shores are minutely indented, and have some small, irregular peninsulas, and their waters are broken by some islands. They run inland along the strike of the rocks, and they appear to increase uniformly in depth seaward. They are therefore usually identified, as by Richthofen (**1886**, p. 304), Suess,[2] and Dinse (**1894**, p. 243), as typical rias.

5. Their Preglacial Shores

Wright and Muff have shown (**1904**) that the southern coast of Ireland is skirted by a raised beach, which dates from preglacial times. The existing bays and headlands were then already there. Glacial and post-glacial denudation have together made no material change in the shape of the coast, and it would, therefore, be very strange if the rias of the immediately adjacent south-western coast were of glacial origin.[3]

[1] C. Blackie, *Etymological Dictionary*, 2nd ed. 1876, p. 67.

[2] E. Suess, *Face of the Earth* (1908), vol. iii. p. 5.

[3] Mr. J. M. Wordie has recently examined this ria coast and found evidence of a preglacial beach which proves the preglacial age of the rias.

The most fiord-like of the Irish gulfs is Killary Harbour, which Kinahan has described as a fiord (**1875**, pp. 184, 195). According to his measurements, it is ten miles long by half a mile wide; and he says that the gut of the channel coincides with a fault, and that each bend and turn in it is due to a fault. The faults range in age from the end of the Silurian to the Post-glacial.

Sligo Harbour has also been identified as a fiord, and it may be accepted as a fiard. Its sides are in places sub-parallel, and its direction is parallel to that of its inner basin, Loch Gill, and to the inner part of the adjacent Ballysadare Bay, which makes a nearly right-angled bend. Sligo Harbour, moreover, has a threshold, Coney Island, on the inner side of which is the "Deep Pit," 68 ft. deep.[1] Dinse compares this depression to an ordinary fiord-basin, but it may only be a "wash-out" due to a tidal eddy.

Reference to the inlets of western Ireland recalls the interesting work by Kinahan (**1875**) in which he maintained that they, the Irish and Scottish lochs and valleys in general, are due to denudation on lines determined by fractures. He had previously explained the basins of the Irish lakes as caused by glacial erosion; but he abandoned that view, maintained that ice could not erode basins (Kinahan, **1875**, p. 120), and adopted the extreme position that rain and rivers are incapable of much by themselves (p. 86). His book is valuable from its early recognition of the influence of fractures on British scenery and topography.

[1] Dinse records the depth of Sligo Harbour as 143 metres (**1894**, p. 214), which is far more than the depth given on the Admiralty Charts: Ireland, Sheet V., and Chart of Sligo and Ballysadare Harbours, Scale 1/24336. Dinse's record (p. 227) of the slope into this pit as 35° is probably based on the same error.

CHAPTER IX

THE FIORD-LIKE INLETS OF FRANCE AND SPAIN

A. THE COAST OF BRITTANY

Far on its rocky knoll descried
  Saint Michael's chapel cuts the sky.
I climb'd ;—beneath me, bright and wide,
  Lay the lone coast of Brittany.

Bright in the sunset, weird and still,
  It lay beside the Atlantic wave,
As though the wizard Merlin's will
  Yet claim'd it from his forest grave.

MATTHEW ARNOLD.

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1. Brittany, its Structure and Inlets.—2. Theory of their Marine Origin.—3. Its Coastal Types.—4. Resemblance to Fiards.

1. BRITTANY, ITS STRUCTURE AND INLETS

BRITTANY consists geographically of a low plateau occupying the site of an ancient mountain-chain. Although originally the country was traversed by high ranges trending east and west, it has been planed down to a surface so level that de Martonne describes it as of a "horizontalité frappante" and another part as being of a "monotonie désespérante" (**1906**, p. 216). The plateau is trenched by many valleys, and they join the sea through inlets which have been often described as fiords. Thus Hahn (**1883**, p. 142) accepts the mouth of the Trieux as a fiord on the authority of Burat, whom he quotes as describing it in his *Voyage sur les Côtes de France* (1880, p. 178), as "un véritable fjord." Hahn accepts the estuaries of Morlaix, Aber-vrach, and Aber-benoist as fiords, and says of this part of Brittany the whole coast structure is reminiscent of the scenery of the skerries of Scandinavia. He claims, moreover, that on the southern coast of Brittany the gulfs and fiords are only inferior to those of Norway because the coasts are much lower. The identification of these inlets as fiords has been accepted by some later authors; and some of these arms of the sea must be regarded as of the same nature as the fiord-like inlets of southern Cornwall. Dinse, on the other hand, emphatically rejects any of these as fiords; and, as Brittany has not been glaciated, their acceptance as fiords would be fatal to the glacier-erosion theory. Some of the inlets have, however, been accepted as fiords by competent authorities. Thus L. Rütimeyer (**1883**, p. 149) says the coast is indented by hundreds of fiords and gulfs, and that the fiords in the Department of Finistère run inland in all directions for distances of from 20 to 30 kilomètres (p. 126). He states (p. 40), that "fiord-formation has contributed to the physiognomy of Brittany its most remarkable and in many places its most imposing features."

2. Theory of their Marine Origin

The fiords of Brittany are of interest, as a special theory of fiord-formation has been advanced to explain them. Rütimeyer insists that these valleys (which he compares to "Strassengraben," or roadside ditches) can only have been formed by ice or water. He rightly points out (**1883**, pp. 17–20) that there is no trace of the existence of glaciers in Brittany, and he therefore concludes that the fiords must be due to water-action. Rütimeyer describes Brittany as a low-lying country with no rivers and only slight, gentle slopes [1]; he

[1] The character of the country as a level-topped plateau trenched by valleys is well shown in photographs by de Martonne (**1906**, pl. xvi, fig. 1, etc.).

therefore denies that the valleys can have been excavated by rivers, and attributes them to the action of the sea (**1883**, pp. 21–24, 50, 141, 142, 151, etc.). Brittany is exposed to particularly violent attack by the sea. The waves during storms have great power of battery, and in quiet weather the sea makes a long advance and retreat with the rise and fall of the tide. The land-locked sea-basins, such as that of Morbihan, are filled and nearly emptied twice a day, and the channel through which the water passes is subject to continual scour; and, as Brittany is a country of great geological antiquity, this process has been at work for a prolonged period. The rocks, and especially the granite, are intersected by many joints; and Rütimeyer (**1883**, pp. 142, 143) claims that valleys are eaten out along these joints by the scour of the tide. All stages can be seen along the coast of the widening of the joint-cracks into clefts, and of clefts into valleys. Rütimeyer, therefore, claims that the fiord-valleys of Brittany are due to the long-continued attack by the sea upon the land.

The efficiency of tidal erosion in suitable places has been maintained by so distinguished an oceanographer as Krümmel (**1911**, pp. 130, 131), and also by Prof. C. Vallaux (**1903**, pp. 28, 29), in special reference to Brittany. But the generally accepted view in recent years is that these inlets are rias, or drowned river-estuaries, though Vallaux maintains that they were drowned in consequence of marine erosion and not by subsidence. Schwind (**1902**), who compiled elaborate measurements of this coast, accepted the inlets as rias. De Martonne rejects Schwind's statistical method as valueless, but he agrees that the inlets are rias. He adopts a different definition of ria from that of von Richthofen; for, according to de Martonne, rias are especially characteristic of coasts which are composed of hard, unstratified rocks and therefore have no grain. So, according to him, rias are commoner on concordant than discordant coasts; whereas von

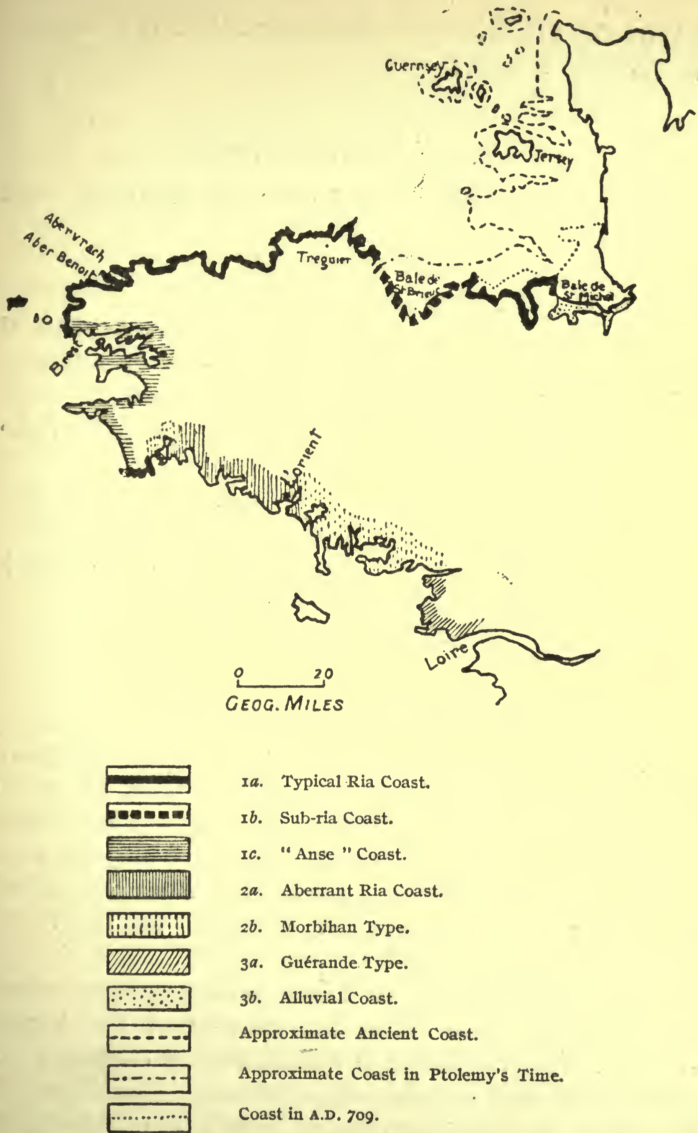

FIG. 36.—CLASSIFICATION OF COAST-TYPES OF BRITTANY (AFTER DE MARTONNE), AND THE ANCIENT COAST-LINE NEAR THE CHANNEL ISLES (AFTER PEACOCK, 1868).

Richthofen's definition of rias restricts them to transverse or discordant coasts.

3. Its Coastal Types

De Martonne (**1903**, p. 8) classifies the Brittany coast as follows:

1*a*. (Fig. 36). Typical ria coast.
1*b*. Local variety of ria at St. Brieuc.
1*c*. "Anses" (*Anse*, a bay or creek). Variety of ria in coasts folded perpendicularly or obliquely to the general direction of the coast.
2*a*. Aberrant rias on coasts folded parallel to the general direction of the coast.
2*b*. Morbihan type. Coast with aberrant rias altered by elevation or deposition of alluvium.
3*a*. Guérande type (Guérande, Loire-Inférieure). Further development of the last.
3*b*. Fully developed alluvial coast.

4. Resemblance to Fiards

The numerous inlets on the southern coast of Brittany and the great harbour of Brest do not seem to me to have any of the special attributes of fiords. The "Fiord de Morlaix" is also not particularly fiord-like, for it is a wide, funnel-shaped bay, all of which has now silted up except a narrow, shallow channel. Its mouth is contracted by a rocky islet.

A few of the Brittany inlets, however, agree more closely with fiords. Thus the estuary of the Rance from St. Malo to Dinant is a long, narrow channel with steep walls and angular, zigzag shores. The shape of the bays and promontories is clearly determined by lines of weakness in the rocks, including probably both faults and joints. The angular intersections of these planes have not yet been rounded off by the weather.

The harbours of Aber-vrach and Aber-benoit, though occurring in a comparatively low part of Brittany, are long and narrow, and are characterised by angular, step-like bends. Their shapes are shown in Fig. 37. Aber-benoit has a depth of only 6 ft. at its mouth, and it deepens within to 18 ft.[1]; its threshold is doubtless only an alluvial bar. These inlets, like those on the opposite side of the English Channel in Cornwall, differ from true fiords by the lowness of the adjacent country and the rounded form of the slopes. But there seems no definite character for their separation from fiards.

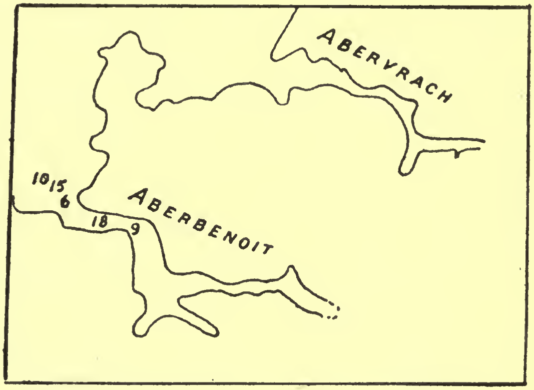

FIG. 37.—OUTLINE OF ABERVRACH AND ABER-BENOIT.
Old fiords on the coast of Brittany (depths in ft.).

The deep depression known as the Gouf de Cap Breton on the south-western coast of France resembles a submerged fiord. It is separated from the great deep in the Bay of Biscay by a well-developed threshold. The Gouf, as shown on the French map on the scale of 1 to 500,000,[2] has a branch at right angles to its main course, and has long, straight, spurless sides, though this aspect may be exaggerated by the fewness of the soundings. This Gouf is probably the old submerged continuation of the valley of the Adour; and it has a southern tributary which is probably the old estuary of the Bidassoa and the Nivelle.

[1] Admiralty Charts: France, North Coast, Sheet VIII, No. 2,644, 1823.
[2] Quarter Sheet No. X, S.E.

B. THE SPANISH RIAS

Tiene de su celaje en los fulgores,
En sus estrañas flores,
La gracia sensual del Mediodía,
Y en sus grandes florestas, salpicadas
De arroyos y cascadas,
Del Norte la tenáz melancolia.[1]

EMILIA P. BAZAN, *Descripción de las Rias Bajas.*

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1. The Five Rias.—2. The Earth-movements of the District.—3. Rias are Drowned, Torrent-cut Valleys.

1. THE FIVE RIAS

The north-western corner of Spain is intersected by a series of gulfs which may be regarded as the typical rias of the world, since that name was introduced into geographical nomenclature from them. Von Richthofen, who adopted the name "ria" for a special type of gulf, remarked, however, that the Spanish rias are less typical than the rias of south-eastern China (**1886**, p. 304).

The Spanish rias include five gulfs, which in order from Cape Finisterre are the Ria de Corcubion, Ria de Muros, Ria de Arosa, Ria de Pontevedra, and Ria de Vigo. They are all funnel-shaped gulfs which are comparatively short in proportion to their width. They all trend south-westward. The length is about seven times the mean breadth in the longest, the Ria de Vigo; it is only a little over thrice the breadth in the Ria de Muros.

The depth should increase regularly seaward in a typical ria, as it does in the Ria de Muros (Fig. 13*a*) and the Ria de Pontevedra. In the Ria de Arosa the depth is 24 ft. greater within the ria than at the entrance. The northern entrance to the Ria de Vigo has a depth of 72 ft., and the southern apparently of 90 ft., whereas the basin within has a depth of 132 ft. (See Admiralty Chart, Plan 2,548.)

[1] In its gleaming reflections, in its strange flowers, it keeps the sensuous graces of the South, and in its big forests, scored with streams and waterfalls, the lasting melancholy of the North.

The Ria de Vigo is the longest of the rias, and is the best known owing to the importance of the port of Vigo.[1] The entrance, contracted by two long islands, leads to a wide estuary which contracts suddenly above the town of Vigo (Fig. 38). The inner part is a narrow, sinuous gulf, up which the view is blocked by the projecting headlands. The scenery of the ria is very picturesque owing to the rugged, mountainous nature of the land and the pretty coves and promontories along the shores. The ria agrees with fiords in the presence of a threshold across the mouth and in the height of the adjacent country. It differs from fiords, however, by its tapering shape, its winding shores, and rounded contours; and also by the absence of cliffs, which occur

FIG. 38.—SKETCH OF THE RIA DE VIGO.
Looking up the ria from near Vigo.

only where the coast has been worn back by the sea, and they are then low and inconspicuous. The scenery is superior to that of most fiords owing to the more graceful lines, the greater variety of slope, and the serrate crests of the higher ridges. All the characteristics are those of a drowned valley cut by river-erosion. The ria-valley is in part very old, for the ridges on both sides slope down towards it, indicating that their crests were part of the floor of an ancient valley when the level of the land was lower than it is at present. Some of the features in the scenery, such as the wide areas of bare rock, the blunt domes on the lower ridges, and the rounded hummocks on their slopes, resemble those due to glacial action. There is, however, no evidence

[1] It is the only one known to me personally.

that ice took any part in the formation of the ria. It is clearly an old valley in a mountainous coast-land, and its forms are due to the prolonged attack of weather and water.

2. The Earth-movements of the District

This part of Spain has been affected by two series of movements which acted at right angles to each other. The first series of movements happened in upper Palæozoic times, and they were due to pressure from north and south; the second series, in which the pressure came from east and west, occurred, according to Prof. Barrois (**1882**, p. 605), between the Eocene and the Miocene. Both these series were accompanied by minor movements, which were transverse in direction to the most important movements. North-western Spain has been affected accordingly by a network of fractures; the main lines of the later series trend north and south, parallel to the western coast of the peninsula.

3. Rias are Drowned Torrent-cut Valleys

Rias have been developed in connection with this system of fractures. The resemblance of these rias to the Norwegian fiords has been remarked by various geographers; it seemed to Prof. C. Barrois (**1882**, p. 616) so striking that he regarded their existence as indicating that glaciers perhaps descended to the sea down the Cantabrian valleys, although he saw no positive evidence of glacier action (p. 615). There are some local beds of clay containing boulders; but the boulders show no glacial scratching, and Prof. Barrois attributes these deposits to river-action. He ascribes (p. 613) the special characters of the Cantabrian valleys to the great erosive power of the rivers, due to their torrential discharge, high gradient, narrow valleys, and steep walls.

The Spanish rias are the drowned mouths of these torrent-cut valleys.

CHAPTER X

The Fiords and Fiards of Dalmatia

With a soft, slow, gentle motion
    Swings the slow tide from the sea,
    Swings the slow tide hushfully
From the distant restless ocean,
    Through the sinuous canals,
    Past the ancient wave-worn walls
That have seen the galleys sweep
With great captains of the deep,
    Fresh from where the Muezzin calls
    The Moslem from the steep
Temple towers that face the sea.

. . . . .

The tides have swept for long
    Round the Adriatic shore.
The very soul of mystery
    Seems brooding here alone.[1]

WILLIAM SHARP.

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1. Dalmatia.—2. Its Geology.—3. Changes of Level.—4. Plan of the Coast.—5. The Fiord of Morlacca.—6. The Fiards of Sebenico.—7. The Fiord of Cattaro.—8. Thresholds; Cause of their Frequent Absence.—9. Polje.—10. Nature of the Dalmatian Inlets.

1. Dalmatia

DALMATIA is the long, narrow land along the north-eastern coast of the Adriatic, between Bosnia, Herzegovina, and Montenegro and the sea. It is fringed by innumerable islands, islets, and rocks, which are regularly arranged and form a chain that borders this part of the Balkan peninsula. The land is intersected by inlets, or "canale," which have been accepted as fiords

[1] Three of these lines have been altered to correct two slight errors in the original.

by some authors, but called pseudo-fiords by others. They have, however, most of the characteristics of fiords; for they are long and narrow; many of them have high, steep banks; the spurs from the hills beside them are often abruptly cut short and faceted; and they are sometimes deeper within than at their mouths, and thus have thresholds across their entrances. They are, therefore, at least closely allied to fiords, and among those of Europe rank in importance only after those of Norway and Scotland.

The geographical history of Dalmatia differs from that of Scandinavia and Britain, as it has not been subject to extensive glaciation; and, owing to the exceptional interest of the classical and historical associations of the country, the beauty of its scenery and its remarkable geological structure, the Dalmatian inlets are the most attractive series of non-glaciated fiords in the world.

2. Dalmatian Geology

The geology of Dalmatia offers a striking contrast to that of Norway and Scotland; for the country is composed almost entirely of rocks which, in comparison with those of the two other great fiord-regions of Europe, are very young. Most of the coastlands consist of Cretaceous and Eocene limestones; the higher land to the east includes Carboniferous, Permian, Triassic, and Jurassic deposits; but no Archean rocks or any earlier than the upper Carboniferous are known in the country, and, in spite of the powerful earth-movements that have affected the country, there appear to be no metamorphic rocks such as crystalline schists.[1] The Cretaceous and

[1] The general geology has been summarised by Dr. R. J. Schubert in his *Geologija Dalmacije* (Zara, 1909, pp. 183, 5 pls.) and his *Geologischer Führer durch Dalmatien* (Berlin, 1909, pp. 176, 1 pl.). The former work has a full bibliography, pp. 169–81. A shorter account is given by Prof. C. Diener in *Die Bäu und Bild Oesterreichs* (1903, pp. 582–8).

Eocene rocks were mainly deposited in the sea. At the end of the Eocene period the country was upraised, and it has since formed part of a land-area. The country was intensely folded and faulted by a series of overthrusts from the east, and was cut down by denudation to a series of pene-planes. Local subsidences formed basins which have no doubt been widened and deepened by denudation. The pene-planes were deeply dissected when the rivers were given increased powers of corrosion by the foundering of the land to the west. Its collapse formed the basin of the Adriatic Sea and separated Italy from the Balkan Peninsula. This happened in geologically recent times; for the jackals on the island of Curzola are regarded as survivors from the time when that island was joined to the mainland; and Dr. Forsyth Major recognises that some of the mammals of the Otranto Promontory in eastern Italy are more nearly related to their Balkan than to their Italian kindred.

3. Changes of Level

Most of Dalmatia can still be recognised as a plateau composed of Eocene and Cretaceous limestones, although it has been severely dissected by the combined influence of earth-movements and denudation. The earth-movements are no doubt still in progress, and one of them probably caused the earthquake which devastated Ragusa in 1667. There is, however, no satisfactory evidence of any regional change of level in historic times. There are no widespread raised beaches indicating an uplift, and the subsidences during the last 1,800 years can have been only very local. Submerged Roman pavements have been repeatedly reported; but some of them are based on evidence which appears unreliable. It is clear that the Palace of Diocletian at Spalato is at the same level above the sea as it was when it was built sixteen centuries ago. Evidence at Scardona, which is said to be the oldest Roman town in Dalmatia, indicates the absence of any appreciable change in the level of the country near Sebenico. At Salona, near Spalato, Roman tombs have been recorded below sea-level; but they may be explained by the usual shrinkage of alluvial deposits on the floor of a valley. The evidence seems fairly clear that, apart from occasional local subsidences the shore line is at about the same level as it was in Roman times.[1]

4. Plan of the Coast

The geological structure of the country is approximately concordant with the coast-line. The grain of the country and of the Dinaric Alps is in general parallel to the shore; and this strike from north-west to south-east is known as the Dinaric strike. There are some local exceptions to it, and in the neighbourhood of Trau and Spalato the rocks strike approximately east and west; and this course is known as the Lesina strike, as it determines the trend of the Island of Lesina. A westerly extension of this strike may be indicated by the change in depth of the Adriatic to the west of Trau; as it is only to the west of that locality that the sea-floor begins to descend from the shallow northern part of the Adriatic to the considerable depths found to the south of a line from Spalato to the Gargano Promontory on the Italian coast. In the area between Sebenico and Spalato the coast is discordant.

The general arrangement of inlets, islands, and straits is in a curved series hanging from the coast like a festoon. The general plan resembles in several features that of the two great series of fiords off western America. Thus

[1] Klöden (**1838**, pp. 369–75) summarised the evidence known to that date for subsidences since Roman times, such as pavements and a marble cippus near Zara, and submerged mosaics reported near Lissa, etc.; but the evidence is not very weighty.

each of these three series of fiords and archipelagoes starts at the north from a broad projection of the mainland; the peninsula of Istria then corresponds to the Fairweather Peninsula of Alaska and to the projection of southern Chile to the north of Ancud Bay. To the south-east of Istria is the deep bay known as the Quarnero, which leads inland, between many islands, to the port

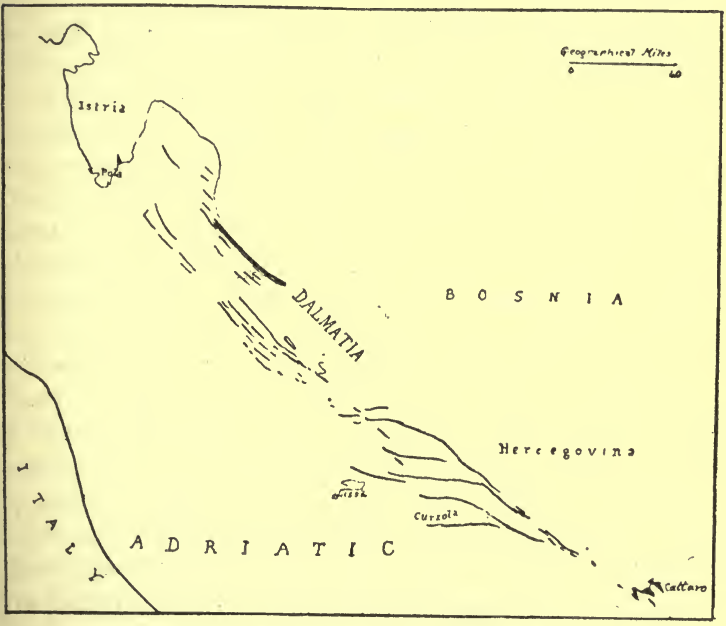

FIG. 39.—PLAN OF THE COAST OF DALMATIA.
The chief arms of the sea are showing in black.

of Fiume. The general course of the coast is here from north-west to south-east.

From the Quarnero a series of numerous fiord-like inlets strikes north-westward into the peninsula of Istria. They are well shown on the Austrian map on the scale of 1 to 200,000 (Sheet Pola, 32°—45°). The most important of this group is the Canale dell' Arsa, which is ten miles long and generally half a mile broad.

It is long and narrow, has parallel sides, and several well-marked rectangular bends. Parallel to it is the shorter Vallone di Fianona, which is shorter and leads to the valley containing the broad Cepic See. That lake is round in shape, but the adjacent island of Cherso has several long, narrow lakes, such as Lago di Vrana, which is three and a quarter miles long and three-quarters of a mile wide.

The northern islands in the Quarnero begin with a trend from only a little west of north to a little south of east; but the southern end of Cherso, the longest island of this series, bends more easterly; and farther south the island chain bends until it trends from north-west to south-east, parallel to the shore of the mainland. The trend of the island of Cherso is oblique to the strike of its rocks; for the middle part of the island extends almost due southward, while bands of Miocene rocks cross it almost from north-west to south-east. At the northern end of the island the divergence between the geographical and the geological lines is less marked, but is still more important. The southward projection of the eastern shore of the Quarnerolo is in conformity with the southern extension of the Triassic rocks of the Velebit Mountains, which rise in bold cliffs above the long, narrow "Canale della Morlacca," and the islands and peninsulas on the seaward side of this channel are parallel to the strike of their rocks.

Farther south, between Trau and Spalato, the islands under the influence of the east-to-west Lesina strike bend round to a course from west to east. As the coast resumes its south-easterly direction the islands of Braza (or Brač) and Lesina (or Hvar) strike in against the mainland from the sea at an oblique angle. The island festoon again becomes parallel to the shore and to the south of Ragusa the islands are few and unimportant, and the great indentations end in Dalmatia with the famous Gulf of Cattaro.

5. The Fiord of Morlacca

The Canale della Morlacca is the longest of the Dalmatian inlets. Its closed south-eastern part is about fifty miles long and from two to three miles wide. Its full length to Porte Re at its northern end is about ninety miles. Its course is continued south-eastwards by a deep, narrow valley containing the two lakes Mare di Novigrad and Mare di Karin. The channel lies near and parallel to the boundary between the older rocks (Triassic to Carboniferous) of the Velebit Mountains and the Cretaceous and Eocene limestones of the Dalmatian coast-lands. The Velebit Mountains rise in very steep, almost cliff-like slopes to the height of from 1,000 ft. in the south-east to 3,000 ft. farther north; from the top of this cliff the ground rises more gently inland to the mountain summits, which, according to the Admiralty Chart, attain the heights of 4,760 ft., 5,351 ft., and in Sveto Berdo, opposite the southern end of the channel, of 5,774 ft.

The channel itself has long and nearly straight sides; its width is, as a rule, fairly uniform, though it is contracted by a sudden rectangular projection of the southern coast near the head. There are also some minor irregularities along the south-western shores through some of which there are sinuous passages out to sea.

The depth is moderate, and upon the whole increases slightly seaward. The main part of the channel gradually increases in depth from 138 to 234 ft.; abundant depths are recorded on the Admiralty Chart,[1] and cross-sections show that the channel has a remarkably trough-like form. The shore sinks so abruptly, as shown for example by the section (Fig. 40 *a*), that almost the maximum depth is reached close to the shore. This flat, trough-like form is characteristic of most of the Dalmatian channels.

[1] Adriatic: East Coast, Sheet III., Grossa Island to Zirona Channel. No. 2,774, 1901.

It is also well shown in a section across the Narenta Channel (Fig. 40 *b*); the sides suddenly descend at the edge of the Lesina plateau, from the height of 1,023 ft. on the north, and from 1,300 ft. on the edge of the plateau at Velo Berdo in Curzola (or Korčula); the slope descends abruptly and close to the shore reaches the depth of

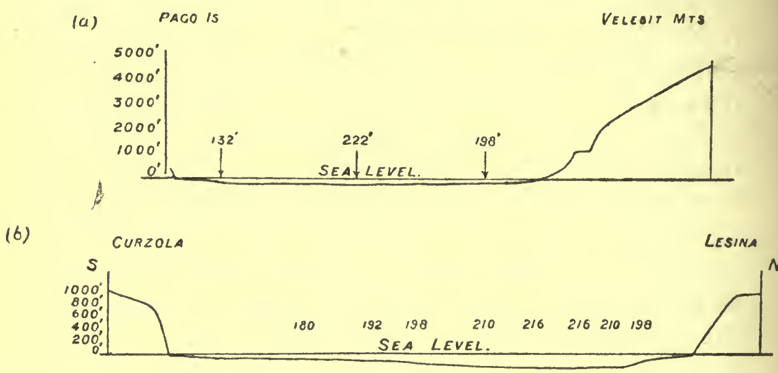

FIG. 40.—SECTION ACROSS TWO DALMATIAN FIORDS.

(*a*) the Canale della Morlacca, and (*b*) the Narenta Channel, showing their form as flat-floored troughs (depths and heights in ft.).

186 ft. on the northern side and 144 ft. on the southern; on both sides the depth is 192 ft. a mile from the shore, while in the full width of eight and a half miles the maximum depth found on the line of section is only 204 ft. The shore of Lesina, on the northern side of the Narenta Channel is as straight as that of any Norwegian fiord, and the channel is as flat-floored.

6. THE FIARDS OF SEBENICO

While the Canale della Morlacca illustrates one variety of the Dalmatian fiords, the neighbourhood of Sebenico illustrates the fiard type, owing to its lesser elevations and gentle slopes.

The view seaward from the hills above Sebenico includes a superb panorama of islands and channels, which are repeated in an alternation of land and water almost as far as can be seen. Sebenico stands at the foot of some limestone hills which rise in terraces at the levels of 400 and 600 ft. to a wide pene-plane that extends far inland, rising slowly to the foot of the Dinaric Alps.

The view northward from the old Venetian fort of S. Giovanni (alt. 423 ft.) shows the eastern end of the pene-plane sloping gently to the sea, but it is dissected by the valley of the Kerka River and by many tributary dales. The Kerka River strikes in the main across the grain of the country, but it makes frequent turns along strike-valleys, and the last of these, the Kerka Inlet, forms the port of Sebenico. The outlet thence is through a narrow and slightly sinuous strait, the Channel of San Antonio, at right angles to the Kerka inlet. The cliffs, though low, are in places so steep that they have been described as "precipitous,"[1] and this channel is probably comparatively new; and a gap a little farther to the north may represent a former outlet, before the subsidence of the country had reached its present stage. The Channel of San Antonio passes beside the Fort of San Nicolo to the Sebenico Channel, which lies between the peninsulas from the mainland and the first line of islands; still farther westward are more arms of the sea and chains of islands that appear to succeed one another until they are lost in the distance. This alternation of sea-channels with peninsulas and islands is strikingly fiord-like, and owes its chief æsthetic effect, like the view seaward from Bergen in Norway, to the frequent repetition of the same geographical form. The resemblance to the fiord scenery of Norway is increased by the form of the hills which rise in bare, rounded hummocks strikingly like those of glaciated countries. Many of them, if seen among the western isles of Scotland or the skerries of Scandinavia, would be at once regarded as indicating former glacial action.

[1] Baedeker's *Austria-Hungary*, 1905, p. 296.

The land beside the Sebenico channels is comparatively low, and, though the slopes are often steep, they are rarely precipitous; but farther inland between the Kerka Inlet and Lake Prokljan the Kerka River flows through deep limestone canyons and the lakes above the Kerka Falls are fiord-like. The coastal district, owing to the lowness of the adjacent land, is, however, somewhat more nearly allied to the Scandinavian fiards than to the fiords. The main outlet is simply the drowned estuary of the Kerka River; and the rest of the channels are valleys that have been drowned by the subsidence of the district.

7. The Fiord of Cattaro

In striking contrast to the rounded slopes by the Sebenico fiards are the majestic precipices around the Gulf of Cattaro, the most remarkable of all the Dalmatian inlets. It has the finest scenery on the Adriatic coast, and its fiord-like character is so striking that it has been identified as a fiord in popular literature. Thus in Baedeker's *Guide to Austria-Hungary* (10th edition, 1905, p. 309) it is described as follows:

"Bocchi di Cattaro is the name given to a fjord or arm of the sea penetrating far into the mainland of Dalmatia, and in form somewhat resembling the Lake of Lucerne. Bounded on the N. and E. by imposing mountains, rising to nearly 6,000 ft., and more open towards the S., the three different basins of this bay, connected in several cases by narrow straits, afford a series of grand and striking pictures."

The gulf was surveyed by Admiral W. H. Smyth in 1818, and an Admiralty Chart [1] that bears the date of 1843 shows the chief variations in depth. The entrance to the gulf through Bocca Grande attains the depth

[1] No. 1,463.

of 200 ft.; the channel increases in width northward, and shallows to 150 ft. and at the northern end to 132 ft. The depth of the channel decreases at its next constriction to 96 ft. and 108 ft. Opposite Castel Nuovo, where the channel makes its first great bend, the depth is 141 ft. A strait thence leads southward over a slight ridge 102 ft. deep, to San Teodo Bay, which is a broad basin with the greatest depth of 138 ft. The Canale della Catena, which continues the channel inland, is so narrow that it was closed by chains; it is only 120 ft. in the deepest part of one cross-section, while the maximum depth in the passage is 138 ft.

Risano Bay, the next great expansion on the northern side of the fiord, is 102 ft. deep, and the strait leading westward to Cattaro has depths of 120 and 132 ft. The innermost section of the Gulf is Cattaro Bay; the middle of its northern end attains the depth of 108 ft., and it shallows thence steadily southward to 48 ft., the greatest depth opposite the town of Cattaro (Pl. VI.).

There is, therefore, a general increase in depth from the head of the fiord seaward; but there are slight thresholds across the straits between the main expansions of the fiord, the three main basins being successively 12, 40, and 60 ft. deeper than their outlets.

8. Thresholds

Many of the Dalmatian inlets increase slowly seaward, and the outer members of a series of parallel channels are, as a rule, the deepest. There are, however, numerous exceptions to this rule, for many of the inlets have deep basins separated from the sea by thresholds. Thus, at Port Tajer (43° 51′ N. and 15° 12′ E.) the main harbour, which has sinuous sides like a submerged valley, has a maximum depth of 210 ft.; but, according to the Admiralty Chart,[1] the maximum depth across the mouth

[1] No. 2,774.

is 156 ft. At Sebenico the channel of Port Sebenico opposite the town trends from the north-east to south-west. The arm to the north-west is known as the Kerka Inlet, and is the outlet of the Kerka River; its depth decreases gradually from 126 ft. opposite the town to 100 ft. two miles up the inlet.[1] This part of the Gulf of Sebenico is a strike-valley; it is long, and has straight, steep, and nearly parallel sides. The outlet from the Port of Sebenico is through the Canale di San Antonio, which cuts across the strike of the limestone nearly at right angles to the direction of the Kerka Inlet. The channel of San Antonio is 140 ft. deep; but opposite the old Venetian fort of San Nicolo the depth decreases suddenly, as a shoal crosses the mouth of the channel, and the greatest depth on one line across it is only 48 ft. The main passage continues west-south-westward and the sea deepens to over 180 ft., and, with occasional slight rises, the depth continues to increase seaward until, on passing the outer chain of islands, the sea-floor descends to 500 ft., and then to over 600 ft.

From Fort St. Nicolo, the Sebenico Channel extends south-eastward parallel to the main coast. Its depth increases almost at once to 130 ft., or, according to the Austrian map, to 180 ft.; from that point a line of soundings can be followed along a continuous channel, which slowly deepens from 120 to 180 ft. near its outlet through a chain of islands off the south-eastern end of Zlarin Island. The main passage between these islands begins with a depth of 168 ft., but it soon diminishes to 54 ft.; and a threshold of that depth, except for one break, where it increases to 72 ft., appears to connect all these islands. Thence in the broad bay between Zuri Island and the mainland at Port Capocesto the depths increase steadily from 180 to over 600 ft.

[1] Admiralty Chart No. 1,581, 1900. Some of the depths above cited are taken from the Austrian Map, 1 to 100,000, Sheet Sebenico (Kol. XIV. Zone 31).

Another example of the inner basins being the deepest is supplied by the outlet from Stretto di Ljubac to the Adriatic by the Stretto di Brevilacqua. The depths in this case are taken from the Austrian Staff Map on the scale of 1 to 100,000 (Kol. XII., Zone 28). The Stretto di Ljubac passes from the Canale della Morlacca at a point where its floor is about 200 ft. deep. The strait has a depth of 180 ft., and leads into the large basin of the Vallone di Ljubac, of which the northern arm has depths of 138, 144, 150, and 125 ft. The southern arm is shallower, the depths decreasing from 125 to 75 ft. The passage seaward through the Vallone di Pogliana Vecchia begins with the depth of 138 ft. and shallows through its western arm, where depths are recorded varying between 88, 65, and 92 ft. Its outlet has no soundings marked deeper than 62 ft. It leads into the Vallone di Nona, where the deepest sounding is 62 ft. This channel deepens north-westward to the sea through the Canale di Pagliana; but its direct westward continuation is through the Stretta di Brevilacqua, which shallows to 7 ft.

These series of straits are a lateral outlet from the Canale della Morlacca, the main course of which deepens north-westward.

Another of the threshold-barred basins is that to the north of Morter Island near Zaravecchia, and near the outlet from Lake Vrana. The long, narrow basin of Vallone di Zlosella runs parallel to the coast and has slightly sinuous sides. Its maximum depth is 82 ft. It has one outlet through a narrow, shallow channel between Morter Island and the mainland, where the depth appears to be reduced to only 12 ft.; and the somewhat wider outlet north-westward between Great Arta Island and the mainland also shallows to only 12 ft.

Notwithstanding the preceding examples, the thresholds on the Dalmatian coast are less conspicuous than in typical fiord areas. The difference may be explained by the special combination of geological and geographical circumstances. Thus the prevalent rock along the coast is limestone, and though some of it has nodules of chert, there is little material available as coarse durable shingle. The rivers, moreover, except in floods, have a very small discharge, and carry to the sea a comparatively small quantity of sediment, and the main rivers of Dalmatia do not pass through the chief inlets. The most important river on the coast, the Narenta, is not connected with the fiords, and the main fiords, such as the Canale della Morlacca, the Gulf of Cattaro, and the Gulf of Sebenico, receive only insignificant streams. The Kerka discharges through the channels of Sebenico, but its flow is small, as the river, a few miles inland, often consists of a chain of pools. Further, the tide in the Adriatic is small, and the coast is not subject to the constant powerful tidal scour, which in most seas sweeps the coarse shingle along the shores and piles it up in the sheltered water at the mouths of the inlets. Hence, owing to the scarcity of beach material and the weakness of the tide, the Dalmatian channels are only blocked occasionally by thresholds.

9. Polje

The existence of some basins deeper than their outlets would be expected, as there are numerous well-developed rock-basins known as "polje" in the adjacent parts of the Balkan Peninsula. The polje are basins which include the most valuable agricultural land in the country; they are often bounded by fault-scarps, and some appear to be completely surrounded by rock-rims; there may be an outlet through a deep, river-cut ravine, or the only outflow may be by subterranean channels. Most of the polje are probably subsidence-basins due to movements along faults. Some of the smaller depressions, known as dolinje, may be solution cauldrons. The limestone is dissolved by percolating water, and the collapse of the ground forms a large cauldron-shaped depression. Some of the basins in the fiords which are deeper than their outlets may be regarded as submerged polje, and are therefore of tectonic origin.

10. Nature of the Dalmatian Inlets

The general characteristics of the valleys in which the Dalmatian inlets lie may be summarised as follows: Their general shape is long and narrow. The sides are usually parallel or sub-parallel. The walls are flat and often spurless, but occasionally the remains of an old spur projects as a gable, which ends in a flat facet, as is often shown in Dalmatian photographs, as in the view of the fiord-wall opposite Cattaro (Pl. VI.). The valleys are not arranged like the members of ordinary river-systems, and the branching and bending are usually rectangular. The floors are flat, and the inlets often contain an inner basin separated from the sea by a shallow threshold. The valleys of adjacent inlets may be connected at their heads by a low pass, as at Stagno over the isthmus which unites Sabbioncello to the mainland, like the "tarbets" or "haulover" places in Scotland, Kerguelen, and other fiord-coasts. If the valley be bordered by high land the walls are steep and the inlet is fiord-like in aspect; but where the land is low the slopes are gentler and the inlets are of the fiard type.

This association of characteristics is strikingly like that of typical fiord-valleys. Accordingly some of the Dalmatian inlets, such as the Gulf of Cattaro, are popularly accepted as fiords, and the whole coast has been often regarded as a fiord-coast. The geological history of Dalmatia differs, however, from that of most fiord areas, since the coast has not been glaciated. Some small local glaciers once existed around the summit of Lovçen, the highest mountain near Cattaro, and also on a few of the highest peaks of the Dinaric Alps; but there is no evidence of glacial action at or near sea-level. Nevertheless, the whole coast has several of the most conspicuous of the usual characteristics of glaciated areas: 1. The contours are gently rounded as in a country which has been smoothed down by the passage of an ice-sheet across it. 2. Many of the inlets have the typical form of "roches moutonnées" and of the ice-worn skerries of Norway and Scotland. 3. There are wide areas of bare rock and very little of the decomposed, weathered rock-material which usually covers most of the surface of non-glaciated lands. 4. The main valleys are much deeper than their tributaries, that occur as hanging valleys (see p. 434), with their floors high above that of the main valley. 5. The walls of the valleys are straight and spurless, though some of the spurs may still be represented by their truncated faceted ends, as is shown in Royle's sketch [1] of a typical part of the Dalmatian coast and in the western face of Trsteno, to the north-west of Ragusa.

These five features are usually due to glaciation, and they are remarkably well developed in Dalmatia. Many of the smaller Dalmatian islets and rocks, if transported to western Scotland, would be explained as typical illustrations of glaciated forms. The resemblance is sufficiently impressive to suggest the possibility of the coast-zone having been formerly so elevated that it was then ice-clad. I searched, however, in vain for any positive proof of glacial action in the Dalmatian lowlands. I could find neither glacial scratches, even on newly exposed surfaces, nor erratic blocks; and I saw no remains of moraines, which should be conspicuous if these valleys had been excavated or even occupied by glaciers.

The five characteristics seen in the Dalmatian inlets which simulate glacial action are capable of explanation without invoking the agency of ice. In warm climates,

[1] Dalmatia Illustrata (1900), opp. p. 4.

CATTARO BAY, THE INNER BRANCH OF THE CATTARO FIORD.

The spurs on the fault-block on the left side of the view show triangular facets due to faulting. The precipitous slope above Cattaro, on the right margin of the view, is a fault-scarp.

bare, rounded, whale-back-like hummocks are often developed, especially in such rocks as limestone and granite, by the combined effects of sudden changes in temperature and of wind-erosion. Clean rock-surfaces are commonly present on pure limestone, as its decay yields only a small quantity of insoluble debris, which is so fine that it is easily swept away by the wind. The main valleys have been over-deepened owing to the porous nature of the rocks of which the country is composed; for the rain sinks quickly underground, and, instead of flowing in well-defined surface-streams, it is discharged by widespread percolation; the main valley may therefore discharge a large volume of water, while the tributaries are usually dry.

The straightness of the valleys and the truncation of the spurs are often both due to faulting, as is clearly shown in Cattaro Bay. From the mountains of Montenegro the fiord of Cattaro is seen spread out as in a map, and the peninsula to the west of Cattaro has all the aspect of a block-mountain bounded by faults. The faults can be seen around Fort Trinita, at the head of the valley that leads southward from the head of the fiord. The faults can be traced northward, and opposite Cattaro they have cut across and faceted the spurs that project eastward toward the shore. The great eastern wall of the valley, which includes the lofty precipices behind Cattaro, is also clearly a fault-scarp.[1]

The whole topography of the inner Cattaro fiord is, in fact, dominated by a well-displayed series of fault-scarps. Prof. Suess (**1875**, p. 92) pointed out that the shore-lines of Dalmatia are fracture-lines. "Our coasts," he wrote, "are bordered by fractures [*Bruchränder*]. The network of narrow canals which divides the Dal-

[1] Unfortunately, my visit to Cattaro was at a time when, owing to political uncertainty, the regulations against photographing, sketching, or examining the neighbourhood of the forts were being strictly enforced. I was therefore unable to examine the facets or search for the eastern fault north of Cattaro.

matian islands quite agrees with the long-meshed texture of cracks which arise so often when a half-rigid body is bent."

The features in the Dalmatian scenery which resemble those of glaciated areas are, therefore, due to the combined influence of earth-movements and to the special conditions of denudation in a warm, dry, limestone district. There is no evidence that the Dalmatian inlets were due to ice or have ever been occupied by glaciers. Many authorities have, therefore, refused to recognise these inlets as fiords. The resemblance is, however, so close that the inlets are called "Pseudo-fiords." Von Richthofen (**1886**, pp. 302, 303) described Dalmatia as a special coast-type characterised as having drowned valleys in a longitudinally or concordantly folded coast. Günther (**1899**, p. 607) adopted the same view and called the inlets "pseudo-fiords." Von Richthofen's view is open to the objection that the inlets were not directly connected with the folding. After the country had been folded it was worn down to a plain, and this was elevated to a plateau and fractured during the uplift. The Dalmatian inlets were then formed along the fractures and their course is often quite independent of the trend of the folds.

Peschel (**1878**, p. 16 and **1879**, vol. i. p. 469) had previously rejected the Dalmatian inlets as fiords on account of their parallelism and the absence of perpendicular offsets. Hahn justly replied (**1883**, p. 143) that inlets at right angles to the main shore-line are present in Dalmatia and absent from some accepted fiord-coasts, so that the argument is invalid on both sides. Peschel regarded the resemblances to fiords as superficial and apparent only on small-scale maps, whereas they appear to me greater in the field than on the maps. Dinse (**1894**, pp. 247, 248) noticed the occurrence of some inlets at right angles to the main series, but he dismissed them as rias; he declined to admit the main inlets as fiords because of the linear arrangement of the islands, which he recognised, however, as an occasional feature of fiord-coasts. Dinse apparently attached most weight to the objection based on the limited variations in depth. The Dalmatian inlets, however, have basins and thresholds as well developed as some admitted fiord-areas. Dr. Otto Nordenskjöld (**1900**, p. 216), in accordance with his conclusion that " there are no true fiords in Europe south of about 55 degrees," also excluded the Dalmatian inlets from the category of fiords. He divided them into longitudinal valleys of the Dalmatian type and into valleys at right angles to the main series; and the smaller inlets he identified as rias (Nordenskjöld **1900**, p. 217). He admitted the presence of the internal basins, but thought them of no significance as being due merely to sedimentation ; but so also are many thresholds in the fiords of glaciated districts.

De Martonne (**1903**, p. 11) referred the main Dalmatian inlets to a class of " aberrant " rias and as similar to those along the western part of the southern coast of Brittany. I have seen part of the Brittany coast to which M. de Martonne refers, and, in comparison with Dalmatia, the differences seem greater than the resemblances. Prof. Supan also classified the Dalmatian inlets as rias, but he remarked their fiord-like appearance (**1911**, p. 803) and character.

The balance of recent opinion is therefore in favour of either regarding all the Dalmatian inlets and channels as rias or of dividing them into two groups—the concordant valleys, or pseudo-fiords, and the shorter cross-valleys which are identified as rias. I fail, however, to see any adequate reason for putting the concordant channels of Dalmatia into a separate class from the concordant channels of Patagonia, Alaska, or Norway. The inlets transverse to the coast seem, moreover, essentially different from rias. They are not rias according to von Richthofen's definition, for he restricted rias to discordant coasts. The Dalmatian inlets are too numerous and gregarious to be rias, which are drowned river-estuaries; and, with the exception of Sebenico, the Dalmatian inlets are not used as such. The chief rivers, which discharge into the north-western Adriatic, such as the Dobra near Fiume, the Cetina near Almissa, and the Narenta, enter the sea on the sides of these inlets and not at their heads. The rivers avoid these arms of the sea instead of using them as estuaries. The Dalmatian cross-fiords, such as Val d'Ombla near Ragusa, are no doubt shorter than those of most fiord-areas. But that fact is easily explained by the structure of the country. If a piece of ordinary glass be broken the cracks will run far into it; whereas in a grained material, such as a piece of pine-wood or grooved glass, the cracks will run much farther along the grain than across it.

Prof. Suess's comparison of the Dalmatian channels to a network of cracks in a bent slab seems to explain their origin. Some of them, such as those at Sebenico, may be regarded as fiards; but those which intersect the highlands and are still bounded by precipitous walls have all the essential characteristics of fiords, for they are narrow arms of the sea in angular, flat-walled, flat-floored valleys in a fractured plateau, which has been partially drowned by subsidence beneath the sea.

CHAPTER XI

OTHER MEDITERRANEAN FIORDS

Woods that wave o'er Delphi's steep,
Isles that crown th' Ægean deep.

GRAY.

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1. Reported Fiords in Corsica, Sardinia, and Italy.—2. The Three Groups of Ægean Inlets.—3. The Gulf of Corinth a Typical Fiord ; its Deep Basin and Thresholds and Faceted Spurs ; its Origin as a Pleistocene Rift-valley.—4. The Eubœan Strait.—5. The Western Coast of Asia Minor.—6. The Disrupted Land of Ægea.

1. Reported Fiords in Corsica, Sardinia, and Italy

The existence of fiords has been often claimed for many parts of the Mediterranean Sea. Some of the reports may be dismissed as based upon the superficial resemblance of narrow gulfs to fiords. Thus Hahn (**1883**, p. 143) described the inlets in Corsica and Sardinia on both sides of the Strait of Bonifacio as fiord-like ; but the charts of that coast show no adequate grounds for the identification of its inlets as fiords.

The occurrence of one fiord has been asserted on the shore of Italy ; for Freeman (**1881**, p. 312), in his description of Brindisi, states that, "in whatever language it is that Brentesion means a stag's horn, the name was not unfittingly given to the antler-like fiords of this little inland sea."

2. The Three Groups of Ægean Inlets

The shores of the Ægean Sea are the most indented part of the Mediterranean coast-line, and some of the inlets on its eastern coast have been claimed by Sir Henry Howorth (**1893**, vol. ii. p. 627) as fiords; and some neighbouring arms of the sea such as the Gulf of Corinth, have all the essential characteristics of fiords.

The inlets into the lands around the Ægean Sea may be divided into three groups. The first group consists of widely open bays like the Gulf of Salonica, of gulfs between the promontories at the end of the peninsula of Salonica, and of the three gulfs at the southern end of Greece.

The second group consists of long narrow gulfs, which have sub-parallel sides, and are often very deep. The two largest members of this group are the Gulf of Corinth, which is separated by a narrow isthmus from the Gulf of Ægina near Athens, and the strait between the Island of Eubæa (Negropont) and the mainland of Greece. They resemble on a colossal scale the smaller bays in Malta and the Balearic Islands, for which Prof. Penck (**1894**, vol. ii. p. 569) adopts the term Calas (Ital., *Cala*, a bay).

The third group consists of the numerous deep gulfs on the western shores of Asia Minor.

The members of all three groups seem to have been due mainly to subsidence, though they may have been partially formed by denudation and afterwards enlarged by subsidence. The broad, open bays of the first group, owing to their tapering, funnel-shaped form and the absence of any thresholds across their mouths, have no resemblance to fiords.

The Gulf of Corinth and the Strait of Eubœa have the essential characteristics of fiords. The Gulf of Corinth has a length of about 110 miles; its width varies from about three miles at the Strait of Patras to a maximum width of twenty miles, including therein the length of one of the secondary bays. The mean width may be regarded as about ten miles. The length is therefore eleven times the mean breadth. The walls are steep, for the slopes rise rapidly to the height of over 8,000 ft. on the northern side and 7,700 ft. on the southern, and levels of 3,000 ft. are reached near the shore. The gulf is in places very deep. The greatest depths in the outer basin, which leads from the Ionian Sea to the Strait of Patras, vary from only 180 and 240 ft., whereas the inner basin deepens to 2,460 ft. The Gulf of Corinth is, therefore, a deep rock-basin with a threshold at the Strait of Patras. The gulf, moreover, cuts across the strike of the rocks almost at right angles. The adjacent country consists mainly of contorted and uplifted Cretaceous limestones, which strike parallel to the shore, from north-north-west to south-south-east. The western coast of Greece is concordant, and the Gulf of Corinth has, therefore, all Richthofen's essential requirements of a true fiord. Its origin is unquestionably tectonic.

3. The Gulf of Corinth a Typical Fiord; its Deep Basin and Threshold and Faceted Spurs; its Origin as a Pleistocene Rift-valley

Prof. Alfred Philippson (**1892**, p. 425) has described the Gulfs of Patras, Corinth, and Ægina as one continuous valley 160 miles long, formed by fault-movements, which cut obliquely across the grain of Greece. The Gulf of Patras is a shallow basin lying in country composed of low hills. The greatest depth of this basin is 410 ft., and it is separated from the Ionian Sea by a bank with depths of only 160 to 200 ft. (Philippson, **1892**, p. 425). The Gulf of Corinth he describes, on the other hand, as "a long, narrow sea-channel, to which high mountains fall unusually steeply on both sides (Giona, Parnass, and Helikon on the northern side, and Chelmos and Ziria on the southern), and continue to somewhat considerable depths." The greatest depth in the Gulf of Corinth known at that date was 2,460 ft., at a point south of Galaxidion, where the gulf is ten and a half miles wide; but Dr. Philippson (**1892**, p. 426) thought that greater depths would be found farther to the east.

It may be significant, though possibly only a coincidence, that the depths of the Ionian Sea outside the Gulf of Corinth are about the same as the maximum depth within, while farther west the sea-floor descends to 2,000 fathoms.[1]

The two shores of the gulf differ greatly in geological structure, and there can be no doubt that the Gulf of Corinth is a rift-valley due to subsidences beginning, as shown by Prof. Philippson (**1892**, p. 430) in the interval between the lower and upper Pliocene; the movements were continued into the Pleistocene. He describes the faults of this Peloponnesus fracture-zone as forming a somewhat tangled net-work cut across a previously folded mountain-country.

Prof. Philippson's map, on the scale of 1 to 300,000, shows that all along the southern side of the Gulf of Corinth the spurs have been as truncated and faceted as they are along ice-worn fiords. But there is no evidence whatever of any glacial action at sea-level in this part of Greece.

Prof. Philippson records the existence of Pliocene beds with marine shells along the southern shore of the Gulf of Corinth. These Pliocene beds at Mavron Oros reach the height of 5,770 ft. (**1892**, p. 426), and the absence of these deposits from the northern side of the gulf indicates that the country to the south has been upraised. The shallowness of the outlet through the Strait of Patras may be due to these movements.

4. The Eubœan Strait

The strait between Eubœa and the mainland of Greece being long and narrow, having sub-parallel sides

[1] Admiralty Chart, Eastern Mediterranean, No. 2,158 B., 1907.

and a basin, 1,200 ft. deep within, separated from the sea at each end by thresholds of only 300 ft. deep, is also very fiord-like. Its south-eastern end cuts across a band of Archean rocks, which are also exposed in the strait leading to its north-western end. The adjacent country consists mainly of Cretaceous limestones.

The geology of Eubœa has been well investigated by Deprat (1904), who has shown that the Channels of Talanta and Egripos, which separate it from the mainland of Greece, form a rift-valley due to a series of sub-parallel faults, which have produced a long, narrow strait. The Gulf of Corinth can be explained most simply as of similar origin. It is a rift-valley, of which the inner part is parallel to the Straits of Eubœa, and the Gulf of Ægina is a continuation of the same rift-valley. These Grecian gulfs, like those of Dalmatia, have all the physiographic characteristics of fiords. They can only be rejected from the category of fiords by regarding a glacial origin as an essential characteristic of a fiord.

5. The Western Coast of Asia Minor

The western coast of Asia Minor is indented by a series of gulfs which Sir Henry Howorth has described as fiords. The six most important in order from north to south are the Gulf of Adramyti, the Gulf of Tchandarly, the Gulf of Smyrna, the Gulf of Skala Nova by Samos, the Gulf of Mandelyah, and the Gulf of Kos. The foundation of the whole of this coast is composed of Archean rocks, which are covered in places by materials discharged in volcanic eruptions, and by some Cretaceous and Kainozoic deposits. The coast shows clear traces of the great fractures by which the ancient land of Ægea has been broken up. Thus the Gulf of Adramyti[1] has a long, straight northern shore, which cuts alike across volcanic, Cretaceous, and Archean rocks. The central part of this gulf is a deep basin, all deeper than

[1] Admiralty Chart, No. 2,836 B.

384 ft., which appears to be separated from the outer sea by a bar across the main outlet in places only 114 ft. deep. Its southern outlet through the Mytilene Channel, between the Island of Mytilene and the mainland, decreases gradually in depth from 264 ft. to 114 ft. The gulf is T-shaped and includes a deep basin.

The Gulf of Smyrna is L-shaped. The entrance channel goes southward between a peninsula of Cretaceous rocks on the west, and the volcanic mountains on the mainland to the east. The channel bends at a right angle, and the inner arm leads eastward across an area of Archean rocks.

The Gulf of Mandelyah[1] is a wide bay, from which numerous fiord-like inlets extend inland into the Archean rocks. The gulf has no irregular variations in depth, such as there are in the Gulf of Adramyti, but its chief geographical lines are parallel or rectangular. As the country has a heavy rainfall and the low land has been submerged by the sea, the shores are now curved and somewhat irregular. One of its outlets, Bargylia Creek, is T-shaped, and, with its narrow parallel sides and rectangular branching, it is decidedly fiord-like. Its arms are parallel to the long, straight coast of the peninsula which forms the southern boundary of the Gulf of Mandelyah.

To the south of this peninsula is the Gulf of Kos, which has a long, straight northern coast composed of Archean rocks, and on the southern side some jagged irregular peninsulas of Miocene deposits. The Gulf of Kos lies along the fracture separating the Archean horst of western Asia Minor from the Miocene deposits at its southern foot.

6. The Disrupted Land of Ægea

The interesting inlets around the Ægean Sea are due to earth-movements. The Ægean Sea, as has been

[1] Admiralty Chart, No. 1,546, 1898.

so clearly explained by Prof. Suess,[1] occupies the site of the ancient land of Ægea. This country was composed mainly of Archean rocks, which are now exposed in Macedonia, along north-eastern Greece, in the Salonica Peninsula, the western part of Asia Minor, and most of the southern islands in the Ægean Sea. Ægea has been broken up by several series of intersecting earth-movements; one series trends approximately from north-west to south-east; a second series lies at right angles to the first and goes from south-west to north-east, and a third series was oblique to the others and extends from east-north-east to west-south-west. The members of this last series have caused the northern shore of the Gulf of Adramyti, the Oreo Channel, which is the strait at the north-western end of Eubœa, and the outer part of the Gulf of Corinth. As the result of the earth-movements, most of the land foundered beneath the sea, and the parts that remained as islands and the shores of the adjacent lands are indented by gulfs and straits which were due primarily to earth-movements. These geographical changes happened in very recent geological times, as has been shown by evidence from Greece and that collected lately in Cyrenaica.[2]

The Gulf of Corinth and the Strait of Eubœa are the most fiord-like owing to their length and the depth of their interior basins. The gulfs on the coast of Asia Minor are at present too short to be regarded as typical fiords, but some deep, narrow valleys such as that of the Mendere (Meander) to the north of the Gulf of Mandelyah, before it was filled up by sediment, would have been strikingly fiord-like.

[1] E. Suess, *Face of the Earth*, vol. i. p. 345.

[2] J. W. Gregory, "The Geology of Cyrenaica," *Quart. Journ. Geol. Soc.*, vol. lxvii. 1911, pp. 604–607.

CHAPTER XII

THE FIORDS AND FIARDS OF ASIA (EXCLUSIVE OF ASIA MINOR)

Where the grey sea goes nakedly between the weed-hung shelves.
KIPLING.

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1. The Poverty of Fiords in Asia.—2. Siberian Fiords and Plover Bay.—3. Inlets on the Persian Gulf.—4. Red Sea.—5. Fiord-like Valleys of Sinai.—6. Chinese Rias and Nimrod Sound.—7. Hong-Kong.—8. The Fiards of Tsusima, Korea, and Japan.

1. POVERTY OF FIORDS IN ASIA

ONE of the most striking facts in the distribution of fiords is that, according to some authors, there is not a single fiord on the whole coast of Asia. The first explanation to suggest itself is that fiords are features of western coasts, and that all the main coasts of Asia face eastward. It is interesting to note that, as was shown in the last chapter, the western end of Asia Minor has a series of fiord-like bays. The western coast of the Malay Peninsula is very irregular, but all the other coasts of Asia facing west, including those of Palestine, Arabia, southern India, Burmah, and Kamtschatka have long, even shore-lines. Nevertheless, though fiords are mostly found on western coasts, they are not confined to them, and numerous fiords occur on eastern coasts. The view that there are no fiords in Asia is not correct, for there are both fiords and fiards on Asiatic coasts.

2. SIBERIAN FIORDS AND PLOVER BAY

The northern coast of Siberia has a series of long, narrow gulfs, similar to those on the northern coast of Norway, but on a larger scale. The largest is the Gulf of Obi, which, though long and narrow, is comparable in area with the White Sea. It is, however, a drowned estuary rather than a fiord. The country beside it is low. The Admiralty Chart (No. 2,282, 1893) describes the shores as covered by sand-dunes, and refers to hills seen eight miles inland, and says that the highest cliffs along the shore, at a locality sixty miles south of Cape Sharan, are from 150 to 250 ft. high. The water, moreover, is shallow. In the southern part of the gulf, from the mouth of the Obi River to Capes Kamenni and Krugli, the depth gradually increases from 10 to 15, 24, 30, 36, 42, and 48 ft. The great arm which then joins from the east has depths of 30 to 48 ft. Farther down the gulf between Capes Kamenni and Krugli on the south, and Cape Sharan, the great projection of the eastern shore, the depths recorded in order are as follows: 36, 42, 48, 60, 54, 66, 36, 54, 84, and 48 ft. opposite Cape Sharan. Beyond Cape Sharan the gulf widens to its mouth, but becomes shallower, with depths of only 24, 36, and 42 ft. Thence it deepens northwards, and the Kara Sea, opposite the mouth of the Gulf, has depths of 504 and 690 ft.

The Obi has the character of a river-estuary in a low-lying country, and has no title to be regarded as a fiord. Farther east, however, there are six small narrow inlets that may be fiords, on the south-western shore of Taimyr Island, which is separated from the Taimyr Peninsula by the Taimyr Sound. Chatanga Bay, to the east of the Taimyr Peninsula, is a ria like the inlets on the northern coast of Norway. The New Siberian Islands are separated by fiord-straits, but Nordenskjöld's map (**1882**, vol. ii. map 11) represents them as free from fiords. The only fiords in Siberia are in its eastern-most corner, the "Chukch" Peninsula. St. Lawrence Bay was described by Baron Nordenskjöld (**1882**, vol. ii. p. 218) as "a not inconsiderable fjord."

He contrasted the coast of this peninsula and that of the main Arctic coast in the following passage. The coasts of Siberia, he wrote (**1882**, vol. ii. pp. 243–4), are straight and "neither indented with deep fiords surrounded with high mountains, like the west coast of Norway, nor protected by an archipelago of islands like the greater part of the coasts of Scandinavia and Finland. Certain parts of the Chukch Peninsula, especially its south-eastern portion, form the only exception to this rule. Several small fjords here cut into the coasts."

These fiords trend in two directions. One series trends north and south; it includes Koliuchin (Koljutschin) Bay (67° N., 170° W.) on the northern coast; also Plover Bay (marked on the U.S. Coast and Geodetic Survey, General Chart of Alaska, 1900, as Providence Bay), and Iskagan Bay, the one east and the other west of 173° W. and opening about lat. 64° 20′. The other series trends east and west, and includes Mechine Bay, and various inlets from Seniavine Strait, a wide strait between Kayne Island and the mainland.

Plover Bay was explored by Muir in 1881, and he revisited the locality with the Harriman Alaska Expedition in 1899. Muir (**1902**, pp. 134–135) then described it as a well-characterised glacier-fiord.

"Its walls rise to an average height of about 2,000 ft. and present a severely desolate and bedraggled appearance, owing to the crumbling condition of the rocks, which in most places are being rapidly disintegrated, loading the slopes with loose detritus, wherever the angle is low enough to allow it to rest. But on the most resisting portions I discovered rounded glaciated surfaces, grooved, scratched, and polished from near the sea-level up to a height of a thousand feet or more. And in high, spacious cirques I found well-formed, unwasted moraines made up of concentric masses shoved together, indicating that the glaciers to which they belonged receded with changes of level and rate of decadence in accordance with conditions of snowfall, temperature, and so on, like those of lower latitudes. When the main glacier which filled the fiord was in its prime it was about thirty miles long and five to six wide, with five main tributaries, which, as the trunk melted, became separate glaciers, and, these melting in turn, left many smaller tributaries ranging from less than a mile to several miles in length. These, also, as far as I have seen, have vanished, though possibly some wasting remnants may still exist in the snowiest recesses of the mountains."

The Harriman Expedition collected on the beaches at the mouth of this fiord some boulders, including tonalite, andesite, and diabase. The adjacent country is represented as composed mainly of granite (Emerson, **1904**, p. 42).

Dr. G. K. Gilbert (**1903**, pp. 190, 191) has also described the form of Plover Bay and his description and sketches show that it is a V-shaped valley, bordered by a cirque, or hanging valley, cut through a level plateau. He saw no indication of glacial action on the plateau, but concluded that the trough-valley was probably due to glacial sculpture. The walls—

" that we passed near betrayed no smoothing, grooving, or other minor feature of glacial abrasion. The shore-walls of Plover Bay are precipitous rock-cliffs at top, and consist of talus at base, one phase passing into the other in a manner suggesting that the original rock-profile was somewhat similar to the one brought about by partial disintegration. They run straight for long distances. The chief agencies competent to produce such features are faulting and glacial sculpture, and in this case glacial sculpture appears to me the more probable agent, although subsequent weathering seems to have destroyed those minor details of configuration which one naturally seeks as confirmatory evidence."

Plover Bay is the best-developed fiord in northern Asia; but it is on the Pacific Coast opposite the fiord-indented districts of Alaska. The Arctic coast of Asia follows the rule that the shores of the mainland around the Arctic Ocean have no typical fiords, but are indented by funnel-shaped rias.

3. Inlets on the Persian Gulf

The Persian Gulf has several secondary gulfs which have been frequently identified as fiords. The mountainous peninsula which, by projecting northward from Arabia into the Persian Gulf, forms the Straits of Ormuz, is indented by a number of narrow inlets which have been claimed as fiords. Rasab Bay (26° 13′ N. and 56° 20′ E.) is thus described by Carl Ritter,[1] who also refers to the Malcolm and Elphinstone Inlets as "die merkwürdigsten Fiorde" on the coast near Ras Mussendom—the promontory on the Arabian side of the Strait of Ormuz. These "fiords" are 180 to 240 ft. deep, and are bounded by hills rising to 500 ft.

Ritter also (**1846**, p. 528) quotes Wellsted as describing part of the coast between Ras Mussendom and Oman, the south-eastern province of Arabia, as one of the most irregular coasts in the world, though Ritter suggests that perhaps Wellsted meant within the tropics.

Another projection northward from the Arabian coast, somewhat similar to Ras Mussendom, occurs 400 miles to the west near the Bahrein Islands, at the south-western corner of the Persian Gulf. It is the peninsula of Katar and is indented by somewhat fiord-like inlets. They lie between Ras al Hasra and Ras Masheirib. Though they include two long, narrow channels, the western of which is 36 ft. deep within and 24 ft. near its mouth, there are no adequate reasons for regarding

[1] C. Ritter, *Die Erdkunde*, vol. xii. 1846 (Asien, vol. viii.), p. 532.

them as fiords.[1] There are, indeed, no fiords on the Asiatic or African shores of the Indian Ocean.

The inlets on the eastern coast of Africa, such as the great harbours beside Mombasa Island and the channels in the island of Pemba have been identified by Mr. Cyril Crossland as fiords (**1902**, **1904**). He justly rejects the view that they are land-valleys drowned by widespread subsidence. He explains them as submarine fault-valleys, the conclusion adopted by the author after examination of Kilindini Harbour in 1893. According to the nomenclature adopted in this work, these inlets should be regarded as föhrden formed by faults, for the adjacent lands are low and are composed of young rocks.

4. The Red Sea

Occasional inlets on the Red Sea, such as Annesley Bay, are fiord-like, and the Red Sea itself has the character of a colossal fiord. It is long and narrow, its length being about eight times its greatest breadth. Its walls are steep and often spurless. Its floor is fairly flat, and sinks, by a slightly undulating slope, to the depth of 6,162 ft. about its middle. Thence, as shown in the section by Sherard Osborn, the depth decreases southward and the Red Sea is comparatively shallow at its mouth. Perim island stands on the threshold of the Red Sea. Captain Sherard Osborn describes its bed as follows:

"The section of the Red Sea between Aden and Suez . . . represents a series of submarine hills of rounded outline, but it will be observed that that outline (which, of course, is the centre of the sea) is everywhere covered with silt, mud, and sand." [2]

[1] *Vide* Admiralty Chart, 2,837 B, 1900. C. Forster, *The Historical Geography of Arabia* (London, 1844, vol. ii. pp. 218–220), describes the Bahrein Gulf as a "deep bay," and refers (pp. 231–2) to the scarcity of ports on the coast of Oman.

[2] S. Osborn, "The Geography of the Bed of the Atlantic and Indian Oceans and Mediterranean Sea," *Journ. R. Geog. Soc.*, vol. xli. 1871, p. 55.

The Red Sea might be regarded as the greatest fiord in the world; but it should be excluded from fiords, owing to its size. It is so large that it must rank as an independent sea and not as an inlet. At its northern end it receives two gulfs, of which the Gulf of Akabah is remarkably fiord-like. This gulf is the lower submerged portion of a valley which continuing northward includes the river Jordan, and Prof. Bonney (**1873**, p. 395) remarked of this valley that "Perhaps also it sometimes formed a fiord into which the river flowed."

The Gulf of Akabah is a long, parallel-walled valley about one hundred miles long and from nine to fifteen broad—a proportion very common in fiords. Its walls are very steep, for the mountains on its western side in Sinai rise to 7,450 ft., and those on its eastern side in Arabia to between 6,000 and 7,000 ft. Unfortunately, the depths are inadequately known. The soundings recorded on the Admiralty Chart [1] show that toward the northern end the depth of the gulf is more than 720 ft., and then over 840 ft., and then for most of the gulf over, and possibly greatly over, 1,200 ft. As the southern end is approached the soundings only record the depth as over 360 ft., and just outside the entrance the depth is recorded as over 420 ft., and then, on reaching the Red Sea, the depth plunges to 3,564 ft. The evidence of the soundings clearly suggests that the Gulf of Akabah is a deep basin separated from the Red Sea by a well-marked threshold. The Gulf of Suez, on the other hand, is comparatively shallow. It increases in depth with fair regularity from Suez southward to 246 ft. at its entrance, where the depth rapidly falls to 1,560 ft. and 2,430 ft. The only interruption in the floor of the Gulf of Suez is the shallow known as Tor Bank, but the channel beside it is 216 ft. deep, which is as much as any part of the gulf above it.

Not only is the Gulf of Akabah a fiord, but the moun-

[1] Admiralty Chart, No. 2,523, 1885.

tains to the west of it are intersected by valleys which, if drowned, would give rise to a most typical series of fiords.

5. The Fiord-like Valleys of Sinai

The Peninsula of Sinai between the Gulf of Akabah and the Gulf of Suez is a high granitic plateau, which has been shattered by the foundering of the rift-valleys on each side. The peninsula is traversed by a network of narrow, parallel-sided trough-valleys, which mostly cross at right angles. In some parts of the peninsula the valleys meet at oblique angles, though the branches occur in parallel series. The character of these valleys is well shown in the map by the Rev. F. W. Holland (**1869**). This map is admittedly only a sketch-map. But the fiord-like nature of these valleys, with their long, straight, spurless sides and rectangled branching is also well shown on the recent geological map of the area by Dr. W. F. Hume (**1906**, pl. xxxiii.). His map of the country around Ras Mohamed Bay, on the shore of the Gulf of Akabah near the southern end of Sinai, shows that if the ground were submerged by the sea the land would be intersected by a series of typical fiords. The existence in the Sinai valleys of cirques and other mountain forms similar to those of the Alps has been described by Prof. Walther (**1891**, p. 402), and he considers but rejects the view of their glacial origin.

6. Chinese Rias and Nimrod Sound

The most important series of fiord-like inlets on the coasts of Asia are on the shores of China and Japan. These inlets extend along the shores of south-eastern China from the mouth of the Yangtse-Kiang River southward to the Canton River near Hong-Kong. The coast-lands here are part of an ancient plateau ; the coast-line has been determined by the great fracture-line of the eastern coast of Asia, which forms the south-eastern coast of China. The rocks are geologically very old, belonging to the Archean and Palæozoic eras; they trend in general from north-east to south-west. They are therefore in part parallel to the coast, though both at the northern and south-western ends of this area the coasts trend more westward, and thus cut transversely across the grain of the country. The middle part of this coast has therefore a concordant, and the ends of it a discordant, structure.

There is no evidence that this coast-line has ever been subject to glacial action; its latitude is from 30° to 22½°, so that it is mainly sub-tropical in position. This eastern coast of China is indented by a series of inlets, due doubtless to sub-aerial denudation. The edge of the Chinese plateau was left liable to rapid erosion by the subsidence of the land that once extended farther eastward. According to von Richthofen, this is the best developed ria coast in the world. Its general geographical features have been described by L. Richards (**1908**, p. 242). He says that, except for the alluvial areas near the great rivers in this part of China—

"All the other parts of the coast are granitic. These offer an uninterrupted series of indentations, the coastal region is hilly, the sea pretty deep, and almost free from shoals. Instead of these latter are countless islands and islets which generally form deep and well-sheltered havens. . . . This latter coast may be further subdivided according as the mountain-chains are parallel or perpendicular to the seaboard. In the former case, long chains of islands generally border the coast. . . . In the latter case, the chain of islands prolongs into the sea the coast of the mainland. They have lengthy and deep bays, which are closed at their extremities. Long excursions must often be made to find through these islands a safe anchorage. Shantung and Chekiang offer a coast-line, especially of the second kind; both kinds are found in Fokien; as to Kwangtung, its coastline belongs rather to the first type."

Richards's descriptions and the Admiralty Chart of this coast show that the bays in many respects agree with

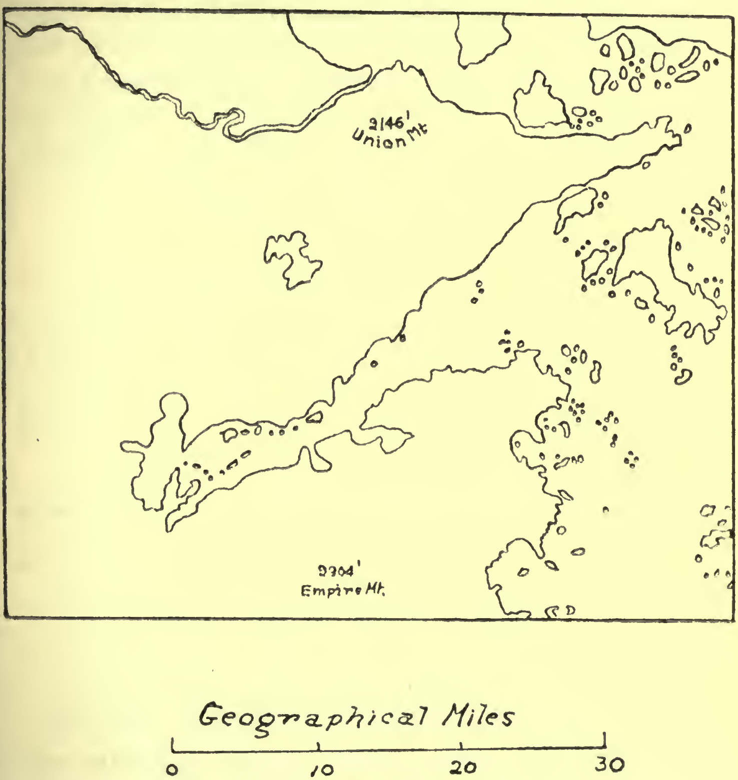

FIG. 41.—MAP OF NIMROD SOUND.
From the Imperial Prussian Landes-Aufnahme, 1902 (Karte von Ost-China, Futschau).

rias. They are comparatively shallow, though this is doubtless a secondary effect due to rapid sedimentation. Their forms are often extremely irregular, like those of a wide valley which has weathered sides and has been flooded by the sea. Thus the great Samsah Inlet has extremely irregular outlines; it is said by Richards

(**1908**, p. 276) to be "very deep"; but, according to the *China Sea Directory*,[1] it is mainly filled by mud-flats.

In other cases, however, the inlets are fiord-like. Thus Nimrod Sound, according to the *China Sea Directory*,[2] is twenty-seven miles long and three miles wide at the entrance; it decreases to the width of eight cables, that is 1,600 yds. opposite Parker Island and then

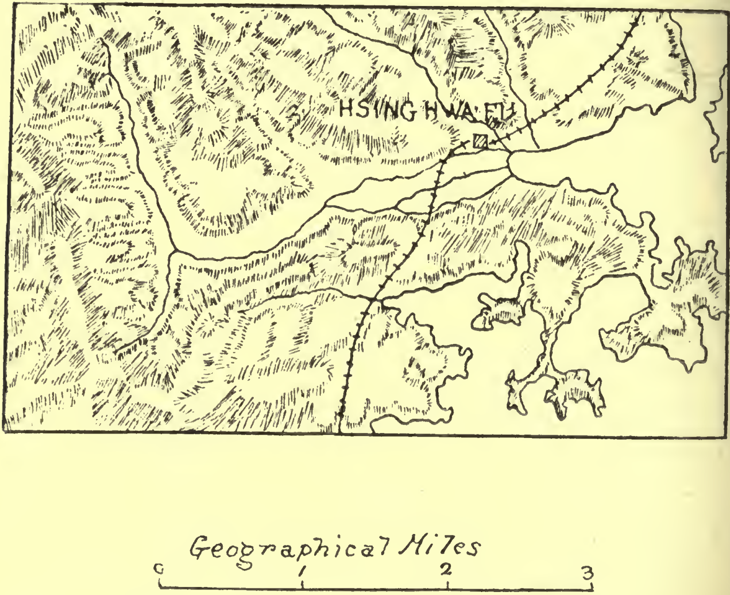

FIG. 42.—RECTANGULAR VALLEYS NEAR AMOY.
From the Imperial Prussian Landes-Aufnahme, 1902 (Karte von Ost-China, Amoy).

increases inland again to two and three-quarter miles wide though broken by islands. Its depth increases from 42 ft. at its south-western end to 120 ft. and 102 ft. about half-way down the Sound, and then shallows to 30 ft. and 15 ft. at its mouth. The land beside Nimrod Sound is mountainous, as it rises to 2,143 ft. on the north-western side of the entrance and to 1,770 ft. on the south-eastern side.

[1] *China Sea Directory*, vol. iii. 4th edition, 1904, p. 290.
[2] *Ibid.* pp. 323–5.

Nimrod Sound appears, therefore, to be a fairly typical fiord as it is long, narrow, steep-sided, and has a threshold at its mouth (Fig. 41).

In adjacent parts of China there appear to be well-developed cases of intersecting trough-valleys, which divide the land into rectangular blocks. This structure is well shown on the Karte von Ost-China published by the Prussian Landes-Aufnahme (Sheet No. 22), Fig. 42. Intersecting valleys there are, however, not fiords, because they are above sea-level.

7. Hong-Kong

Another remarkable network of narrow valleys, some of which are inlets of the sea, forms the most striking feature of the British Colony of Hong-Kong, which is near the south-western end of the Chinese riá coast. Its coast is extremely indented, and its name is said to mean "the place of sweet lagoons." [1]

The colony is formed of the islands of Hong-Kong, the peninsula of Kowloon on the mainland, and a number of adjacent islands. The colony has a very irregular shape, that bears a marked resemblance to that of Greece, but with the sides reversed. It has many branching peninsulas, and the irregularity of its shores is indicated by such names as Crooked Harbour and Double Haven. The whole colony is traversed by a series of parallel mountain-lines running from north-east to south-west. They attain the height of 3,130 ft. on the peninsula of Kowloon. The highest mountain-line is continued south-westward as the isand of Lan-Tau, where a height is attained of 3,065 ft. Between the mountain ridges are a series of inlets that begin on the north-east with the Tolo Channel, the most important;

[1] Map of Hong-Kong and of the Territory Leased to Great Britain under the Convention between Great Britain and China signed at Pekin on June 9, 1898. Scale $\frac{3}{4}$-inch to the mile. War Office, August 1905.

it widens inland into the irregular basin of Tolo Harbour, whence runs a narrow, fiord-like branch known as Tide Cove. The line of these inlets is continued as the West Lamma Channel between Hong-Kong and the Lan-Tau Islands.

The land is also indented by a series of bays trending north-west and south-east. These as a rule have very irregular sides, which break up into numerous peninsulas and islands. The bays themselves tend to be widely open or funnel-shaped, and occur along parallel lines. The colony is thus broken up by a network of valleys many of which have been drowned from the sea.

Geologically the colony of Hong-Kong consists of granite and syenite. Geographically it may be described as part of an ancient plateau, which has been broken up by double sets of fractures.

The regular angular intersection of the valleys of Hong-Kong, the arrangement of the geographical elements in two series of parallel lines, and the intersection of the two series at right angles, are features characteristic of typical fiord-districts. Owing, however, to the high rain-fall—the mean for the year is 90 inches—and the ready weathering of the granite into rounded forms, the sides of the valleys are sinuous and irregular. Hence, in spite of the height of the land, the inlets from the sea are fiard-like rather than fiord-like.

8. The Fiords of Tsusima, Korea, and Japan

The coasts of Japan and the opposite peninsula of Korea on both sides of the Strait of Korea have many inlets which are strikingly fiord-like.

The first European to visit the Island of Tsusima in the Strait of Korea was Laurence Oliphant in 1861, and he gave the following description of Tsusima Sound:

"It is difficult," he says (**1863**, p. 180), "to conceive anything more striking of its kind than the reticulation of deep channels, which, dividing the hilly country in every direction, forms a water-labyrinth, which can only be compared to Norwegian fiords; but the scenery, instead of being wild and rugged in character, is soft and rounded. Everywhere massive foliage droops into the water. Here the whole navies of the world might be concealed without an anchor down, for every ship might be moored in deep water to the trees on the banks. Some idea may be formed of the extent of these lanes of water by the chart furnished to the Admiralty by

FIG. 43.—MAP OF TSUSIMA SOUND (AFTER OLIPHANT).

Captain Ward, who had surveyed this sound a few weeks previously; but to appreciate its beauties one must explore its infinite recesses in a boat."

Oliphant describes the whole island as hilly rather than mountainous, and this extremely jagged inlet is therefore rather a fiard than a fiord, owing to the lowness of the adjacent country. According to the *China Sea Directory* (vol. iv. 1884, p. 122), the mountains to the south rise to the height of 2,126 ft., but the country to the north is less elevated.[1] Tsusima Sound has, however, been de-

[1] It remarks that the water appears to have receded, as the depths noticed by Lieut. Balleston in H.M.S. *Vigilant* in 1875 were less than those of the earlier survey.

finitely claimed as a typical fiord by various authorities, as by Hahn (**1883**, p. 147) who calls it the most striking fiord in Asia.

The southern coast of Korea opposite Tsusima is extremely jagged, and is fringed with islands. It appears, from the Admiralty Chart,[1] to be rather a fiard than a fiord coast. Along the western coast, Shoal Gulf includes a broad basin 102 ft. deep, while its outlet is only 66 ft. deep.

The south-western shores of the Japanese Archipelago are also very indented. The geology is complex, and the strike of the rocks is very variable and often transverse to the length of the land, so that the coast is partly discordant. The south-western parts of the archipelago are especially irregular and have deep bays which have been described as fiords. Thus Sir Rutherford Alcock (**1863**, vol. i. p. 76) remarks, in his description of Nagasaki Bay, that—

> "The first aspect of the bay itself strongly recalls to the European traveller some of the more picturesque fiords of Norway, especially the approach to Christiania, the capital. The hills rise boldly from the water's edge, and the pine grows plentifully here as there. But the Swiss lakes also produce scenes much more resembling this, than one could have anticipated. On landing only, something more tropical appears in the trees and shrubs. . . .
>
> A beautiful bay it is, and perfectly land-locked."

The view he gives of it (Alcock, **1863**, vol. i. p. 73) is certainly fiard-like.

The entrance to Nagasaki Harbour is through a narrow channel which leads north-eastward and then bends sharply to a wide basin known as Omura. The harbour extends from north-north-west to south-south-east, and has irregular sides ; but some of its upper branches have

[1] No. 2,347, 1900.

parallel walls. The harbour has depths of 72 ft. within and 54 ft. at the entrance. The inner end of Nagasaki Harbour is separated from the outer part of Simabara Gulf by an isthmus, on which stands the town of Nagasaki. Simabara Gulf extends inland at right angles to the direction of Nagasaki Harbour, and also makes a rectangular bend; hence its upper part is parallel to the main length of Nagasaki on a line farther inland. Still more to the south along this coast is the Yatsushiro Sea, a long bay trending north-eastward. Its mouth is blocked by an island, the passages beside which are 42 ft. and 102 ft. deep, while the harbour within deepens to 150 ft. There is also a passage from it to Simabara Gulf with a depth of only 24 ft.

At the southern end of Kiusiu Island is the Kagosima Gulf, which is forty-three miles long and has a maximum width of eight and a half miles, but with a narrow entrance. The depth of its outlet is 216 ft., and it deepens within to a basin of 762 ft.

Between the islands of Kiusiu and Nipon is the well-known Inland Sea of Japan, the Suwo Nada. Its coasts have often been compared to those of Scandinavia, owing to its indented shores and projecting rocks. Its headlands are doubtless due to bands of hard rock, as they are parallel to the strike of the beds in the south-western end of the Island of Nipon. The Suwo Nada has several outlets. That to the west through Simonoseki Strait has depths as low as 24 ft., whereas the Suwo Nada itself has depths of 162 ft. The main outlets, however, are south-south-eastward through the Bungo Channel, which is 342 ft. deep, and the Iyo Nada, which goes north-eastward between Nipon and Shikoku, and has depths of 216, 174, and 186 ft. Sir Rutherford Alcock (**1863**, vol. ii. p. 100) gave a view of the outlet from the Suwo Nada, which appears intermediate between a fiord and a fiard.

The coasts of Korea and the south-western part of the

Japanese peninsula have many features similar to those of a fiord district, for there is a striking parallelism of the chief geographical lines throughout them. Thus the south-eastern outlet from the Suwo Nada is in line with the eastern coast of Korea, and is parallel to the main extensions of Nagasaki Harbour and Simabara Gulf and to the general course of the south-western coast of Kiusiu Island. Tsusima Sound is in line with the western part of the southern coast of Korea, and with the long strait that extends from the Suwo Nada eastward between the islands of Nipon and Shikoku.

Korea is well known to be a horst which has been left standing by the subsidence of the surrounding country; and the main lines of fracture caused by the earth-movements appear to have determined the direction and position of the narrow inlets in the adjacent lands.

The earth-movements have naturally produced different results on Korea and Japan; for Korea is a plateau, and Japan consists mainly of a line of fold-mountains bordered by occasional plateaus. It is in these plateau-areas that the Japanese fiards occur. Both countries have been shattered by earth-movements, but Korea has been left as an oblong peninsula, while Japan has been broken up into islands by subsidences along lines parallel to the boundaries of Korea; and the submergence of the Japanese valleys has produced inlets which have been often and justly compared with those of Scandinavia, though they are fiards rather than fiords.

CHAPTER XIII

THE FIORDS OF SPITSBERGEN, FRANZ-JOSEF LAND, AND NOVA ZEMBLA

For surely once, they feel, we were
  Parts of a single continent.

. . . . . .

And bade betwixt their shores to be
  The unplumb'd, salt, estranging sea.

MATTHEW ARNOLD.

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1. Spitsbergen and its Recent Uplift.—2. Geology.—3. The Chief Inlets.—4. The Fiord-valleys Tectonic in Origin.—5. The Fault-system and its Connection with the Fiords.—6. The Straits and Fiords of Franz-Josef Land and Nova Zembla.

1. SPITSBERGEN AND ITS RECENT UPLIFT

SPITSBERGEN is an archipelago of special importance on account of its historic interest and as the most accessible land in high Arctic latitudes. It ranges from about 76½° N. to 80° 50′ N. Its western coasts have long been well known, for they were frequented by large whaling fleets during the seventeenth century. Its coasts have been examined in detail by numerous expeditions during the last sixty years, and the interior has been explored, since the first traverse across the mainland by Sir Martin Conway's Expedition in 1896.[1] There is no area in so high a latitude whose structure is so well known. The history of the exploration of Spitsbergen has been well told by Sir Martin Conway in his *No Man's Land*; he has carefully worked out its geographical nomenclature,

[1] A full bibliography of the Swedish explorations in Spitsbergen has been published in Ymer, 1909.

which is particularly confused as English, French, Dutch, and Scandinavians have shared in the exploration of the country, and several names belonging to different languages have often been given to the same locality. The archipelago of Spitsbergen consists of a plateau in a comparatively young stage of dissection. It has recently undergone great geographical changes. It has been uplifted, and the differences between some early charts and the present topography may indicate that the uprise of the land is still in progress in some parts of the archipelago. The ice-sheet by which it was once completely covered has been broken up into a number of smaller sheets and glaciers.

2. Geology

The geological structure of Spitsbergen is very varied and complex. The foundation of the northern part of the main island and of North-East Land consists of Archean rocks covered by the Hekla Hook Formation, which is mainly Silurian but probably contains some pre-Cambrian sediments. The middle part of the northern half of the mainland consists of a broad block of Old Red Sandstone, which has been dropped by faults between two areas of Archean and Hekla Hook Formations. A wide band of Permian and Carboniferous rocks crosses the middle of the island from west to east; and from it a narrow band of the same rocks extends southward and flanks the western mountains throughout the southern part of the mainland. A northern band of the same rocks extends northward from the head of the Ice Fiord to Hinlopen Strait and then passes into the island known as North-East Land. Most of the southern half of the mainland consists of Mesozoic rocks, which are covered by terrestrial Kainozoic deposits.

The older rocks of Spitsbergen, the Archean and Hekla Hook Formations, are very contorted; but most of the upper Palæozoic and younger rocks are approximately horizontal, though they have been disturbed in places by overthrust faults. The contrast between the contorted, uptilted rocks of the western mountains and the flat-topped, horizontally terraced plateaus of the interior is one of the most striking features in Spitsbergen. The horizontally bedded rocks have, however, been dislocated by a series of powerful faults. Where the Devonian and post-Devonian rocks occur in contact with the older rocks they have been brought together by faults. Spitsbergen, in fact, consists of a series of slabs of rock fitted together like a mosaic along fault-planes. The country has, therefore, no well defined structural grain; but the main trend of the rocks is from north-north-west to south-south-east parallel to the western coast. The most conspicuous mountains are the chain of folded mountains along the western coast. The rest of the country consists of plateaus or dissected plateaus, which are separated by deep valleys. The country is indented by long arms of the sea, some of which are fiord-like from their length and sub-parallel sides.

3. The Chief Inlets

One of the chief attractions of the country to me, when I was invited by Sir Martin Conway to accompany him on the expedition which in 1896 first crossed the interior of Spitsbergen, was the study of the fiords and the valleys in which they lie. These inlets were not regarded as fiords by their discoverers and early explorers. They called them sounds, inlets, bays, and waters; and it was the least fiord-like of them all, Stor Fiord, that has been most generally called a fiord.[1] The best known of these inlets is marked in the Admiralty Charts as Ice Sound, though it is now generally known as Ice Fiord. It extends inland from the western coast,

[1] The term "fiord" has, however, been adopted for many of the inlets by geologists such as A. E. Nordenskjöld, de Geer, Nathorst, and von Drygalski.

and subdivides into Ekman Bay, Dickson Bay, Klaas Billen Bay, Sassen Bay, and Advent Bay. The chief inlets on the western coast, in order from north to south, are called Magdalena Bay, King's Bay, and its northern branch Cross Bay, St. John's Bay, Ice Sound, Bell Sound, and Horn Sound. Sir Thomas Smith Inlet, renamed by the Dutch Wijde Bay, is the most fiord-like of all the Spitsbergen bays, owing to its length, narrowness, and sub-parallel walls.

The fact that so many of the inlets were first named by British seamen does not explain the fact that they were not called fiords, for the Scandinavian explorers who renamed many of them did not call them fiords. The name "fiord" is usually applied only to Ice Fiord, its northern branch North Fiord, the West and East Fiords, the two branches of Sir Thomas Smith Inlet, and to Stor Fiord, the triangular sea between the main island and the two eastern islands, Barent's Island and Edge Island. The Stor Fiord, of which the older name is Wybe Jansz Water, is not fiord-like in form and Ice Fiord, if a fiord, is only a representative of the Bukken type, for it is a basin with very irregular shore-lines. Low Sound (Van Mijen Bay) is more fiord-like, but its length is only three and a half times its maximum breadth and eight times the breadth of the narrower part of the outer sound. Axel's Island, like a long, narrow threshold, lies nearly all across the mouth of Low Sound, separating it from Bell Sound.

Some of the Spitsbergen inlets are certainly entitled to rank as fiords; for they, with the valleys connecting them, form a network of steep, straight-walled valleys intersecting a recently fractured plateau-land.

4. The Fiord-valleys Tectonic in Origin

The origin of the Spitsbergen fiords is clearly dependent upon the structure of the archipelago and on the earth-movements that have broken it into blocks. Thus Sir Thomas Smith's Inlet lies along the fault between the Archean rocks of New Friesland on the east and an Old Red Sandstone plateau to the west; its eastern wall is remarkably straight, but the western wall we found to be broken by ten valleys.

In most cases the tectonic valleys have been greatly modified by preglacial denudation. The effects of denudation have no doubt in most cases obscured the exact course of the old fractures; for the earth-movements were doubtless, in the main, of preglacial date. Post-glacial uplift has certainly occurred, and it has been of a differential character, so that the country has been tilted. Thus the beaches on the sides of the Sassendal have been tilted near Sassen Bay as they approach the shore of Ice Sound.

5. The Fault-system and its Connection with the Fiords

The faults which have fractured Spitsbergen belong to several distinct periods (Fig. 44).[1] The most important series connected with the fiords was formed in middle or upper Kainozoic times [2]; it was post-Eocene and probably post-Oligocene in age; and it was most likely due to the foundering of the Arctic Ocean.

The faults probably formed a series of rift-valleys, one of which is represented by the band of Carboniferous and Permian rocks which is faulted down between plateaus of Archean and Devonian rocks, and forms the floor of the valley between Sir Thomas Smith's Inlet and Klaas Billen Bay. The latter bay is itself probably part of the same rift-valley.

The fiord-valleys belong to two main series, of which

[1] For the earlier faults reference may be made to de Geer (**1909**), or Nathorst (**1910**).

[2] This conclusion is also advocated by de Geer in his recent important paper (**1912**).

one series trends approximately east and west, though varying from east-south-east and west-north-west to east-north-east to west-south-west. The members of the second series trend approximately north and south, though varying from north-north-west and south-south-east to east-north-east and west-south-west. Both series are parallel to the two main groups of faults that have fractured Spitsbergen, and all the main fiord-valleys were clearly formed in preglacial times.

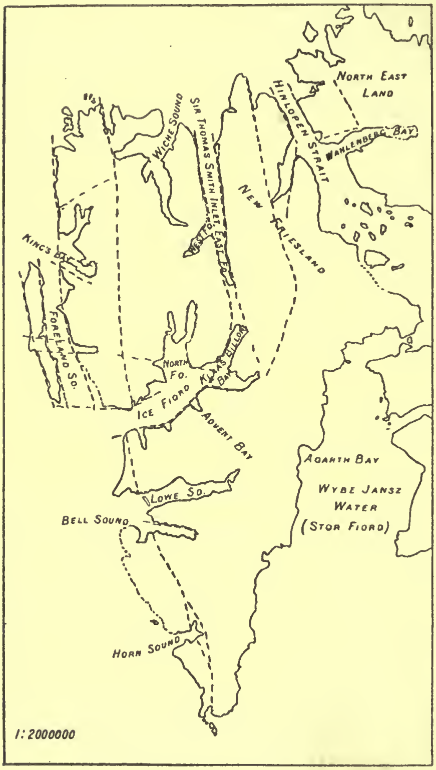

Fig. 44.—Sketch-map of the Chief Fracture-lines in Spitsbergen.
For Agarth Bay read Agardh Bay.

The connection between the great fractures in Spitsbergen and the formation of the fiords was recognised in 1872 by Hanns Höfer, the geologist with the Wilczek Arctic Expedition. In the section of his report on the structure of Spitsbergen, he pointed to the evidence of great dislocations near Horn Sund and Prince Charles Foreland; and he recognised the existence of fissures oblique to the great dislocations along the western coast and bounding the fiords and sounds. He considered the possibility of the glacial erosion of these fiords, and rejected the hypothesis. The Spitsbergen fiords, he said, " are in many cases preglacial, and have originated especially by means of dislocations." He recognised that glaciers could lengthen fiords, but that the conversion of bays or steep valleys into fiords could only be effected under especially favourable circumstances (Höfer, **1874**, p. 227).

The origin of Ice Fiord has been investigated in detail by Baron de Geer, who claims " that the whole of the great fiord, with its many large branches and its coastal plains, form a deeply sunken part of the earth's crust " (**1896**, p. 262).

Ice Sound is traversed by a series of faults, and is clearly due to them ; but, owing to its great width in proportion to its length, it is a sunk-land rather than a rift-valley.

During Sir Martin Conway's expedition most of our time was occupied in crossing the country from Ice Fiord to Agardh Bay on the eastern coast ; but we were able to examine some of the coasts of Ice Fiord, and a cruise along the western, northern, and north-eastern coasts in a small steamer gave us an opportunity to examine the chief coast-types. At Advent Bay, which we were able to search more carefully than elsewhere for traces of recent trough-faults, there seemed no clear proof that the bay or the valley at its head was due to earth-movements or was formed as a rift-valley by the subsidence of its floor.

There yet appears clear evidence of the formation of many Spitsbergen fiords by subsidence. It is, for example, quite obvious that the strip of Carboniferous rocks, which lies between the Archean plateau of New Friesland and the Old Red Sandstones to the west and forms the floor of the valley connecting Sir Thomas Smith's Inlet and Klaas Billen Bay, was dropped to its present position by trough-faults. At first the inlets were attributed to glacial erosion, a view confidently advanced by Baron Nordenskjöld (**1867**, p. 7, and **1876**, p. 17), who regarded the glacial denudation as having been in continuous operation since the close of the Miocene period. Baron de Geer in 1882 also accepted the glacial-erosion theory, but subsequently he recognised that the glacial action was of secondary importance, the valleys being due in the main to tectonic causes. Prof. Nathorst endorses the view that the fiords are due to cracks (*spalten*) and dislocations.

"For," he says, "in a multitude of places I have seen disturbances of the beds on the shores and in the valleys, although the beds in the adjacent mountains were quite undisturbed. Klaas Billen Bay is the only exception in which, in 1870, the appearances could be connected with thrusting from the adjacent mountains" (Nathorst, **1910**, p. 400).

Prof. von Drygalski (**1911**, p. 8) also accepts the importance of the rift-valleys and fracture-lines and remarks (p. 13) that in Klaas Billen Bay some of the features are due to tectonic movements which may be of post-glacial age.

The fiords of Spitsbergen are of the type usual around the Arctic Ocean and consist of comparatively isolated wide channels. They have high parallel walls except where subsidence or the denudation of areas of soft rock has converted them into basins with irregular fiard-like shores. The fiords intersect a plateau-land which shows abundant evidence of oscillation and fracture. The major valleys are of great antiquity, probably dating back to Miocene times or perhaps even earlier. The plan of their arrangement is that of a series of tectonic cracks and not of a glacial valley system. The view that they were of glacial formation, which was once generally accepted, has been abandoned with increasing knowledge of the geology of Spitsbergen.

6. The Straits and Fiords of Franz-Josef Land and Nova Zembla

Of the other Arctic islands to the north of Europe, Franz-Josef Land is traversed by a series of straits and inlets, some of which are named fiords. The general topography of this archipelago suggests that it is a fractured land. The details of the structure are, however, too little known for its evidence at present to affect the problem of the origin of fiords.

Nova Zembla, of which the coasts have been described by Spörer (**1867**, pp. 58, 59) has no well developed fiords, but it is indented by many short, narrow inlets which are most abundant on the western coast. Parts of the land have been cut off as islands by crescentic fractures such as Kostin Shere, near the south-western corner, and that of which Bear Bay, on the eastern coast of the northern island, is the southern outlet ; these curved fractures were probably due to the subsidences which formed the Barents Sea to the west and the Kara Sea to the east.

CHAPTER XIV

THE FIORDS OF AMERICA

A. THE GENERAL DISTRIBUTION OF AMERICAN FIORDS

All that creation's varying mass assumes
Of grand or lovely, here aspires and blooms;
Bold rise the mountains, rich the gardens glow,
Bright lakes expand, and conquering rivers flow.

MOORE.

THE coasts of America are richly indented with fiords, collected into six chief groups—Greenland, the Arctic Archipelago, Labrador, the maritime provinces of Canada and Maine, Alaska and British Columbia, and Patagonia. The most important on the mainland are along the Pacific Ocean, and they occur in Alaska and British Columbia in North America, and in Patagonia in South America. The intervening coast is indented by occasional great gulfs, such as the Gulf of California, and by some spacious harbours, as at San Francisco and Guayaquil; but the coast-line is almost free of fiords.

The Atlantic coast of America has well developed fiords in Labrador, and a series of inlets on the coast of Maine the true nature of which has been much disputed. Farther south, though the eastern coast of the United States is indented by a succession of great gulfs, there are no fiords.

The eastern coast of South America has some picturesque harbours along the Brazilian coast, including that for which Rio Janeiro is world-famous, and also some broad open bays; but there is nothing, even in far southern latitudes, similar to the crowded fiords of the Pacific coast of Patagonia.

The shore of the mainland of America facing the open Arctic Ocean has no fiords; but the off-lying Arctic Archipelago is broken up by fiord-straits, and its islands and Greenland are indented by numerous typical fiords.

The American fiords follow the general rule that they are most numerous on western coasts, and are absent from low latitudes. In North America the western fiords are almost restricted to Alaska and British Columbia; and their distribution even in those provinces is irregular. The coasts of Alaska facing the Bering Sea are indented by large bays such as Kotzebue and Norton Sounds, and deep tapering gulfs such as Kiukokwin Bay; but there are not along this coast any true fiords. On crossing the Alaska Peninsula into the northern Pacific the fiords and fiards become more conspicuous. Kadiak Island is indented on all sides by fiords. Shelikof Strait, between that island and the base of the Alaska Peninsula leads northward into Cook Inlet, which though wide and having a slightly tapering form, is essentially a fiord. The mountains beside it on the mainland rise to more than 10,000 ft., and on the other side the summits of the Kenai Peninsula reach the height of 7,200 ft. The inner part of Cook Inlet is 90 ft. deep, while, owing to a rise on the floor opposite East Foreland, there is apparently a threshold only 72 ft. deep.[1]

The eastern side of the Kenai Peninsula is fiord-indented, and the wide King William Sound, with an inner basin 1,800 ft. deeper than the sea at its mouth, is a fiord of the Bukken type (cf. p. 82). Then, for

[1] General Chart of Alaska: U.S. Coast and Geodetic Survey, 1890.

300 miles, the coast has long, even curves, and is quite free from fiords ; and their absence is the more striking as the land is capped by the greatest glacier in the world outside the Polar Regions. A high, ice-covered plateau, which bears the Bering and Malaspina Glaciers, faces the sea, and ends seaward with steep slopes and a long, regular shore-line. Then, passing farther to the south, the character of the coast suddenly changes. It becomes intensely irregular and indented, and is pierced by some of the longest fiords in the world, including the Lynn Canal. The fiords continue along the whole of the western coast of Canada.

Farther south in the United States the fiords almost disappear, though some minor fiords have been described near San Francisco. A recent elevation of the Californian shore-line is indicated by a raised line of caves and notches on the cliffs, and of caves worn out by the surf ; but this recent movement is attributed to local earthquake uplifts, and the last great emergence of the land on the western shores of the United States happened earlier than in the fiord-coast further to the north. There is no such widespread evidence of recent upraising of the land in the tropical coasts of America, as is indicated by the raised beaches of Alaska and British Columbia. In parts of Peru evidence of raised beaches, which have been reported to me by Mr. Beeby Thompson, indicate recent uplift ; but they are less developed than in Canada and Patagonia. The Pacific coasts of Central and most of South America are remarkably free from any inlets comparable with fiords. Even where, as in parts of Peru (see Fig. 10, p. 44), the grain of the country is oblique to the coast, the shoreline is straight.

In northern Chile the coast is similar. It is long and straight, and has no good harbours ; but the coasts of southern Chile and Patagonia are indented by one of the greatest fiord-systems of the world.

B. THE FIORDS OF GREENLAND

Amidst a tortuous labyrinth of seas,
That shine around the Arctic Cyclades;
Amidst a coast of dreariest continent,
In many a shapeless promontory rent;
O'er rocks, seas, islands, promontories spread,
The ice-blink rears its undulated head.

J. MONTGOMERY.

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1. General Distribution of the Fiords.—2. Geological Structure of Greenland.—3. Characteristics of the Fiords.—4. Depths of the Fiords.—5. Oscillations in Level of Greenland.—6. Origin of the Fiords: (*a*) Evidence of Glacial Erosion; (*b*) Limited Extent of Glacial Erosion; (*c*) Evidence of the Forms of the Fiords; (*d*) their Preglacial Age; (*e*) their Dependence on Joints or Diaclases.—7. Summary.

1. GENERAL DISTRIBUTION OF THE FIORDS

The island of Greenland is a great plateau of which the interior is covered with ice. The inland ice sheet is separated from the sea by an ice-free coastland which is intersected in most places by fiords. M. C. Engell (**1910**, p. 309) describes Greenland as having one of the best-developed of all systems of fiords, and Dr. Otto Nordenskjöld refers to it as the greatest fiord-region on earth (**1900**, p. 210), and to the eastern coast as including "perhaps the most magnificent system of fiords in the world" (**1908**, p. 158).

Though fiords occur along most parts of the Greenland coast, they vary greatly in character in accordance with the nature of the rocks they intersect. Where the rocks are hard the fiords are bounded by steep walls. In areas of softer sedimentary rocks the inlets widen out to basins; but if their tributary inlets pass into hard rocks they become true fiords. Where the coastland is low the fiords are replaced by fiards, which are frequent along the south-western coast.

The most typical fiord-system occurs in southern

Greenland. From Cape Farewell to Disco Bay on the western coast and to Kjoge Bay on the eastern coast the land is indented by narrow fiords which are approximately at right angles to the coast and are usually unbranched.

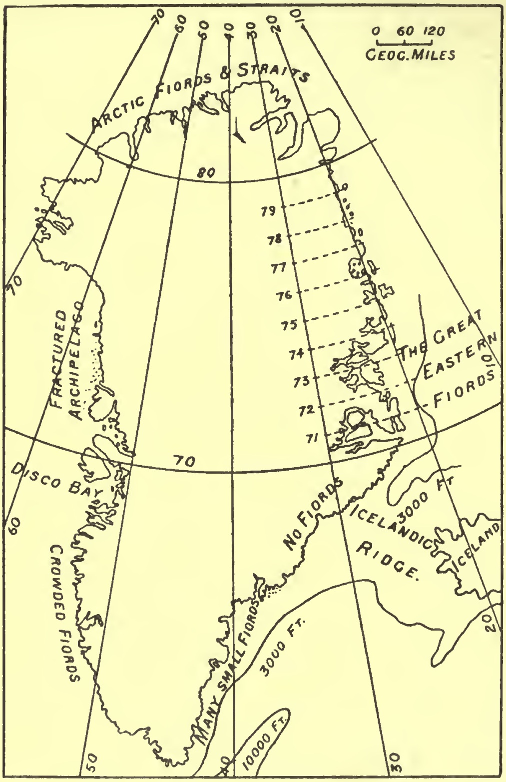


FIG. 45.—SKETCH-MAP OF GREENLAND.

Showing the distribution of Fiords; their absence on the eastern coast opposite the Icelandic Ridge; the occurrence of the great eastern fiords opposite those of Disco, between the sinking area of southern Greenland and the rising or stationary area of northern Greenland.

At Disco Bay the Archean rocks are covered by a thick series of sedimentary deposits and sheets of basalt, and this part of the coast is indented by wide open bays, with numerous short fiords on their margins. Umanak Bay, farther to the north, repeats the same characteristics; and then, from Upernivik to Cape Malm, follows a long extent of coast indented with short fiords and guarded by a complex series of islands. Still farther north the shore is comparatively even, and Melville Bay is a wide bight. Further north again along Smith Sound and Robeson Channel the inlets take on another form; they are less numerous, but much larger than the fiords of southern Greenland, and they often expand regularly seaward. Inglefield Gulf is the best known example. In the southern part of this district the fiords trend east and west, but to the north of the basin known as Kane Bay they trend from north-west to south-east.

Peary Land is nearly separated from the mainland of Greenland by two deep fiords, Denmark Fiord, at the north-eastern corner of Greenland, and Haagen Fiord, which recall some of the characteristics of Magellan Strait and the Otway Water. The two fiords, which, until the return of the Mikkelsen expedition, were regarded as the two ends of one strait, can be most easily explained as the two drowned ends of one tectonic valley.

The eastern coast of Greenland is less known than the western, in spite of the work of many famous expeditions. The southern part is intersected by many small, simple fiords, which lie at right angles to the coast. Farther north, near the Polar Circle, the land projects eastward as Christian IXth Land, which extends to 70° N. It consists of a basalt table-land, notched by many fiords which appear short, possibly because they are filled by ice. At 70° N. great fiords reappear in Scoresby Sound—named after the pioneer in the exploration of this coast. From 70° to 77° the land is intersected by several great fiords, including King Oskar Fiord and Kaiser Franz-Josef Fiord; they unite inland and form a network of channels through an archipelago of block-islands. Where the tributaries of these fiords intersect Archean rocks the walls are long and parallel; but where the banks consist of softer sediments the slopes are gentler and the valleys expand into basins. This section of the coast was explored by the adventurous "Second German North Polar Expedition" under Koldewey. A geological map of this region has been given by Dr. O. Nordenskjöld (**1908**, pl. xii.).

North of Dove Bay, from 77° to 79° N., is Lambert Land, the existence of which was reported by the Spitsbergen whalers in 1770 and 1775. This coast has been described by de Gerlache (**1906** and **1907**) as containing few fiords.

The eastern coast north of 79° was the last part of the country of which the geographical characteristics were determined. This region was first explored by the Danish Expedition of 1906–1908. König Friedrich VIII. Land projects north-eastward towards Spitsbergen and to the south are numerous fiords and straits which separate the great island of Germania Land from the mainland; these fiords become fewer but larger as the coast is followed northward to the Arctic fiords of northern Greenland.[1]

2. Geological Structure of Greenland

Greenland appears to consist geologically (so far as can be judged from the rocks exposed on the margin) of a great block of Archean rocks, which are mainly gneisses and schists. They are covered in places by sedimentary rocks including representatives of most of the geological systems. Near the coast there are wide sheets of basalt, which in eastern Greenland near Scoresby Sound cover an area of over 15,500 square miles, or an area equal to half that of Ireland. The fossil plants associated with these lavas show that they were erupted at the same time as those of Iceland and Scotland. They are lower Kainozoic and perhaps Eocene.

The old view of the geographical structure of Greenland represented it as saucer-shaped, with coastal mountains surrounding a central depression; but it appears to be more probably a high plateau which has been cut off

[1] Reference to the literature on eastern Greenland is not included, as a list of it has been given by O. Nordenskjöld, **1908**, pp. 156–7; for the northern part of the country reference should also be made to the recent work of J. P. Koch and O. Wegener, **1911**.

on all sides by the foundering of the adjacent areas along fractures. Thus, according to Dr. O. Nordenskjöld (**1908**, p. 280) the eastern coast lies along a great fracture ; and some features of the western coast suggest that its position has also been determined by features.

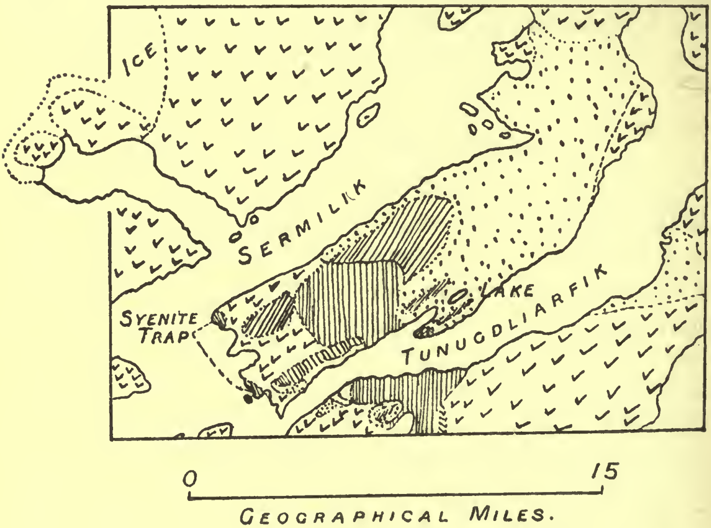
The coast-lands of Greenland are traversed by numerous faults and by conspicuous series of joints or diaclases, which have had a powerful influence upon the topography.

3. Characteristics of the Fiords

The fiords are best known in the south-western half of the western coast, which is the most accessible part of Greenland. The geographical and geological structure of this coast has been well described in a series of memoirs published in the *Meddelelser om Grönland.* Most of these south-western fiords are unbranched, and, as a rule, they are not united by cross-fiords. Some of them, according to Engell (**1910**, p. 309), are as straight as if they had been drawn with a ruler. The longest is Nagsugtok Fiord, which is ninety-four miles long, and the valley at its head continues for another twenty-five miles till it ends at a glacier. The width of the fiord is nearly two miles, and the country beside it rises to the height of 2,000 ft., though much is lower. It has a flat floor covered by drifts, and, according to the soundings by Jensen, has a maximum depth of 1,640 ft.

As an example of the fiords at the extreme southern end of Greenland, reference may be made to those around Julianehaab in lat. 61°. They have been described by Steenstrup (**1881**), who refers to their striking general parallelism and the tendency of their branches to occur at right angles ; they sometimes bifurcate seaward, forming triangular peninsulas or islands. Steenstrup especially refers to the peninsula between Sermilik Fiord and Tunugdliarfik as showing that the shape of the land-blocks is not directly dependent on the geological structure (Fig. 46)..

The fiords of the west coast from 64° to 67° have been described by J. A. D. Jensen (**1889**, p. 310). Where the coast consists of gneiss the land is generally low, as the variety found in that district is easily worn



Red Sandstone.
Sodalith Syenite.
Syenite.
"Trap."
Granite.

FIG. 46.—GEOLOGICAL MAP OF PARTS OF THE SERMILIK AND TUNUGDLIARFIK FIORDS IN THE JULIANEHAAB DISTRICT.

Showing the independence of the fiords of the older geological structure.

down by weathering. Jensen refers to the striking parallelism of the fiord-system in this part of the coast, although the fiords are developed on many different plans. Thus Kangerd-lugsuak, or Sudre Strömfjord, is a long, simple, nearly straight fiord about 110 miles long, with an average width, judged from Jensen's map, of a little over 1½ miles.

The next important fiord to the south—Evighedsfjord

—has the same trend near its mouth, but inland it makes a series of angular turns and gives off many straight branches ; it has the same type of branching as the Sogne Fiord of Norway. Natsito, in the same district, represents the cruciform arrangement (Fig. 47).

The western coast from 68° to 70° N. is especially well known, as it includes Disco Island. This district has been often described, as in a memoir by R. R. J. Hammer (**1889**),[1] who described, to the east of Disco Island, an arrangement of fiords and lakes which cannot be easily explained as initiated by glacial erosion; they might well be due to the enlargement by glaciers of pre-existing rift-valleys.

FIG. 47.—THE FIORDS AROUND GODTHAAB.
With the cruciform fiord of Natsito.

A geological map of Disco Island is included in a memoir by Steenstrup (**1883**), dealing with the coast from 69° 10′ to 72° 35′ N. The most conspicuous geographical lines are seen along the fiord-strait of Vaigat[2] between Disco Island and the Nugsuak Peninsula. The glaciation of Umanak Fiord on the northern side of the Nugsuak Peninsula has been discussed by Prof. G. H. Barton (**1897**, pp. 236 and 240).

[1] The glacial geology of Disco Island has been described by Chamberlin, **1894**.

[2] A geological map of this strait is given in Steenstrup, **1874**, pl. vii.

The trend of that and of other peninsulas, of the Umanak Fiord to the north of Nugsuak, and of many of the islands and lakes, is approximately from west-north-west to east-south-east. In the northern districts especially there are some conspicuous lines from north to south; but they have a tendency to curve westward at their southern ends. Thus Umiarfik Fiord, which starts on a north and south line, bends till its outlet trends to west-north-west, and the long Svartenhuks peninsula, the main axis of which runs north and south, is also notched by short fiords with the west-north-west trend.

The fiord-valleys have not the trend that would be expected in valleys due to glacial erosion, as they often bifurcate seaward, leaving islands like deltas between the branches of the fiords. But, unlike deltas, these islands are high rocky masses. Though there are structures in the map which suggest faults, the plan of the fiords is not always to be explained by simple faulting. According to Steenstrup (**1883**, p. 219), Vaigat Strait was caused by subsidence; it is a drowned rift-valley.

The explanation of other fiords in this district is suggested by sketches given by Steenstrup (**1883**, pp. 193, 195) of the southern side of the island of Storö, and of the coast of Umanak Fiord; they show that the conspicuous foliation of the gneiss, even when bent into a trough, as in the latter (see Fig. 80A, p. 458), is cut across by parallel vertical jointing (" Klövning "), which has probably determined the position of the valleys in the district.

The archipelago near Egesminde on the southern side of Disco Bay is known from the investigations of Petersen and Pjetursson (**1898**); the islands vary in height from a little over 100 to 920 ft.; most of them are low and the scenery is of the fiard type. Nordre Strömfjord, or Nagsugtok, represents the type of fiord on this part of the mainland which is much branched; and some of the branches nearly convert blocks of land into islands.

The western fiords extend farther north past Upernivik, which has been mapped and described by Ryder (**1889**). The intersecting fiords here break up the coast into an archipelago of angular block-islands (Fig. 48); many of the fiords would have been transverse to the flow of the ice from the Greenland ice-cap toward the sea. Farther north the fiords cease round the long, even shores of Melville Bay.

Greenland, as a whole, is buried under one vast sheet of ice which in some places was once more extensive than at present. Evidence has, however, been adduced to show that in many localities the ice is now at its maximum extension. There have been recent oscillations in level, and, owing to them, the ice-margin has varied locally; but observers in many parts of Greenland have described mountains and districts which show no sign of having been glaciated. Kane proved this fact for part of the North Greenland coast (**1861**, pp. 131–2). Thus, in south-western Greenland, Jensen (**1889**, p. 316) described peaks near Evighedsfjord (66° N.) as bold and non-glaciated. Profs. Chamberlin and Salisbury (*e.g.*, **1895**, pp. 875–8 and in other memoirs) have also inferred, from the serrate peaks which they saw at 64½° and around Inglefield Gulf, that the ice in various places in western Greenland is now at its maximum.

According to Chamberlin (**1895**, p. 219) of the one thousand miles of ice-free coast which he examined in western Greenland one half has never been glaciated; and he concludes: "The inference seems unavoidable that the ice of Greenland, on its western side at least, has never advanced very greatly beyond its present border in recent geologic times."[1]

Prof. G. H. Barton, on the other hand, maintained,

[1] Sir Henry Howorth has called attention to the weighty biological evidence in favour of this conclusion (**1905**, vol. ii. pp. 488–91).

FIG. 48 —THE FRACTURED WESTERN COAST OF GREENLAND (AFTER RYDER).

North of 72½° N.

two years later, that the ice-sheet of Greenland was once much more extensive, and flowed out so far into Baffin Bay and Davis Strait that it possibly coalesced with the ice-sheets of Labrador and Baffin Land (Barton, **1897**, p. 244). He attributes the jagged aspect of the peaks which have been regarded as unglaciated to the action of subsequent frost and atmospheric erosion (pp. 237–40).

O. Nordenskjöld (**1908**, pp. 227, 228) has advanced evidence which supports Chamberlin's view, for he shows that parts of eastern Greenland north of 70° along the Liverpool coast and Jameson Land were never ice-covered.

The non-glaciated aspect of many peaks and areas in Greenland and elsewhere has been attributed to shattering by frost after the retreat of the ice; and no doubt rocks weather very quickly on the edge of a sheet of ice. This explanation is, however, not altogether satisfactory; the line of division between the areas showing glaciated and non-glaciated features is often so sharp that it appears difficult to believe that both can have been glaciated in the same glacial period. The explanation that the difference in appearance is due to post-glacial weathering would appear to carry the admission that atmospheric denudation is much more effective than glacial erosion, and that the ice acted as a protective covering to the rocks beneath it.

The evidence is, however, still inadequate to determine the interesting problems whether the Greenland ice-sheet is now at its maximum, or whether it may not be even still increasing.

4. Depths of the Fiords

The depths of the Greenland fiords are still imperfectly known. Jensen sounded many on the western coast, and showed that the variations in depth along Nagsugtok Fiord, going eastward up the fiord, are 1,124, 971, 1,335, 1,624, and 764 ft. (**1881**, p. 136). He has also shown that, of two small fiords near Godthaab, Fiske Fiord, which is 28 miles long by 1 mile broad, has a depth near its mouth of 866 ft., and becomes shallower inland to 279 ft., then deepens again to 1,100 ft., and shallows to 135 ft. at the inner end. The Sermilik Fiord, which is in 63½° N. and is 12 miles long by 2 broad, has, on the other hand, a more regular floor; the four depths quoted vary from 403 to 420 ft. According to Engell (**1910**, p. 311), the Franz-Josef and König Oskar Fiords have a maximum depth of 2,510 ft., and shallow to 510 ft. at the mouth. Engell's own soundings in Tasiussak Fiord and in Torsukatak Fiord, 70° N., found that in the latter the maximum depth is 2,428 ft. and the fiord shallows towards its mouth to 1,887 ft. or perhaps less (**1910**, p. 311, pl. 54). This fiord has a second outlet through Ikarasak Fiord, where, according to Engell's chart, the depth is greatest (1,624 ft.) at the mouth. According to Engell (**1910**, p. 312), the maximum depth hitherto discovered in the Greenland fiords is 3,281 ft.; it was obtained by Ryder (**1889**, pl. xxi.) in the Upernivik Fiord, which is 28 miles long by 4½ miles wide.

The foregoing depths show that many of the Greenland fiords are shallower at their mouths than within, but so many of them have no thresholds that Dr. O. Nordenskjöld (**1908**, pp. 243, 272) has remarked that it may not be correct to regard them as typical fiords. There is nothing to show that in many cases the shoaling at the mouth of the fiord is due to any other cause than banks of drift.

5. Oscillations in Level of Greenland

Greenland has certainly undergone great oscillations in level during recent times. Evidence of the uplift is unmistakable on both the eastern and western coasts. Thus Hammer (**1889**, p. 305) has referred to evidence of an uplift of 100 ft. in the Disco district. Jensen (**1889**, p. 315) has quoted similar evidence from Evighedsfjord. Pjetursson (**1898**, p. 342) has proved an uplift of 354 ft. at Egedesminde south of Disco. Dr. Nordenskjöld (**1908**, p. 255), in Jameson Land on the western coast, found drift-wood at heights which imply an elevation of 1,000 to 1,300 ft.

The evidence for subsidence is equally widespread. The fiords themselves, as drowned valleys, imply submergence by the sea. More precise evidence is given by Steenstrup (**1883**, pp. 237, 238), for the Umanaks district, and by Pjetursson (**1898**, pp. 343–7) in one section of his memoir. He records that a ringbolt, used for tying up boats at Ritenbenk, sank nearly eight inches a year between 1880 and 1897, that ringbolts in the same district have been completely submerged, and old buildings have had to be removed or they would have been invaded by the rising sea.

6. Origin of the Fiords

The origin of the Greenland fiords has been long discussed. The inland ice-sheet gives rise to many glaciers that flow to the sea through valleys which are the continuation of fiords. Hence some observers have hastily concluded that the glaciers must have made the valleys through which they discharge.

(*a*) *Evidence of Glacial Erosion.*—It is true that the valleys have no doubt been moulded by the ice that passed down them. They have probably been straightened, their walls flattened, and the spurs worn away. The illustrations of coast-types on both sides of Greenland show the characteristic features of ice-smoothed walls.[1]

[1] See, for example, O. Nordenskjöld (**1908**, p. 251 and pl. xiv.), K. J. V. Steenstrup for the faceted spurs on Svartenhuks Peninsula (**1883**, pl. vii. fig. 3).

Hence the glacial origin of the fiords has been warmly maintained, as by Robert Brown (**1871**) in a controversy with Tayler and Murchison. This view has been frequently reaffirmed, as by O. Nordenskjöld (**1908**, p. 243) for the fiords on the western coast: "On the other hand," he writes, "most fjords are true basins, and must have originated from the direct erosion of moving ice, be it with or without discharge of loose material." Engell (**1910**, p. 313) in rejecting the view that the valleys were formed by river-erosion, says that all Greenland geologists are convinced that they were eroded by ice.

(*b*) *Limited Extent of Glacial Erosion.*—There is, on the other hand, a great weight of authority on behalf of the view that fiords are due either directly or indirectly to tectonic causes. It is recognised that in many places the effects of glacial erosion have been slight. Thus Chamberlin (**1895**, pp. 207–10) pointed out that even the steep glaciers on Northumberland Island in Inglefield Gulf are creeping seaward over moraine matter of their own deposition, although in such a place the ice would have especially great excavating power. Tayler (**1870**, p. 157) had previously remarked that the glacier north of Frederikshaab has made no fiord as it has been even unable to clear away the loose debris from its path.

Fairchild has referred to the literature on the glacial geology of Greenland, and claims that all the geologists who have visited the country agree that the amount of glacial erosion there has been very small. "It will not be necessary," he says (**1905**, p. 34), "to refer at length to the literature, as fortunately there is no essential divergence of opinion over the fact of slight ice-erosion."

(*c*) *Evidence of the Forms of the Fiords.*—It has often been observed that the plan of the fiords is inconsistent with their glacial origin. Thus Tayler (**1870**, p. 158), who had lived for many years in the neighbourhood of Frederikshaab as an official at the famous cryolite mine, gave a diagram of the second fiord south of Arksut, and referred to its shape as quite inexplicable on the supposition that it was of glacial origin.

Along the western coast Jensen (**1889**, pl. x.) shows that Godthaab is on a sub-peninsula nearly isolated by a simple, singly bent fiord; this valley could hardly have been cut by ice, because there would have been no collecting ground for an independent glacier; and there would appear no reason why a branch from the main glacier should have followed such a course, unless there had been an earlier depression or line of rotten rock.

Hammer (**1889**), as already quoted, has shown that the plan of the fiord-valleys near Disco, with the T-shaped form of Atasund and Kangerdluarsk, cannot be explained as initiated by glacial erosion, and that view has been supported by the passages from Steenstrup summarised on page 253. The cross-fiords parallel to the coast near Upernivik are equally inexplicable by glacier action (Ryder, **1889**).

Otto Nordenskjöld, an advocate of the glacial-erosion theory, has observed that the directions of the connecting branches of Scoresby Sound, such as Röde Fiord and Rype Fiord, and other longitudinal channels, show that they cannot have been exclusively formed by ice-erosion (**1908**, p. 272).

(*d*) *Their Preglacial Age.*—The most fatal objection to the glacial origin of the fiords is the preglacial age of their valleys. The term "preglacial" must have a different meaning in reference to a land in so high a latitude as Greenland from that in connection with the British Isles. If Greenland had maintained its present level for a long period, its glaciation would have begun far earlier than that of north-western Europe. The occurrence, however, of driftless areas on the border of the Greenland ice-sheet throws doubt on its antiquity. A definite limit to the glaciation of Greenland is given by the fossil-leaf beds found in the middle or lower Kainozoic rocks of the country. When these plants were growing the climate was milder than it is at present, although the change of climate which they indicate may have been often considerably over-estimated. It must, however, be recognised that in Greenland glaciers probably existed much earlier than in the British area, so that glacial erosion has been in operation for a much longer time.

The comparatively limited geological knowledge of Greenland renders the evidence of the age of its fiords less complete than that from more accessible lands. Notwithstanding, there is a strong weight of opinion in favour of the preglacial origin of the fiord-valleys. Tayler (**1870**, p. 158) declared: "I maintain that the fiords were in existence prior to their invasion by glaciers." His opponent, Robert Brown, admitted that the fiord-valleys were in existence before the ice entered them; but Brown claimed that it was the glaciers which deepened the valleys into fiords.

Dr. Otto Nordenskjöld (**1908**, pp. 281, 282) has recognised the preglacial origin of the valleys in north-eastern Greenland as some of the valleys were initiated before the eruption of the basalts; their formation may have begun even in Eocene times. According to Kornerup (**1881**, p. 244)—"It is, then, very probable that the principal existing lines of relief in the land of Greenland had already been traced before the water and ice had commenced their work of erosion."

(*e*) *The Dependence of the Fiords on Joints, or Diaclases.*—The plan of the fiord-valleys appears to have been determined by tectonic causes. As remarked on p. 253, the outline of Greenland has been determined by marginal fractures, from which clefts have run inland, either in simple lines at right angles to the coast or as a network of intersecting cracks. Faults are numerous around the Greenland coast, and in many cases they coincide with the fiords. Thus, Hurry Inlet has been shown by Nordenskjöld (**1908**, p. 281) to lie along a fault, as proved by the presence of friction-breccias. Steenstrup has referred to the influence of the vertical jointing in determining the position of fiord-valleys near Disco. Pjetursson [1] shows that the forms of the land around Egedesminde have been determined by faults, and that some of the valleys there are sunken belts of land. Engell, though doubtful whether the valleys are due to dislocations, recognises that the joint (*kluft*) systems have had a great influence in guiding glacial erosion (**1910**, p. 313); and he explains the frequent parallelism of the fiords as due to the parallelism of the joints. Watson (**1899**, p. 657) refers to the lakes and valleys of the Nugsuak Peninsula as determined by joint-planes, basins being worn out where two joint-planes intersect.

The classical memoir demonstrating the influence in Greenland of joints and other fissures in rocks upon the general topography and on the fiord-valleys is that by Kornerup (**1881**, pp. 162–81, 234–44). He described the area around Holstenborg from 67° to 68° 15′ N. He showed that the topography is dominated by parallel lines which may be recognised on the straits, islands, fiords, and bays, and that these lines are due to master-joints known as diaclases (*vide* p. 392). He says that the relief of the country, alike in its principal features and in its details, is determined by the diaclases. The shapes of the mountains are controlled by two systems of parallel diaclases. The members of one series are vertical, and trend 22° east of north. The other series is inclined 40° south-west, and trends 58° east of north. The influence of these diaclases on the outlines of the coast is well shown in Kornerup's sketch of the coast

[1] *E.g.* at Kronprinsens Island. Pjetursson, **1898**, p. 289

near Holstenborg (**1881**, pl. viii.). The lines are parallel, the apparent convergence in the illustration being due to perspective (Fig. 49).

The direction of the diaclases, he says, remains invariable for astonishingly long distances, but when

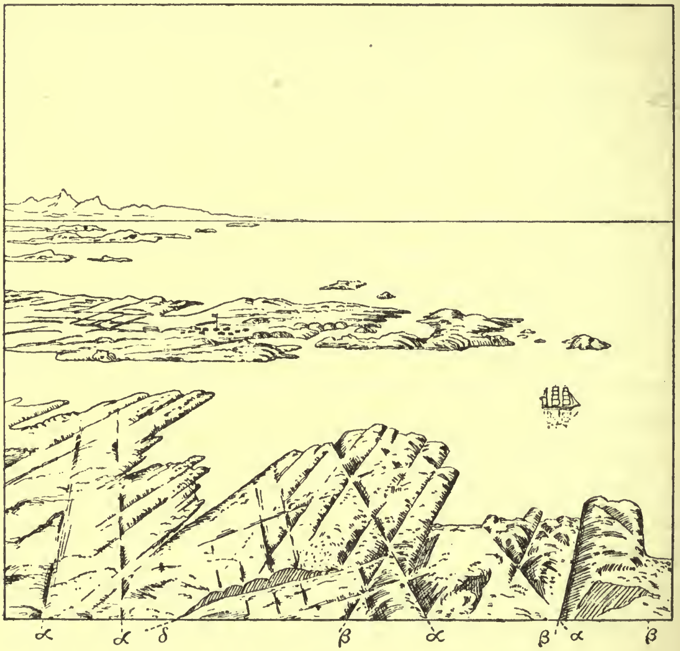


FIG. 49.—THE COAST NEAR HOLSTENBORG, S.W. GREENLAND.
After a sketch by Kornerup, showing the dependence of the coast on the joints.

traced across the country they may gradually deviate, owing to the influence of the foliation in the rocks. He also attributed to the diaclases some of the cirques and smooth faces of the mountains. He insists that the diaclases have been the dominant influence in determining the relief of the country. The ice and the structure of the underlying rocks have been only secondary influences. Kornerup remarks that it is natural to suspect that the fiords would be due to the parallel structure of the gneisses ; but, he says :

"This is not the case. On the contrary, in some localities there is no direct relation between the stratification of the gneiss and the direction of the fiords, which may suddenly change without any sensible variation in the layers of gneiss ; while, moreover, the direction of the foliation in the gneiss is in general oblique to that of the fiords, and is rarely parallel to it. Reciprocally, in other localities the direction of the gneiss varies greatly, without that of the fiords undergoing any change" (Kornerup, **1881**, p. 242).

The work of the ice, he says (**1881**, p. 244), consisted in detaching, shattering, and carrying away the rock-masses split off by the diaclases ; and he insists that the topography of mountains, valleys, fiords, lakes, and islands have all been fundamentally determined by the system of diaclases. He concludes that the function of ice is to round and to polish, and hardly to erode at all.

Von Drygalski (**1893**) has shown that the essential character of the valley which he selected for detailed description as typical of the fiord-valleys of Greenland, was due to denudation along pre-existing rifts or joints ("klufte") in the rocks. This valley is a branch from the Sermitdlet Fiord ; it is 3½ miles long and three-fifths of a mile wide ; it is trough-shaped, and has on its floor three lake-basins, of which the edges are only formed in part by rocks (Drygalski, **1893**, p. 50). Owing to its trough form and undulating floor, von Drygalski points out that the valley would, if submerged, form a typical fiord.

In discussing the origin of this valley von Drygalski (**1893**, pp. 52, 53) rejects the view that it can have been cut out by rivers, for it is unlike the river-valleys in the same district.[1] He dismisses the "spalten" theory, and attributes the valley to the removal by ice of the decomposed material lying along a series of joints. He regards the trough shape as evidence of the power of ice to clear out valleys. Hence he regards this typical fiord-valley as due to denudation acting along planes of weakness which were caused by movements in the earth's crust.

7. Summary

The Greenland fiords may therefore be described as a series of drowned valleys, which occur along the fractured border of a plateau. Many of the valleys are arranged as networks of cracks, and others are parallel to the coast with directions showing that they can hardly have been formed by glaciers, which would have flowed from the interior seaward. Neither are they simply river-cut valleys, from which they differ, amongst other respects, in having their branches divergent seaward instead of convergent like the tributaries of a river-system. Numerous observers, following Kornerup, have shown that the positions of the valleys are due to dislocations and disruptions; bands of rock were thereby weakened, and were easily removed by denudation. The fiord-valleys are preglacial in age. Hence as Tayler (**1870**, p. 156) remarked, if the theory of the glacial origin of fiords means that glaciers have caused "fiords to be where none were before—glacier the cause, fiord the effect"—then the theory is inadequate to explain the distribution or character of the Greenland fiords.

[1] He uses the term (p. 53) "ausraumender," which implies rather the sweeping out of a valley than primary excavation.

C. THE ARCTIC ARCHIPELAGO

Lift—lift, ye mists, from off the silent coast,
    Folded in sunless winter's chill embrace,

. . . . .

But Northern streamers flare the long night through
    Over the cliffs stupendous, fraught with peril,
Of icebergs tinted with a ghostly hue
    Of amethyst and beryl.

HOOD.

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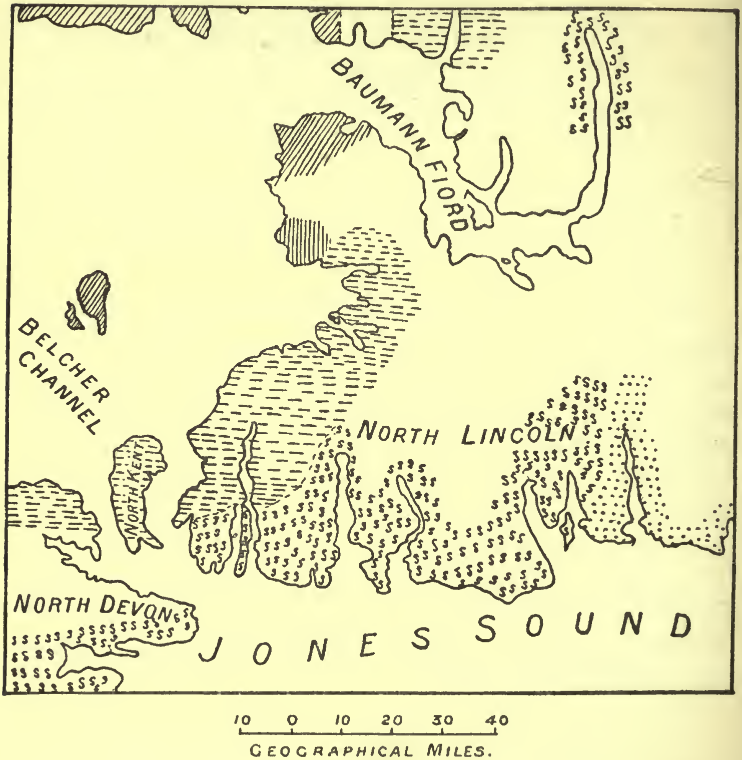
1. The Dominant Geographical Lines.—2. Geological Structure.—3. Tectonic Origin of the Channels.—4. The Fiords of Baffin Land.—5. Glacial Geology and Preglacial Age of the Fiords.—6. The Nature of the Fiords and Channels.

The Arctic Archipelago consists of a group of large islands situated to the north of Canada and the west of Greenland. It includes sixteen large and many small islands, while the Melville, Boothia, Adelaide, and Kemp Peninsulas, which project northward from the mainland of North America, are geographically homologous, as a slight further subsidence would convert them into islands. The arms of the sea which separate the islands are sometimes wide basins, such as Fox Channel between Baffin Land and the mainland, and Melville Sound, a nearly closed basin in the western part of the Archipelago.

1. THE DOMINANT GEOGRAPHICAL LINES

The typical channels, however, are long narrow straits, whose shores are straight except where the land is low and a submergence of the area has rendered the coast irregular in outline. The channels show a remarkable parallelism, they intersect at regular angles, and their directions are similar to those of the prominent geographical features of the adjacent lands. Thus the westward projection of northern Greenland, which forms the northern shore of Melville Bay, is continued by Jones Sound to the north of the island of North Devon; and this line continues along the northern boundary of the Parry Islands. To the south of this



Mesozoic.
Carboniferous.
Devonian.
Silurian-Cambrian.
Archean.

FIG. 50.—THE GEOLOGY OF THE SOUTH-WESTERN PART OF ELLESMERE LAND.

Showing its parallel inlets and geological structure.

line and concentric with it are Lancaster Sound, Barrow Strait, and Banks Strait. Still farther south is the less regular line of straits which separate the Arctic Archipelago from the mainland of North America.

These three series of channels trending east and west are connected by others going north and south. The islands are indented by fiord-like inlets which run inland at right angles to the coasts. Thus Isachsen's chart of the inlets on the northern side of Jones Sound includes eight north-and-south channels in a length of one hundred miles, and the arrangement of these inlets is independent of either the geological structure of the land or the natural arrangement of the drainage. They do not correspond with the arrangement of river-cut or glacier-cut valleys, and are only explicable by coincidence with a series of parallel fissures (Fig. 50).

The geographical features of the archipelago are determined by two main dominant lines. In the central area the chief directions are from east to west. In the south-eastern part the main lines run from north-west to south-east, as in Baffin Land, the north-eastern coast of which is parallel to the north-eastern coast of Banks Land, of Prince Albert Land, and other less extensive coast-lines. Both the east to west and north-west to south-east coasts have branches, straits, or fiords, at right angles. There is nothing to explain why the local ice should have worn out channels whose directions coincide with the greater geographical lines in Greenland and North America. Hence any share which the ice may have taken in moulding the topography of the archipelago has no doubt been controlled by preglacial features, which were due directly to earth-movements.

2. Geological Structure

Geologically the Arctic Archipelago consists mainly of Palæozoic rocks.[1] Baffin Land, eastern Ellesmere

[1] A geological map of the archipelago and a summary of its geology was published by G. M. Dawson, **1886**. The geology of western Ellesmere Land and Heiberg Land is known from the work of Dr. Schlei (**1904**).

Land, and eastern North Devon consist of Archean rocks, and the Archean axis of the Boothia Peninsula continues northward through the islands to Barrow Strait. The south-western islands consist mainly of Silurian and Devonian rocks; a band of them continues northward through North Devon and western Ellesmere Land into Grinnell Land. The north-western members of the archipelago consist of Carboniferous rocks, including some coal, and they trend from Banks Land through north-western Heiberg Land to the west of Ellesmere Land into Grinnell Land.

Dr. Schlei (1904) found Mesozoic rocks in western Ellesmere Land and the adjacent islands. The only other stratified rocks are Kainozoic deposits containing plant-beds of the same age as those found in Greenland, Spitsbergen, and Iceland.

The trend of the rock series shows no definite relation to the plan of the archipelago. Occasionally bays may be worn out along bands of softer rocks. Thus Frobisher Bay, in southern Baffin Land, lies along a belt of Silurian. Some of the channels, such as Jones Sound, are almost at right angles to the trend of the rocks, while others, such as the Prince of Wales Strait, are oblique to it. Hence the fractures of the archipelago appear essentially independent of its geological structure, though the fractures were locally deflected by the varying resistance of the rocks.

3. Tectonic Origin of the Channels

The whole aspect of the archipelago is that of a land which has been broken into islands by channels, of which one series lies along fractures concentric with the foundered basin of the Arctic Ocean and the others are radial fractures across the main east and west series.

The nature of these channels as straight-walled scarps is clearly represented by the sketches of some of the early investigators. Thus Beechey's sketch (in Parry, **1821**, pl. opp. p. 35) of the northern coasts of Barrow Strait east of Cape Fellfort represents the land as projecting in angular blocks with the walls as straight and the angles as sharp as in a pile of masonry. Finden's engraving of Back Inlet [1] shows that its sides cut across the irregularities of the adjacent land with the straightness of an artificial canal. The sketches show how these channels impressed the early explorers, and subsequent work has shown that their diagrammatic illustrations faithfully represent the essential geographical features. The channels may have been straightened and the walls flattened by glacial action; but their essential features appear to be due to the fracture of a once continuous land. The formation of the main channels by glacial erosion is most improbable; and, as the lesser straits and fiords differ only by their smaller size, they are probably equally independent of a glacial origin.

4. The Fiords of Baffin Land

The most accessible island of the Arctic Archipelago is Baffin Land, and its fiords may be selected for consideration as representative of those of the whole group. Baffin Land lies to the west of Greenland and to the north of Labrador. Its shores along Baffin Bay and Davis Strait are intersected by numerous fiords; its western coasts opposite the mainland of America and on Hudson Bay are more regular; for they extend in long curves around broad bays and blunt peninsulas.

The north-eastern coast has been described in some detail by Boas (**1885**), and his account and maps show that it repeats many of the features of the opposite coast of Greenland. The north-eastern coast of Baffin Land trends from north-west to south-east; it has

[1] In Franklin, **1828**, pl. 28.

the same trend as the south-eastern part of Greenland, some fiords and straits in western Greenland, the coast of Labrador and eastern Newfoundland, and the north-eastern shores of Banks Land and Prince Albert Land—the two south-western members of the Arctic Archipelago. The south-eastern coast of Baffin Land is broken up into three peninsulas by Cumberland Sound and Frobisher Bay.

Some of the most typical fiords are in Cumberland Peninsula, which lies between Cumberland Sound and Davis Strait. Boas's description shows that this peninsula originally consisted of one continuous plateau, which has been divided into three plateaus by two long, straight, narrow valleys described as "spalte," *i.e.* fissures due to splitting. These great valleys are parallel to the general trend of the indented south-eastern coast of the peninsula from Cape Mercy to Cape Walsingham. Behind this coast is the plateau of Saumia. Boas describes some of its summits as peaks and pinnacles, which give the country an Alpine aspect and indicate that this district was never completely overridden by ice. Saumia is bounded to the north-west by a narrow "cleft" valley, of which both ends are occupied by fiords; three lake-basins lie on the valley floor near the divide. To the north-west of this valley is a long, narrow plateau known as Kingnait. It is bounded on its north-western side by another long, straight-walled valley with a fiord at each end, both named Pangnirtung. Beyond this valley the land rises into the wide plateau of the Penny Highland.

These two valleys cross the Cumberland Peninsula approximately at right angles to the coasts; and it seems incredible that they could have been made by glacial action. Their arrangement and Boas's description of their characters indicate, that they are a series of clefts initiated by the earth-movements which broke up a once continuous plateau.

While the Cumberland Peninsula has been cut across from shore to shore by these tectonic valleys, some curved fractures have detached parts of the coast-land as islands or nearly severed them as peninsulas. Thus a long, curved valley strikes inland from Davis Strait through the fiord of Narpiang; it crosses a low short isthmus to the fiord of Maktartugjenak, and continues by the strait to the south of Kekertalukdjuak. This curved fracture has severed from the Penny Highland and Kingnait an extensive irregular peninsula and a number of islands.

Some of the land in this district is low, and in these places, as in the opposite coasts of Greenland, the inlets have the character of fiards.

The tectonic origin of the dominant lines in Baffin Land is suggested by the fact that the south-eastern coast of the Cumberland Peninsula is in line with the south-eastern shore of Disco Island on the opposite side of Davis Strait, and the north-eastern coast is parallel to the north-eastern shore of Disco Island and other important lines in the Disco area.

Further north, in north-eastern Baffin Land, the direction of the fiords and inlets is different. The lines no longer trend from north-east to south-west, for they are under the influence of the lines going from east to west, and from north to south; thus the north-eastern corner of Baffin Land has been cut off as Bylot Island by an L-shaped strait, from the base of which fiord-like inlets extend southward into the land.

5. Glacial Geology and Preglacial Age of the Fiords

The glacial geology of southern Baffin Land has been described by Tarr (1897), and according to him the hills were once entirely ice-covered, and now the whole country shows glaciated contours. Although the ice has retreated very recently, the effects of post-glacial denudation are already well marked. Tarr, however, clearly points out, in a series of passages, that the most striking features in the topography of the country date from preglacial times. He says, for example, "The preglacial topography, which still forms the most striking features of the present land-form, consists of valleys and hills which are mainly parallel to the strike of the rocks (about N. 10°–30° E., magnetic)" (Tarr, **1897**, p. 194).

That the valleys were not due to ice-erosion is shown by the fact that the ice flowed across them obliquely, so that they were unquestionably in existence before the ice entered them. "The valleys," he says, "extend diagonally to the direction of ice motion, and hence were not ground out by ice-erosion. They certainly represent irregularities of preglacial origin, which the ice-erosion has not been able to wear away."

Cumberland Sound Tarr described as presenting very nearly the same conditions

". . . though the details of the preglacial topography are perhaps even more perfectly preserved. The surface of the hills is extremely irregular. . . . Nothing in the topography indicated that the ice did not cover even the highest hills that could be seen. It was astonishing to find how little effect in smoothing the surface was accomplished by the ice-invasion of this land; but very nearly the same condition exists on those parts of the Greenland coast which were studied in detail" (Tarr, **1897**, p. 195).

Tarr, though once a most enthusiastic champion of glacial erosion, clearly recognised that in this district its effects were comparatively slight. He concluded that some of the small basins were scoured out by differential ice-erosion, but that many were certainly due to differential preglacial weathering" (**1897**, p. 195).

The ice may have removed decayed rock and deepened the depressions, but, as he remarked, the "ice-erosion would not in this case be the prime cause of the basin." Tarr's conclusions are apparently accepted by Professor G. H. Barton (**1897**, p. 242), who has also visited southern Baffin Land, and he noted that the glacial erosion there was much less than any he had seen in Greenland.

6. The Nature of the Fiords and Channels

Most of the Arctic Archipelago is still too little known geologically for use as a test-case of the origin of fiords and fiord-straits. This region may therefore be considered briefly. The formation of the channels through the archipelago by fissures is the view adopted in the recent contributions to the geology of the north-eastern part of the archipelago by Dr. Schlei, the geologist with the expedition in the *Fram* under Captain Sverdrup. In reference to the part of the archipelago visited, he says, "A system of fissures has again divided it into plateau-like areas" (Schlei, **1904**, vol. ii. p. 462). The origin of the fissures is probably connected with a great upheaval of which he found evidence to the extent of 600 ft. in Heureka Sound.

Glacial action in this region appears to have been comparatively unimportant. Schlei describes this part of the archipelago as containing numerous glaciers but no great sheet of "inland ice," and he insists that the glaciers have not been greater than they are at present either during or since the last great subsidence of the area; and that the lands which are now unglaciated have no glacial drifts upon them.

The available evidence, however, both as to the main and minor features, renders it most improbable that glacial erosion has played any serious part in the excavation of these channels. They are primarily of tectonic origin, and though undoubtedly enlarged by various agents of denudation, probably originated as rift-valleys in a formerly continuous land. The Arctic Archipelago represents, in fact, a northward extension of the Dominion of Canada which was shattered by an intersecting network of cracks formed in connection with the subsidence of the basin now occupied by the Arctic Ocean.

D. THE COAST OF LABRADOR

On the dismal shore
Of cold and pitiless Labrador.

—MONIE.

1. Labrador and its Indented Coast.—2. Geological Structure.—3. Glaciation.—4. Preglacial Age of the Valleys.—5. Nachvak Bay as an Example of the Fiords.—6. Unequal Uplift of the Coast.—7. Tidal Erosion of Gorges.—8. Summary.

1. LABRADOR AND ITS INDENTED COAST

The Atlantic coast of the mainland of America begins on the north with the peninsula of Labrador, a rugged, mountainous country 500,000 square miles in area. Its essential geographical structure is a worn plateau. "The peninsula of Labrador," says A. P. Low (**1897**, p. 21), "is a high, rolling plateau." The peninsula is said to include in the Torngats Mountains[1] the highest land along the Atlantic coast of America, excluding the mountains beside the Caribbean Sea. Its western coasts facing Hudson Bay and its southern coast along the Gulf of the St. Lawrence are even; but its north-

[1] According to Lieber (Daly, **1902**, p. 232), these mountains may be 10,000 ft. high; but Grenfell (**1911**, p. 415) could find among them no summit above 5,000 ft. high.

eastern coast is intersected by a series of inlets which Dr. W. T. Grenfell (**1911**, p. 408) has described as "her glorious fiords."

This indented coast is over 700 miles in direct length from Cape Chidley to Belle Isle, in the strait between Labrador and Newfoundland. The coast trends from north-north-west to south-south-east, in the northern part, and from north-west to south-east near the southern end. Its trend, according to Daly, is determined by the course of the mountain-system of which the Labrador plateau is a fragment. So indented is the coast with its fiords and "tickles"—the local name for the sea-ways between the islands—that, according to Dr. Grenfell (**1911**, p. 416), there is at least one harbour within every ten miles of coast from Belle Isle to Cape Chidley. According to Prof. Daly (**1909**, p. 57) there are "thirty or more larger fiords." The largest is navigable for 140 miles inland, and twelve of them for between thirty and fifty miles.

A map of Labrador in four sheets on the scale of twenty-five miles to an inch, containing all the geological information then available was issued by the Geological Survey of Canada in 1895, to accompany the report by A. P. Low (**1897**). This map shows the fiard-like nature of the coast in the south-eastern district between Hamilton Inlet and the Strait of Belle Isle. Daly's photograph (**1909**, pl. opp. p. 117) shows that the inlets around Hopedale are also fiards, but further north they pass gradually into fiords, which are best developed beyond 56° N.

The fiords along this coast trend in the northern area from east to west, as Nachvak Bay and Grenfell's Tickle, which separates Cape Chidley Island from the mainland. In the southern part of the coast the fiords, curving round with the changing trend of the coast, run inland to south-west or west-south-west; and Lake Melville, the inner part of Hamilton Inlet, the longest fiord in

Labrador, is in line with the long straight reach of the St. Lawrence that extends inland to Quebec.

2. Geological Structure

The general structure of Labrador has been determined by Packard,[1] Bell, and Low, who have shown that it is a dissected plateau. The geology of the fiord-coast has been described by Prof. R. A. Daly (**1902**, and in Grenfell, **1909**, pp. 81–139). The country consists of a foundation of crystalline Archean rocks, including granites, syenites, and gabbros. These igneous rocks are covered by sedimentary rocks including the Ramah Slates, the Domino Quartzite, and the Mugford Series, which is composed of slates, quartzites, sandstones, quartz-breccias, volcanic agglomerates, and sheets of igneous rocks. The sedimentary deposits rest on the Archean unconformably, but they are all regarded as pre-Cambrian in age. Daly (**1902**, p. 221) compares them with the Torridonian rocks of the Scottish Highlands, owing to their occurrence in plateau-like masses and their relation to the underlying rocks.

The Labrador plateau is, therefore, composed of some of the oldest known rocks, and the plateau is itself so old that its edge is extremely worn and ragged. From the Straits of Belle Isle for 500 miles northward to Cape Mugford, says Prof. Daly—

"Numerous fiords, ria-like bays, and a vast archipelago of outlying islands or skerries form a coastal fringe. The similarity of landscape is so great that Forbes's description of the coast of Norway on the route from Trondhjem to Bergen may be repeated for this portion of Labrador. A series of inlets penetrates 'in all directions a low, bare, rocky land, partly island, partly continent, nowhere rising but to a very small height above the sea,

[1] A bibliography of the earlier literature on Labrador is given by A. S. Packard, jun., *The Labrador Coast* (1891).

and so monotonous in character, and destitute of long reaches, or natural landmarks, as to seem to require an almost superhuman instinct for its pilotage'" (J. D. Forbes, *Norway and its Glaciers*, p. 104. Edinburgh, 1853). (Daly, **1902**, p. 210.)

3. Glaciation

Like Norway, Labrador has been intensely glaciated; but apparently the ice did not cover the highest peaks, for Dr. Grenfell describes the mountains around Ryan Bay, north of Nachvak Inlet, as very rugged in character. "The peaks," he says, "are bare and sheer; one, rising to the south-west, reminded me strongly of the Matterhorn." [1] Daly (**1909**, p. 102) also describes the mountains of this district as "truly Alpine in form." The ice was no doubt continuous across the lower country; but it does not appear to have made any fundamental change in its topography. "At the beginning of the Glacial Period," says Daly (**1909**, p. 114), "the Labrador Peninsula had essentially the main topographic features of the present time."

4. Preglacial Age of the Valleys

The valleys, therefore, are of preglacial age, a view also held by A. P. Low. According to him "the fiords appear to be valleys of denudation of very ancient origin"; and he refers to "their remote antiquity" (**1897**, p. 20).

5. Nachvak Bay as an Example of the Fiords

Nachvak Bay, which has been well described by Daly, may be taken as a typical Labrador fiord (Fig. 51). It is 25 miles long by 1½ miles wide, and the fiord-valley

[1] Grenfell, **1909**, p. 62, fig. 6; see also sketch, p. 60, for serrate ridge near Big Bay.

is continued inland by a wide, deep-glaciated vale. The walls of the fiord vary from 1,500 to 3,400 ft. in height, and, though they are nearly continuous, they are notched by a series of hanging valleys, and by other valleys the floors of which are below sea-level. The picturesque cascade of Korlortoaluk rushes from a hanging valley 750 ft. above sea-level, and, as the fiord is there 500 ft. deep, the discordance between the tributary and the main valley is 1,250 ft.

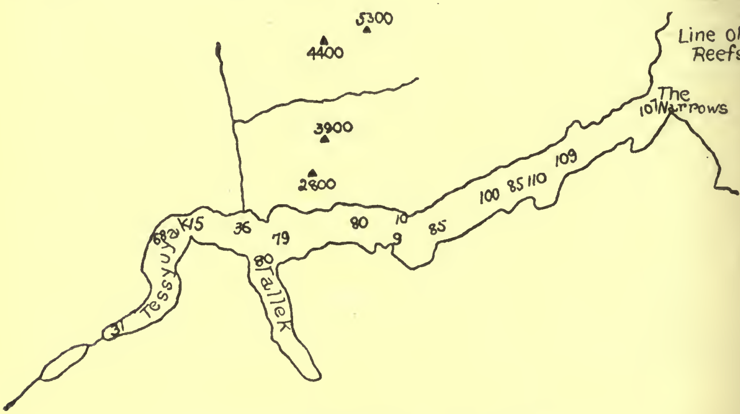


FIG. 51.—NACHVAK BAY (AFTER DALY).
Scale 7 miles to 1 inch; depths in fathoms; heights in ft.

6. UNEQUAL UPLIFT OF THE COAST

Daly took twenty-one soundings in the fiord, and found that undulations on its floor divide it into three basins separated by two thresholds; there is a third due to a line of reefs across the mouth. The innermost, or western basin, is 408 ft. deep, and it is bounded by a threshold 90 ft. deep. The central basin reaches the depth of 480 ft., and is separated from the outer basin by a threshold 96 ft. deep. The outer basin has a maximum depth of 660 ft., and is bounded seaward by a line of reefs. These basins have been attributed to unequal glacial corrosion of the valley floors; but they are probably due to unequal movements of the land.

The drowned valleys and fringe of islands suggest the recent subsidence of the coast, though Daly remarks that these sea-filled valleys may have been excavated by glaciers when the land was at its present level; the water may have been displaced by the ice which corroded the valley floors. There is, however, conspicuous evidence of a recent uplift (**1902**, pp. 252–66),

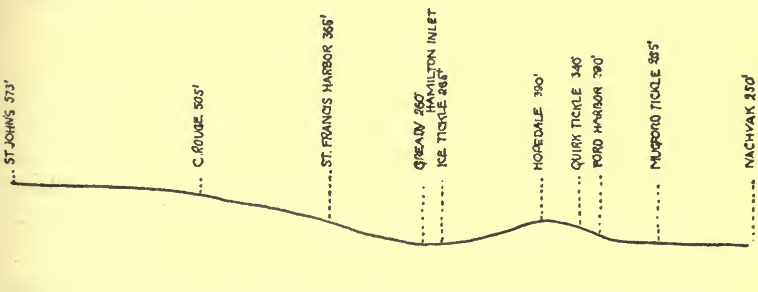


FIG. 52.—THE DIFFERENTIAL UPLIFT OF THE COAST OF LABRADOR (AFTER DALY).

Heights in ft.

which was different in amount in different localities. It ranges from 575 ft. at St. John's in Newfoundland to 250 ft. at Nachvak Bay. Daly has given an instructive diagram (Fig. 52) showing the varying amount of elevation along the coast. The valleys must have been warped by this unequal uplift and the rock-basins may therefore be the direct result of earth-movements.

This uplift is explained by Daly as an isostatic movement due to the removal of the load of ice from the plateau; hence it is probable that the valleys were drowned by a previous subsidence due to the weight of the ice; and, if so, the main fiord-valleys were preglacial.

During these unequal movements the rocks of Labrador must have been strained, fresh fractures were formed, and new movements took place along the old faults. Some of these disruptions may be indicated by such clefts as that on the mountain known by the name of "the Bishop's Mitre." According to Daly (**1909**, p. 108, Fig. 16) the mountain is indented by "a sharp notch about 500 ft. in depth—the uppermost part of a long ravine cleaving the mountain to its base at the shore two miles from the notch." Daly, describing the scenery of these fiords, felt what had been felt by many observers in other fiord-districts, when he referred to them as "these wonderful cleavages in the mountains" (**1909**, p. 55).

7. Tidal Erosion of Gorges

Some of the minor fiord-like chasms along the Labrador coast are excellent illustrations of the formation by marine erosion of miniature fiords. The coast in places consists of gneiss intersected by dykes of igneous rock. These dykes resist subaerial denudation better than the gneiss, but the surf wears them away more rapidly than the rock into which they have been ejected. Thus near the mission-house at Hopedale there is a chasm 300 yds. long, which has been worn out by the surf along a trap dyke.

8. Summary

Hence, the main fiords of Labrador, like those of Baffin Land, occupy valleys, worn by preglacial denudation in an ancient and faulted plateau, which has undergone unequal uplift and subsidence in recent geological times.

E. THE FIARDS OF THE EASTERN COASTS OF THE UNITED STATES AND CANADA

And this wild ruin of a once new shore
    Scooped by new waves to waves of solid rock
Dark-shelving—white-veined, as if marbled o'er
    By the fresh surf still trickling block by block!

GORDON HAKE.

1. THE FIARDS OF MAINE

Newfoundland, the maritime provinces of eastern Canada, and the adjacent part of the United States, have very irregular shore-lines; thus, according to Shaler (**1893**, p. 118) the length of the coast of Maine from headland to headland between the towns of Portland and Calais is a little over 200 miles; but the actual distance around the inlets and islands is more than ten times as great. The inlets are generally concordant with the grain of the country, though many of the smaller fiards and some of the straits are discordant. The grain of the country, however, was impressed on it by very ancient movements, to which the direction of the valleys is only indirectly due. The great changes in level which, according to some authorities, the whole region has recently undergone may have caused new fractures or reopened old lines of weakness.

The inlets range from broad, open gulfs, such as the Bay of Fundy, to intricately branched inlets such as Bras d'Or on Cape Breton, which Shaler calls a "beautiful fiord," with an aggregate coast-line of over a thousand miles (**1893**, p. 118). The shores of these inlets are extremely irregular, for the main bays are broken up into secondary bays by jagged peninsulas. The axes of these peninsulas generally trend from north to south;

but in some parts of the coast they incline to the east of north and the west of south. The parallelism of the inlets is shared by the islands, for, though their outlines are often very sinuous, they are usually long and narrow, and occur in continuous chains.

The adjacent country stands at a comparatively low level; some of the highest peaks are on the islands, and the inlets themselves are not deep. They are being filled by sediment, but the usual fiord-thresholds are irregularly developed. Shaler (**1893**, p. 115) indeed describes them as altogether absent; but his own chart (pl. xxv.) shows an occasional shallowing at the mouth of the inlets. Thus, whereas the inlet known as New Meadow River has a depth of 150 ft., the depth outside diminishes to 60 ft. Many of the larger inlets are the estuaries of considerable rivers.

These arms of the sea, therefore, differ from typical fiords owing to their irregularly indented shores, their expansion in width seaward, the frequent absence of thresholds, their shallowness, their service as river-estuaries, and the comparatively low level of the adjacent country. In these respects they agree with fiards and not fiords.

The inlets and the channels between the islands along this coast have, however, been accepted by some authorities as typical fiords. Thus Shaler, in his monograph on harbours, gives a chart of the coast near the New Meadow River as a typical representative of a fiord. According to him (**1893**, p. 161) the Bay of Fundy is "in general character a great fiord." A fiord-like nature has been claimed by Belt (**1864**, p. 463) for the bays in Nova Scotia.

Opinions have varied greatly as to the exact position of these inlets in relation to fiords and fiards. Penck (**1882**, p. 349) regarded them as undoubtedly fiords, and a proof that fiords cannot be limited to highlands, since these inlets occur in a low country. Similarly

Ratzel (**1880**, p. 394) claimed that great depth was not an essential feature of fiords, as those of Maine are shallow. Other authorities, however, owing to the low level of the adjacent lands, have classified them as fiards, or föhrden (Werth, **1909**). The balance of authority is in favour of regarding them as more nearly related to fiords than to fiards, a view adopted by Supan (**1911**, p. 802) and by Dinse (**1894**, pp. 210, 235), who remarks that they are the least typical fiords in the world, and are the first members of the chain leading to the fiards, föhrden, and the skerry-fringed coast of Finland. E. Richter (**1896**, p. 188) regards the coast of Maine as a weakly developed fiord-coast and intermediate between the fiord and schären, or skerry-fringed, types of coasts. O. Nordenskjöld also regards these inlets as an intermediate variety (**1900**, pp. 159, 184), though he finally classifies them as fiards (**1900**, p. 235).

According to the definitions given in Chapter III., these East American inlets are fiards.

2. Oscillation of the Land

There is evidence in this district of great oscillations in level in recent geological times, and, as is usual with fiards, the most important of the recent movements has been a subsidence. According to Upham,[1] the country was elevated to the height of 3,000 ft. at the beginning of the glacial period, and it was this high elevation of the land which caused the development of the glaciers in the district. During the uplift the rivers flowed south-eastward to the Atlantic, and carved out deep valleys which have since been drowned by a subsidence of over 3,000 ft. The last movement has been one of emergence of the land; for, though all the chief

[1] W. Upham (**1899**, pp. 80–82) and elsewhere. He infers, from the Hudson River trench, that the elevation near New York was 2,800 ft. (**1890**, p. 565).

features in the physiography of the coast are due to submergence, there are some raised beaches that prove a recent slight elevation. Thus Gulliver (**1899**, pp. 158, 167) has described the coast of Maine as a region with a young topography which has undergone depression, followed by elevation.

The evidence for the great uplift assumed by Upham is at least uncertain, but there is clear evidence of considerable oscillation in level. When the land stood at its greatest elevation the rivers carved out their present depressions, the directions of which were largely determined by previous fractures and joint-planes.

During the glaciation of the district the glaciers flowed down the valleys, removed all the decayed rock-matter, crossed and wore down the ridges between the valleys, and thus had a general levelling effect; but, as the decay of the rocks had probably affected a greater depth along the valley-floors than on the ridges, the ice doubtless deepened and enlarged the valleys.

3. The Fiord-valleys Preglacial

The East American fiards have, therefore, been attributed to glacial action. The glaciers, however, appear to have only moulded and not originated the fiard-valleys, which are preglacial; and in some cases their directions do not coincide with the course of the ice-flow.

The preglacial age of the valleys was accepted by Dana (**1873**, p. 199); and it was asserted by Shaler: "Thus" he says, "the principal fiords from New Jersey to Nova Scotia are manifestly old river-valleys which have been somewhat modified by the ice-streams which recently occupied their beds." And he adds that in the greater portion of New England the old stream-ways are still evident, with "shapes not greatly altered from their preglacial form" (Shaler, **1893**, p. 117). He repeats (p. 162) that most of the inlets between New Brunswick and New York are due to glacier-ice having deepened and widened pre-existing depressions.

The divergence between the direction of the fiards and the movement of the glacier-ice may be illustrated by reference to Mount Desert Island.

Mount Desert Island, one of the most instructive localities on the coast of Maine, has been described by Shaler (**1889**). The island consists mainly of hornblende-granite. It is crossed by the remains of an old mountain range, in whicn the highest summit rises

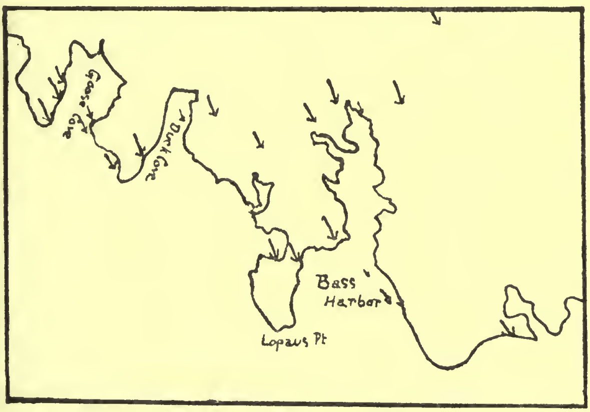


FIG. 53.—THE ICE-FLOW ACROSS MOUNT DESERT ISLAND (AFTER SHALER).
Showing its independence of the topography.

1,527 ft. above sea-level. The island was covered by ice from the mainland, where it flowed from 40° W. of north; but the current was deflected by the mountains on Mount Desert Island, and the ice flowed eastward and westward along the intervening strait (Shaler, **1889**, p. 1004). The ice-erosion modified the old topography, but the fiords and lake-basins were clearly preglacial. Thus, on the south-western corner of the island there are two small fiords known as Duck Cove and Goose Cove, and a jagged projecting peninsula which ends at Lopaus Point to the west of Bass Harbour. The glacial striæ there, according to Shaler's map (*op. cit.* pl. lxiv.; part of it is copied as Fig. 53), pass obliquely across these two coves and the peninsula; but in the outer part of Bass Harbour the striæ bend till they are parallel to the adjacent shore. Duck Cove and Goose Cove, though short, have the characteristic forms of the lake-basins and inlets of the island. Shaler explains the inlets and the lakes, such as the Long Pond and Seal Cove Pond, as a series of old valleys which trend north and south and are continued on the mainland. He objects to the view that they can be old river-valleys which have cut through the mountain-chain, because, as he truly says (Shaler, **1889**, p. 1006), "it is quite unreasonable to suppose that nine deep valleys could, by river-action, be cut transversely through a mountain-range only twelve miles long." And the fact that some of the lake-floors lie below sea-level he holds as further evidence against their formation by river-action. He explains the valleys as due to denudation along a series of north and south dykes, which vary in direction from north to north 20° W. These dykes are injected in the granite, and they facilitated the formation of the valleys by their ready decay. Their injection probably increased the jointing in the adjacent rocks (Shaler, **1889**, p. 1007).

The general character of the inlets of Maine and south-eastern Canada appear, then, to repeat the characters of the Swedish fiards, with which the country agrees in many respects, as in the age and character of its rocks and in its recent geological history.

4. Inlets South of Maine

Along the coast to the west of Cape Cod, in Massachusetts and the adjacent part of the state of Rhode Island, the shore is generally of the same type as that of Maine, but the inlets are smaller. The rapid deposition of the silt in these valleys in post-glacial times has obliterated the old fiords. The term "fiord" has been applied to these bays and to those in Long Island and on the opposite coast of Connecticut; but none of the existing inlets should be regarded as a fiord. The coast, however, in all probability once had numerous fiords, which have been destroyed by denudation and sedimentation. The deep gorge of the Hudson River has some of the characteristics of a fiord, but it differs from true fiords by its isolation and by the fact that it is the estuary of a great river. The Hudson Valley has itself been formed by fault-action, as has been shown, for example, by Hobbs. He has, moreover, shown that the valleys of the Harlem River, to the north-east of New York, and of the East River to the east of that city, are also fault-valleys, while many of the small valleys now used as the main streets of New York occur along a network of fractures (Hobbs, **1905**, p. 180, pl. xxxv.).

To the south of the Hudson River the shore of New Jersey has long, even curves and low shores, indented however, by the vast estuaries off Delaware Bay and Chesapeake Bay, which have been described by Shaler (**1893**, p. 176), no doubt accurately, as drowned valleys.

In Carolina there are somewhat similar bays; the chief are Albemarle Sound and Pimlico Sound, which are guarded by a long, low bar; but there are no inlets in that State, or farther to the south, which can be classed with fiords. The eastern coasts of the United States may, therefore, be described as having a series of fiards in Maine and Massachusetts, and the relics of a lost series of fiords in New York of which the Hudson River is the most striking.[1]

Though the coastal inlets of Maine and eastern Canada are now fiards rather than fiords, they were no doubt

[1] Supan (**1911**, p. 794) quotes Meinhold as giving an elaborate classification of the coast-types of the eastern coast of the United States. Meinhold's paper was published as a doctor's dissertation, and I have not obtained access to a copy.

fiords before the country had been worn down by denudation to its present low relief. This former fiord area is bounded to the south-west by the trough of the Hudson River at New York and on the north-west by the analogous trough of the St. Lawrence, which, according to Ratzel (**1880**, p. 393), "has an old fiord for its bed." These two great trough-valleys are analogous to the great fiord-channels and funnel-shaped gulfs on the borders of other fiord-areas, as on the northern coasts of Norway, Greenland, and in the Arctic Archipelago.

F. THE FIORDS OF ALASKA AND BRITISH COLUMBIA

Out and in and out the sharp straits wander,
  In and out and in the wild way strives,
Starred and paved and lined with flowers that squander
  Gold as golden as the gold of hives,
Salt and moist and multiform; but yonder,
  See, what sign of life or death survives?

SWINBURNE.

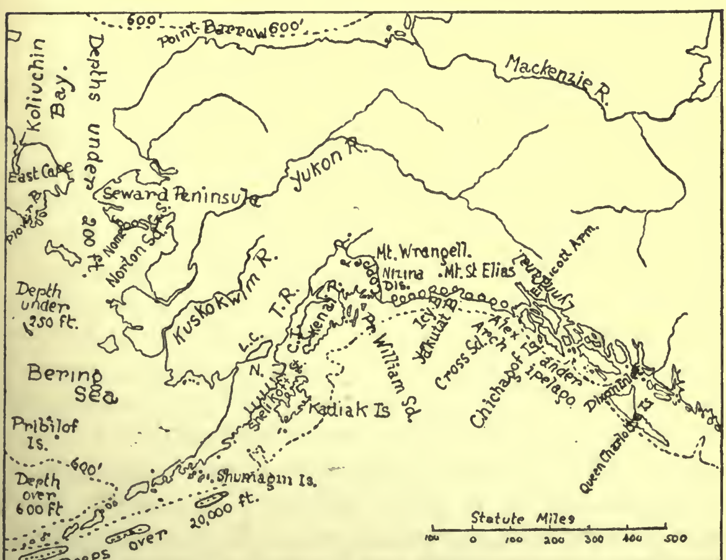
1. The Alaskan Coast.—2. The Fiordless American Shore of the Bering Sea; Absence of Fiords due to Nature of Earth-movements, not to Non-glaciation.—3. The Fiord-coast of the Alaska Peninsula and Prince William Sound; Cook Inlet and its Differential Dislocations; Prince William Sound and its Four Uplifts.—4. The Fiordless Coast between Prince William Sound and Cross Sound; Yakutat Bay and Faulting along its Fiords in the Earthquake of 1899; Cause of Absence of Fiords on this Section of the Coast.—5. The Fiord-system of South-eastern Alaska and British Columbia; the Lynn Canal and its Inland Continuation; Geology of the Coast; Plan of the Fiords.—6. Theory of the Glacial Origin of the Fiords.—7. Evidence of the Plan of the Fiords.—8. The Fiord-valleys Preglacial.—9. Tectonic Origin of the Fiords; the Successive Foldings and Earth-movements; the Valleys cut by Preglacial Rivers along Fractures; Differential Nature of the Movements.

1. THE ALASKAN COAST

The Alaskan coast is one of the most impressive fiord-coasts of the world. Mr. John Burroughs (**1902**, p. 19) declares that for 1,000 miles northward from Victoria, the capital of British Columbia, the coast has " probably the finest scenery of the kind in the world that can be seen from the deck of a ship—the scenery of fiords and mountain-locked bays and arms of the sea." Dr. Henry Gannett (Burroughs, **1902**, p. 277) is no less enthusiastic.

" There are glaciers, mountains, and fiords elsewhere, but nowhere else on earth is there such abundance and magnificence of mountain, fiord, and glacier scenery. For thousands of miles the coast is a continuous panorama. For the one Yosemite of California Alaska has hundreds. The mountains and glaciers of the Cascade Range are duplicated and a thousand-fold exceeded in Alaska."

The Alaskan coast is not however, fiord-indented throughout. Fiords occur along it from the Alaska Peninsula to Prince William Sound, and from Cross



----- Line of 600 ft. deep. oooo Glaciated coasts without fiords.
⊥⊥⊥⊥ Non-glaciated coasts with fiords.

FIG. 54.—SKETCH-MAP OF FIORD DISTRIBUTION IN ALASKA.

Bay southward along the coast of British Columbia to the United States. But in the remaining areas, including most of the American shores of the Bering Sea, and from Prince William Sound for 400 miles to Cross Sound, the coasts are smooth and simple, except for one interruption at Yakutat Bay.

The western coast of North America north of the United States may therefore be divided into four sections (Fig. 54) : the Bering Sea, of which the American coast has no fiords ; the southern shore of Alaska Peninsula and thence eastward to Prince William Sound, and this section has many fiords ; from Prince William Sound to Cross Sound, between which there are no fiords except as tributaries in Yakutat Bay ; the fiord-belt from Cross Sound along southern Alaska and British Columbia.

One of the most striking facts in connection with the Pacific fiords of North America is their absence from the first and third of these sections.

2. The Fiordless American Shore of the Bering Sea

The country around the famous gold-field of Nome, on the southern side of the Seward Peninsula in lat. $64\frac{1}{2}°$ N. and long. 165° W. is a good representative of the northern section of the fiordless coast of Alaska. The coast is here formed of continuous beach deposits with long, even, gentle curves. The town of Nome stands on the northern side of the wide bay known as Norton Sound. The absence of fiords from this country seemed at first easily explained by the fact that, according to some authorities, it had never been glaciated. The absence of any regional glaciation of this area was first advocated by W. H. Dall (**1870**, p. 461), and this view was subsequently supported by G. M. Dawson (**1894**), J. Stanley-Brown (**1892**), and by W. C. Mendenhall (**1901**, p. 208), who reported that the Norton Bay district "has suffered no general glaciation." Spurr (**1898**,

p. 270) stated that "throughout nearly the whole of Alaska there are no signs of regional glaciation." Muir (**1885**), on the other hand, claimed that the whole of this area has been subject to a regional glaciation, and he attributed the formation of the whole Bering Sea to glacial erosion. Some of his evidence has been denied by later explorers, and it is generally agreed that his main conclusion was exaggerated. There appears, however, to be more evidence for glacial action in this area than was at first thought. Thus while Messrs. A. H. Brooks, G. B. Richardson, and A. J. Collier state (**1901**, pp. 43, 46) that in the Seward Peninsula "there is no evidence of regional glaciation," they have shown that two extensive and two smaller areas had been glaciated in the part of the country they had studied. Thus the Kigluaik Mountains to the north of Nome and their eastern continuation, the Bendeleben Mountains, were both ice-covered. Glacial valleys extend inland into the Kigluaik Mountains, where they end in cirques bounded by cliffs 1,000 ft. high. The photograph (Brooks, etc., **1901**, pl. vii. fig. B) of the Sinuk River, which reaches the sea to the west of Nome, has very characteristic glacial features. Mr. Brooks and his colleagues attributed this glaciation to a very recent date, when the land stood at its present level. The moraines occur down to sea-level, and there is some evidence of the southern coast having been slightly submerged at the time of the glaciation. Mr. Brooks reports that the Cape Nome miners attribute the placer-gold deposits to glacier action (Brooks, etc., **1901**, p. 43).

The recent bulletin by Messrs. P. S. Smith and H. M. Eakin (**1911**) on the area to the north of Norton Bay and to the east of Nome shows that the mountains there were formerly occupied by valley-glaciers of the Alpine type. In the Darby Mountains the glaciers were only local, and the topographic map with that report represents those mountains as lacking the usual characteristics of strong glaciation. Throughout the Bendeleben Mountains the authors observed the evidence of former glacial action. The ice in this district did not descend so low as it did farther eastward near Nome; and it apparently did not reach Golofnin Sound, which was not glaciated.

The glaciers in this part of Alaska seem to have had no great effect on the topography. Thus Spurr (**1898**, p. 263) reports that the valleys of the lower Yukon "existed in practically their present condition previous to the glacial period," for the mountain-glaciers entered them when "they were in practically the same condition as now."

Golofnin Sound is not a fiord at present, for on this part of the coast the last movements were uplifts. Spurr showed in **1898** (p. 263) that the main elevation of this region was either in the late Miocene or early Pliocene, as some of the Miocene beds have been folded and tilted while the younger beds have been only slightly disturbed. There appears no clear evidence of recent subsidence. The raised beaches along Golofnin Sound described by Smith and Eakin prove that this country has been upraised about twenty-five feet. The rivers were thus given increased powers of eroding the silt along their valleys and carrying the material into the Sound, which was thus largely filled up. It is, therefore, now only a shallow inlet with an irregular shore due to the deposition of silt. But the contoured map published by Smith and Eakin shows that the submergence of the adjacent country to the height of 400 ft. would convert the valley of the Fish River through the Palæozoic mountains to the east of the town of Council into a fiord: for it would be a long, straight, narrow arm of the sea, 200 ft. deep, with steep walls, with numerous branches at right angles to its main course, and it would be bordered by truncated faceted spurs. A submergence to the height of 800 ft. would produce further fiords and fiord-straits, and this part of the Norton Sound area would become a typical fiord-coast.

Hence in the northern section of the Alaskan coast, the evidence shows that the glaciers reached the sea in the fiordless area around Nome, but not in Golofnin Sound, although it was probably once a fiord.

Absence of Fiords due to Nature of Earth-movements, not to Non-glaciation

The absence of fiords is not due to the absence of glaciation, but to the nature of the earth-movements along this coast. This fact was recognised by Spurr (**1898**, pp. 272–5). He quoted the abundant evidence of recent uplift. He then remarked that the—

> " deep valleys which were eroded subsequent to the Neocene uplift now exist as fiords on the shores of the Gulf of Alaska, while the shores of Bering Sea, on the contrary, are low and flat and the water is very shallow, the deep valleys which are found in the interior usually not reaching to the sea. It may be inferred from this that the shores of Bering Sea are now more elevated than they were during the post-Miocene period of erosion, and that the shores of the Gulf of Alaska are more depressed. The difference in the character of the coast-line is very marked, as shown on the Coast Survey Chart of Alaska ; even between the northwest and southeast sides of Alaska Peninsula there is a great difference. This is susceptible of explanation, by supposing irregularities in the post-Miocene elevation or in the more recent uplift " (Spurr, **1898**, pp. 274, 275).

He therefore infers that the contrast between the present fiordless shores of the Bering Sea and of the fiord-indented Gulf of Alaska is due to the former having been elevated and the latter lowered in level.

3. The Fiord-coast of the Alaska Peninsula and Prince William Sound

The second section of the coast includes the southern shore of the Alaska Peninsula, and contains one area which is said to have escaped glaciation, but is indented by fiords and has fiord-lakes. Thus, according to Spurr, the land end of the Alaska Peninsula was not glaciated; he states that around the Naknek lakes there are "no signs of glaciation" (**1900**, p. 145); and, although Cook Inlet was clearly glaciated, the Tordrillo Mountains to the north-west of it, according to Spurr (**1900**, p. 252), underwent no general glaciation; and the extension of the non-glaciated area thence into central Alaska has been proved by Brooks (**1900**, p. 455), who found "no evidence of general glaciation" in the valley of the White River.

Spurr has pointed out that considerable glaciers occur on the north-western side of the Aleutian Range near Naknek Lake, while on the south-eastern side glaciers are few or absent. But on the latter side the shore is richly indented by short fiords. Kadiak Island (Fig. 55), on the opposite side of Shelikof Strait, has been shown by Dr. G. K. Gilbert[1] to have been glaciated by local ice, and the Kadiak fiords might therefore be of glacial origin; but from Spurr's work (**1900**, pp. 254, 255) it appears that the continental shore of Shelikof Strait has never been glaciated, and, if so, its fiords could not be due to ice-erosion.

Cook Inlet and its Differential Dislocations

The coast to the east of the Alaska Peninsula was clearly glaciated, but the fiords are in valleys which are

[1] G. K. Gilbert (**1903**, p. 178). A chart showing the outline of Kadiak Island and of the opposite coast is given by Becker (G. F. Becker, **1898**, pl. xxvi.). O. Nordenskjöld (**1900**, pp. 205, 206), accepts the inlets on Kadiak Island as "true fiords."

FIG. 55.—OUTLINE OF KADIAK ISLAND.

preglacial and apparently of tectonic origin. Cook Inlet has been well described by G. H. Eldridge (**1898**) and A. H. Brooks (**1911**).[1] Eldridge's map (pl. ii.) shows that its channel is 140 miles long and usually fifteen to twenty-five miles wide; it bends at right angles at its inner end as the Turnagain Arm, which, ac-

[1] According to O. Nordenskjöld (**1900**, p. 205), Cook Inlet is "no fiord."

cording to Brooks (**1911**, p. 122), "is essentially a fiord" (Fig. 56). The main channel includes two basins: the upper basin is in places 114 ft. deep and is separated by a threshold only 72 ft. deep between the projecting West and East Forelands; the outer basin is in places 264 ft. deep, but it appears to become shallower between its deepest locality and the mouth. Cook Inlet is con-

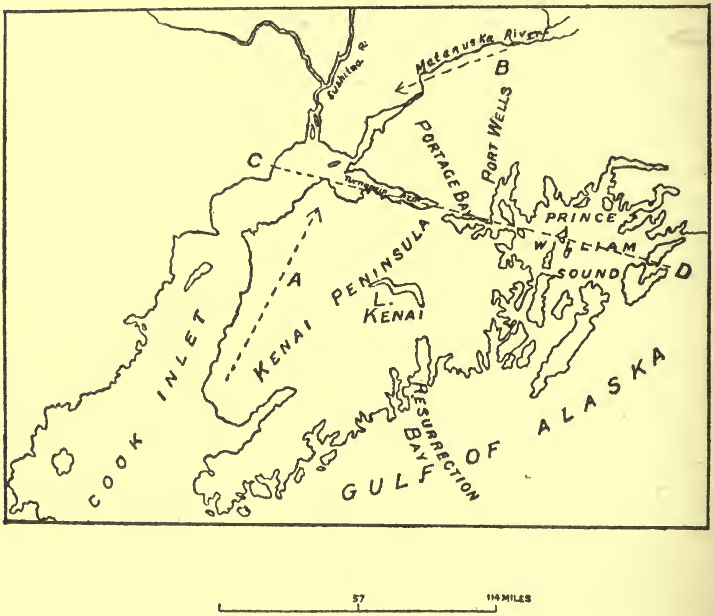


FIG. 56.—SKETCH-MAP OF COOK INLET AND PRINCE WILLIAM SOUND.
A, *B*, General slope; *C*—*D*, Line of minimum uplift according to Mendenhall.

tinued inland by the wide valley of the Sushitna River, which is now filled with alluvium. Eldridge (**1900**, p. 7) describes both Cook Inlet and its inland continuation as "a structural mountain-basin of vast size."

Mr. Mendenhall (**1900**, p. 329), who describes Cook Inlet as having been once ice-filled, concludes that the Matanuska Valley, which enters the upper end of Cook Inlet, was cut by river-erosion and was subsequently modified by ice. If so, the basin of the Cook Inlet and the chief valleys opening into it would all be of preglacial age.

This view is fully confirmed by Brooks (**1911**, p. 34), who is emphatic that the valleys of this district were excavated in preglacial times. He has shown (p. 122) that the basin of Cook Inlet itself was originally formed early in the Eocene; for it has been filled with fresh-water beds of upper Eocene age, belonging to what is known as the Kenai Formation. The existing basin has been formed by the subsequent erosion of these soft sediments. According to Brooks, ice played no important part in this erosion. Glaciers, it is true, covered the whole of the Pacific slopes of the adjacent mountains (the Alaska Range, the Chugach and Kenai Mountains) to a height of between 2,500 and 3,000 feet; but, he says—

"There is little evidence of the amount of erosion effected by these ice-sheets, but it is believed to have been relatively small. . . . The chief work of these glaciers was the removal of the loose material accumulated during the long epoch of subaerial erosion which had immediately preceded. In other words, the Pleistocene glaciers followed the valley systems established in the previous cycle and probably deepened them to a certain extent" (Brooks, **1911**, p. 135).

The Cook Inlet basin shows clear evidence of powerful dislocations and earth-movements in recent geological times. Thus the Kenai beds have been intensely folded and faulted (Brooks, **1911**, p. 97). Brooks has also clearly demonstrated that the last movements in this area were differential, so that they would naturally have formed rock-basins. Thus, in the Matanuska Valley the land has been tilted toward the sea (p. 123). "It cannot," he says, "be too strongly emphasised, however, that Alaska as a whole has been the scene of many earth-movements since Tertiary times, and that these movements have been differential" (p. 135).

Prince William Sound and its Four Uplifts

Prince William Sound (see Fig. 56) on the eastern side of the base of the Kenai Peninsula consists of a wide basin partially enclosed by a series of islands across its mouth, and with a series of narrow fiords running inland. The Sound is described by Dr. Gannett (**1902**, p. 262) as an irregularly shaped bay, with a "multitude of islands and fiords." The three chief fiords are Port Valdez, which extends thirty miles inland; Port Wells on the north-western side, which extends forty miles into the interior and ends as Harriman Fiord; and Passage Canal, which leads to the portage route overland to Turnagain Arm of Cook Inlet.

The main basin of Prince William Sound has been open to the sea, according to Mr. Muir's estimates based on the age and generations of trees which have grown there, for "probably a thousand years or more" (Muir, **1902**, p. 133); but the glaciers are said to have vacated Harriman Fiord only within the last few years.

The general trend of the chief islands and intervening straits at the mouth of Prince William Sound is from north-east to south-west; but farther north on the shore of the mainland the predominant directions are approximately east to west and north to south. Thus, Port Gravina and Port Fidalgo both run nearly east and west; the latter is continued on the western side of the Sound by the channel between Esther Island and the Kenai Peninsula, and by Portage Arm, which continues westward toward Cook Inlet and leads to the long fiord, Port Wells, which runs inland due northward.

The geology of this district has been studied by Messrs. Schrader and Spencer. They describe the country as composed of a foundation of Archean gneisses and schists, upon which rest a series of lava-flows, the "greenstones," which are of Silurian age. Some sedimentary rocks are assigned to the Devonian, but the evidence for that date appears unconvincing. The Chitistone limestone, though no fossils had been found in it, was formerly identified as Carboniferous from its lithological character. This limestone has, however, since been proved to be Triassic (Moffit and Capps, **1911**, p. 23). It is succeeded by Triassic rocks, the age of which is proved by their fossils, and a series, the Kennicott Formation,[1] assigned to the uppermost Jurassic or the base of the Cretaceous (Schrader and Spencer, **1901**, p. 50).

After the deposition of the Kennicott Formation the country underwent great uplifts at four distinct periods. The first uplift was followed by extensive denudation, which formed the wide Chugach pene-plane.

The second uplift caused a further elevation of from 3,000 to 3,500 ft. The rivers immediately began to deepen their valleys; and then were formed some of the hanging valleys along the upper part of the Copper River.

The third uplift raised the country another 2,000 or 2,500 ft. and enabled the rivers to deepen their valleys still further; during the later part of this erosion the valleys were occupied by glaciers that widened them and gave them their present U-shaped, ice-worn form.

The last uplift was only local in range, and the evidence for it is incomplete; afterwards the glaciers continued to mould the narrow valleys and deposited large quantities of drift on the floor of the lower valley of the Copper River.

The effect of the glaciers on the form of the country is shown by the maps in Messrs. Schrader and Spencer's report. Thus, on the map of the Copper River District

[1] The Kennicott Formation is included in the Upper Jurassic in the legend to Moffit and Capps' geological map (**1911**, pl. iii.); but the possibility of its being Cretaceous is recognised in the text (*Ibid.* p. 38).

on the scale of 1 to 250,000,[1] many of the spurs beside the Chitina River are represented with the flattened, faceted ends which are so commonly met with in glaciated areas. The country is traversed by many powerful faults, of which the most prominent is pre-Cretaceous, as it is earlier than the Kennicott Formation. The old faults only affect the topography indirectly by their influence upon denudation. The country appears, however, to have been disturbed by some recent faults which are glacial or post-glacial in date. Thus, according to Schrader and Spencer (**1901**, p. 72), there is evidence at Wood Canyon, through which the Copper River enters the Chugach Mountains, of a probable fault or sharp fold; this movement probably amounted to a rise of 500 ft. in height, and took place during the glacial period. The authors of this report did not recognise any evidence of recent subsidence of the country; and they therefore attributed the formation of the fiords and Prince William Sound to glacial erosion. The wide basin of the Copper River they assigned to erosion by rivers before its occupation by ice (Schrader and Spencer, **1901**, p. 74); but they conclude—

"that the fiords were excavated while the land stood practically in its present relation to the sea, and if this be so, their erosion was accomplished below the level of the sea, and must, therefore, be attributed to glacial action. The valley of the lower Copper was probably at one time a fiord which has been filled up with materials brought down by the river, and to it a similar origin is attributed" (Schrader and Spencer, **1901**, p. 82).

The authors, however, admit that the district has been disturbed by very recent earth-movements, and its general topography suggests that the fiords there, as elsewhere, are submerged valleys. Schrader (**1900**,

[1] Schrader and Spencer (**1901**, pl. ii.); and also in the maps of the adjacent Nizina District (Moffit and Capps, **1911**, pl. ii.).

p. 404) has himself shown that the land around Prince William Sound is still subsiding, and quoted evidence that it was subsiding in 1794.

A more recent memoir by Messrs. Moffit and Capps (**1911**, p. 44) on the Nizina District, in a tributary valley of the Chitina, remarks that "the dissection of the area in preglacial time had been accomplished by normal stream-erosion." The valleys thus made were subsequently modified and deepened by the glaciers; as the ice flowed down the valleys it picked up quantities of rock-waste, which supplied an abundance of abrading material, and thus the glaciers wore away the projecting spurs and gave the valleys their U-shaped, trough-like form. Messrs. Moffit and Capps consider that the glacial erosion may have deepened the valleys to the extent of 1,000 to 1,500 ft., an estimate based mainly on the height of the hanging valleys.

The evidence, therefore, shows that the distribution of the fiords in the Alaska Peninsula is not coincident with the former distribution of ice. The main fiords in this section of Alaska are connected with Cook Inlet and Prince William Sound, which are both areas of recent earth-movement.

4. The Fiordless Coast between Prince William Sound and Cross Sound

The third section of the Alaskan coast extends from Prince William Sound eastward to Cross Sound. It is a long, even coast broken only by Yakutat Bay. The absence of fiords is especially remarkable as the country is covered by a series of immense glaciers; and, as it lies between two once intensely glaciated areas, the existing glaciers have probably been at work there throughout the glacial period.[1] The ice, moreover, in

[1] The glacial features of this coast have been described by E. Blackwelder (**1907**).

the district around Prince William Sound is receding with great rapidity. Thus, according to Mr. John Muir (**1902**, p. 128), the Hugh Miller and Muir Glaciers have receded two miles in the twenty years before 1910, and the Geikie, Rendu, and Carrol Glaciers perhaps from seven to ten miles in the same period. Hence, if there were fiords along this coast, their ends should already have been unmasked; but, though there are no fiords on the main outer coast, there are several inland, including Russell Fiord,[1] as tributaries to Yakutat Bay.

Yakutat Bay

The geography of the Yakutat Bay region has been described by the late Professor Tarr (**1906** and **1909**). He refers in his later monograph (**1909**, p. 12) to the striking contrast between the unbroken coast in this part of Alaska and "the remarkably irregular coast farther south-east." Yet this fiordless coast lies below the Malaspina glacier, which Tarr describes as the greatest on the American continent.

The land around Yakutat Bay rises from the Pacific to a high plateau; and the beautiful photographs taken by the Canadian Boundary Commission (see *e.g.* Tarr, pl. xxxv., opposite p. 132) show the plateau to be a pene-plane dissected by a series of fiords and fiord-valleys. The uplift which raised the old plain into a plateau appears to be very recent, for the Fairweather and St. Elias Mountains rise abruptly from a remarkably straight, seaward-facing front, and they are "still in process of uplift" (Tarr, **1909**, p. 11). I. C. Russell reported that there was no evidence in this area of preglacial erosion; but Tarr recognised that its influence has been profound, for the ice only occupied and enlarged a system of preglacial valleys.

The valleys that branch off from Yakutak Bay have

[1] Gannett (**1902**, p. 261).

the characteristics of true fiords, owing to their long, straight, spurless walls clearly seen in the photographs by the Canadian Boundary Commission published by Tarr (**1909**). These valleys appear to be determined by faults, and the recognition of that fact by so keen an advocate of glacial erosion as the late Prof. Tarr renders his conclusion of special interest. In describing these valleys he says :

"The walls are often remarkably straight, and in some instances coincide with demonstrable fault-lines, notably in the case of the eastern shore of Yakutat Bay and of both shores of the Northwest Arm of Russell Fiord. On the other hand, many of them, for example the South Arm of Russell Fiord, extend across structure lines and form a network of troughs which bears little resemblance to the pattern of valleys produced by normal mountain drainage. In form also they are peculiar, being broad and U-shaped, with tributaries commonly hanging.

"Some of these features are unquestionably due to glacial erosion, as is shown in the chapter on glacial erosion (pp. 107–119) ; others are doubtless due to preglacial drainage development ; but it seems impossible to completely block out the main preglacial drainage lines without the postulation of faulting. There is a peculiar rectilinear arrangement of the valleys, especially noticeable in the branches of the fiord, which seems to demand such an explanation (Tarr, **1909**, p. 29).

He adds that ice-erosion has deepened and enlarged the valleys (*Ibid*. p. 31).

Faulting in the Earthquake of 1899

The interesting memoir by Tarr and Martin in 1906 connects the fault-movements that bound these fiord-valleys to uplifts, of which the last accompanied an earthquake in September 1899. The two authors discovered convincing evidence of very recent uplift, such as the occurrence of delicate white films of bryozoa still encrusting rocks 40 ft. above sea-level. They also saw conspicuous raised beaches and deltas which were not recorded as having been seen either by I. C. Russell in 1890 and 1891, nor by G. K. Gilbert in June 1899, and were therefore probably not in existence when those geologists visited the bay. Native testimony asserts that the uplift took place at the time of the 1899 earthquake.

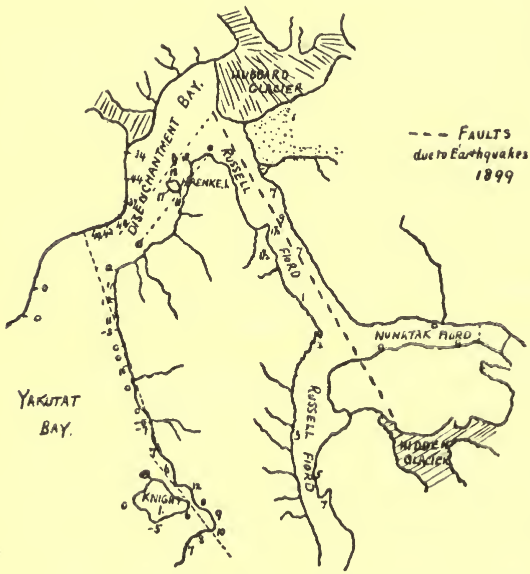


Fig. 57.—Earthquake Faults at Yakutat Bay (after Tarr and Martin).

There is also evidence of quite recent subsidence, such as the invasion of the forests by salt water, which has killed the trees (Tarr, **1909**, p. 46).

The earth-movements probably occurred as parallel faulting with subsidence of the land between the faults. A miniature rift-valley was formed on a glaciated rock-surface on Gannett Nunatak[1]; its fault-scarps are only three feet high, and the valley itself is only thirty feet wide. The authors are confident that these fault-scarps, which are certainly post-glacial, cannot have been in existence for more than six years before their visit. As this

[1] Tarr and Martin (**1906**, p. 50, pl. xxi.).

valley was formed by trough-faulting, some of the larger valleys in the district were probably due to the same cause.

Disenchantment Bay was disturbed by two faults. The western shore was uplifted as much as 47 ft., whereas most of the eastern shore was raised only from 7 to 9 ft.[1]; the decrease in the uplift proceeding north-eastward to Gilbert Point Tarr and Martin attribute to the influence of the fault along the north-western arm of Russell Fiord. The changes due to the earthquake-movements in Russell Fiord are assigned to one fault along the axis of the fiord; but the shores of this fiord appear to lie along two old faults, the prolongation of which formed the valley occupied by the "Hidden Glacier"; and movements along the two faults would explain the facts as well as along one fault.

This earthquake illustrates how fiord-valleys have been formed by parallel trough-faults, and the clear evidence of the differential movements along these faults shows how basins are formed on the floors of the valleys. Tarr and Martin, however, concluded that they could not be certain that the faulting originally initiated the outlines of the fiords, and they attributed the present depth and form of the fiords to glacial erosion and not to faulting. But in a later memoir (**1909**) Tarr attached less importance to glacial action.[2]

Tarr and Martin's memoir shows that the formation of fiord-valleys by trough-faulting is still in progress in Alaska.

Cause of Absence of Fiords on this Section of the Coast

The absence of fiords along the outer coast of the Pacific in this district is one of the most significant

[1] Tarr and Martin (**1906**, pp. 61, 62).

[2] He has also similarly reduced his estimate of the power of glacial erosion in other areas, as in the Finger Lake Region of New York—the lake-basins of which he originally regarded as excavated by glaciers.

facts in connection with the fiords of north-western America.[1] It is probably due to causes analogous to those which have substituted a fiordless for the fiord-coast which once existed in the western United States. This part of the Alaskan coast consists of a great curve between the fiord-coast trending south-westward along the Kenai and Alaska Peninsulas and the fiord-coast nearly at right angles to the other in south-eastern Alaska and British Columbia. Lines continuing these two fiord-coasts would meet almost at right angles near the sudden bend in the main mountain-chain of this region, at the end of the Alaska Mountains near Mount Wrangell. The coast rounds off this angle, and its fiordless nature is probably due to the earth-block at this angle having been subject to much less tension than that which cracked the land along the main lines of dislocation.

From Yakutat Bay the even-coast line continues from north-west to south-east, as far as Cross Sound, where begins the main western fiord-system of North America.

5. The Fiord-system of South-eastern Alaska and British Columbia

At Cross Sound the coast bends round to south-south-east, and the coastal region is continued as the Alexander Archipelago. Cross Sound, the first of the fiords, strikes directly inland and is joined by Glacier Bay, which extends north-westward parallel to the coast and behind the coastal mountains. To the south of Cross Sound is Chichagof Island, which is traversed by a series of five fiords; they cross the island obliquely, for they retain the north-west to south-east strike, while the outer coast-line trends south-south-eastward.

[1] Dr. O. Nordenskjöld (**1900**, p. 205) has suggested that the glaciers here did not erode fiords because their motion may have been slow.

Chichagof Island is separated by a narrow, irregular strait from Baranof Island, the two forming a long triangle, tapering southward. The north-west to south-east lines can be recognised in many small inlets on Baranof Island and farther southward on both sides of Clarence Strait.

The most important of the Alaskan fiords is the Lynn Canal and its outer continuation, Chatham Strait, which together form the longest straight fiord in the world. Its total length is about 230 miles.[1] Its average breadth is from eight to ten miles. It is divided into a series of basins by rises upon its floor. This great fiord trends only a few degrees eastward of south, so that it strikes out to sea at an angle of about 45° to the shore-line. Hence, says Dr. Nordenskjöld, "it is distinguished entirely from true fiords as its course is not radial to the coast"[2]; its direction is inclined 45° to the coast-line. He says, however, if it be a fiord it is the greatest formation of its kind in the world (Nordenskjöld, **1900**, p. 200).

The Lynn Canal and its Inland Continuation

The line of the Lynn Canal is continued inland from Dyea by a great valley including a series of fiord-like lakes such as Lake Bennett; and approximately parallel to this valley are a series of other fiord-like lakes. Their valleys are connected by cross-valleys, which have the same relations as the intersecting concentric and radial fiords on the coast.

[1] Illustrations showing the fiord nature of the Lynn Canal and that the country around its head is a dissected plateau are given by Moe (**1900**, pp. 24 and 73).

[2] O. Nordenskjöld (**1900**, p. 199). He, however, refers (p. 198) to the Endicott Arm (57½° N.), as being otherwise a typical fiord, though it is still more oblique to the coast; this fiord is twelve miles long by from half a mile to one and a quarter miles wide; and it contains a basin 1,200 ft. deep, while the threshold at its mouth is 432 ft. deep. Endicott Arm is named Sunidum Bay on the map of the Alexander Archipelago by Becker (**1898**, pl. xv.).

Dr. Nordenskjöld (**1900**, p. 203) recognises some of these valleys as of preglacial age. Thus, he says of Lake Lebarge that its valley is preglacial and that, though " ice-erosion has evidently had a great influence in the neighbourhood of the lake, there is no indication that it was directly originated by ice-erosion " (p. 204).

Spurr (**1898**, p. 271) has shown that a much greater lake once existed near Lake Lebarge, and deposited silt of which the bluffs are 150 ft. high; and he thinks that these lakes were drained in consequence of a further uplift accompanied by slight tilting of the neighbourhood.

The inland continuation of the Lynn Canal is probably an old river-valley, and Brooks has suggested that the White and Tanana Rivers of central Alaska, which are now tributaries of the Yukon, once had their outlet through the Lynn Canal; subsequently he modified this conclusion, and considered that these rivers followed a more westerly route and entered the Alsek Valley, and so reached the sea to the south-east of Yakutat Bay (Brooks, **1900**, p. 454, foot-note).

Geology of the Coast

Geologically the coast of the mainland consists of vast blocks of granite associated with various gneisses and schists.[1] The off-lying islands consist mainly of sediments, including representatives of most parts of the geological record; and patches of these rocks occur on the mainland.

Plan of the Fiords

The fiords are arranged in a great crescentic series which runs out from the land at both ends and is parallel to the coast in the middle (Fig. 58). The main channels

[1] See, for example, section on map of part of British Columbia: Geological Survey, Canada, 1879–80. Report B, Sheet I.

FIG. 58.—COAST OF SOUTH-EASTERN ALASKA AND BRITISH COLUMBIA.
Showing the plan of the fiords and the numerous fiord net-works.

are therefore discordant at either end of the coast, but concordant in the middle. The main chain of fiords begins in the north in the Lynn Canal, which is itself the lower end of a long land-valley of preglacial age; it passes out to sea through the Chatham Channel and is continued by a series of straits, including the Hecate Strait between the Queen Charlotte Islands and the mainland, and Queen Charlotte Sound and the Strait of Georgia, which curve inland again between Vancouver Island and southern British Columbia.

Concentric with this main series is an inner chain, which includes in the north Stephen's Passage beside Admiralty Island, Clarence Strait, which separates the Prince of Wales Island, the narrow straits between Banks Island, Pitt Island, Princess Royal, and other islands, and the numerous inlets which run inland on the northern side of the Queen Charlotte Sound.[1] These two crescentic chains of water-channels are crossed by a radial series, many of which are approximately at right angles to the coast. The inlets maintain a general parallelism with those in the same district; but the directions proceeding towards other sections of the coast gradually vary.

The Portland Canal (Fig. 59) along the boundary between Alaska and British Columbia, Douglas Channel, Knight Inlet, Bute Inlet, Jervis Inlet, and Howe Sound are some of the more noticeable of the transverse or radial fiords. Some of them are simple, and, like typical fiords, consist of straight reaches with angular bends. Some of them are connected by cross-channels parallel to the coast, and thus form networks enclosing islands. Some, as *e.g.* Howe Sound, the only member of the series which I have visited, are fiards at the mouth, but pass inland into well-defined fiords. The presence of thresholds

[1] The network of channels to the north of Queen Charlotte Sound is well shown on the geological map of northern Vancouver Island and the adjacent coasts by G. M. Dawson (**1887**).

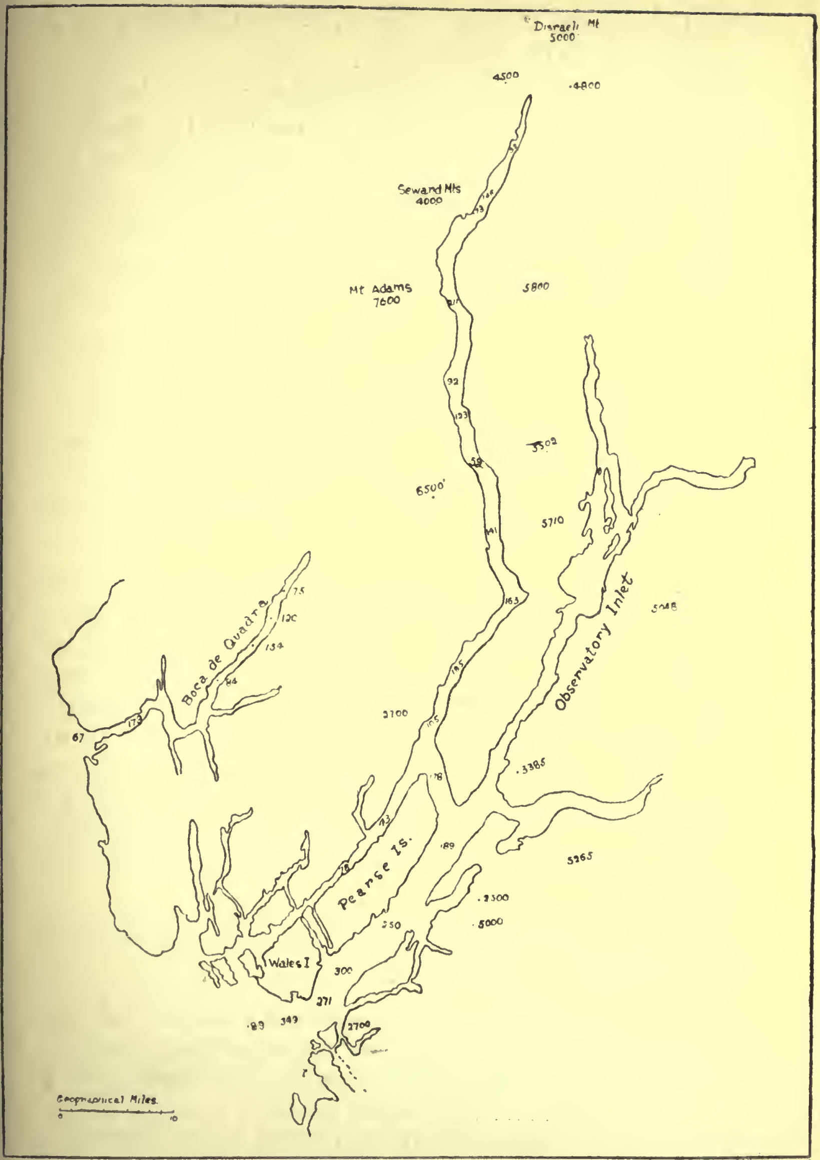


FIG. 59.—PORTLAND CANAL, BRITISH COLUMBIA.
Depths in fathoms ; heights in ft.

near the mouths of some of the fiords is shown in a table of depths given by Dinse (**1894**, p. 258).

Many parts of the coast are fringed with an archipelago due to the complex network of fiords. The general plan of a curved concentric outer series connected by transverse branches is apparent throughout this fiord-area; and, though there are many local diversions in direction, the channels show a constant tendency to return to the same lines.

6. Theory of the Glacial Origin of the Fiords

The valleys of the Alaskan fiords and canals have been generally attributed to glacial excavation. Thus Mr. John Muir (**1902**, pp. 128, 129) recognised that the Alexander Archipelago had been overwhelmed by ice, and claims that its islands—

"all have the form of greatest strength with reference to their physical structure and the action of an over-sweeping ice sheet. The network of so called canals, passages, straits, channels, sounds, fiords, and so on, between the islands manifest in their forms and trends and general characteristics the same subordination to the grinding action of a continuous ice-sheet, being simply the portions of the margin of the continent eroded below the sea level and therefore covered with the ocean waters, which flowed into them as the ice was melted out."

Dr. Gannett advocates the same conclusion. According to him (**1902**, pp. 258, 259)—

"The relief features of this region, its mountains and its gorges partly filled by the sea, are all of glacial origin, presenting everywhere the familiar handwriting of ice. Every canyon, every water passage, whether called strait, canal, or bay, is a U-shaped gorge, and its branches are similar gorges, commonly at higher levels—'hanging valleys' they have been called. Above the cliffs of the gorges the mountains rise by gentle slopes to the base of the peaks. The cross profile of each gorge and its surroundings is that of ice, not of water carving. It is the work of channel erosion, not of valley erosion, and the channels were filled with ice. It is a colossal exhibition of the eroding power of water in solid form."

This conclusion is faced by serious difficulties. The evidence now available shows that the distribution of fiords in Alaska does not coincide with the distribution of glacial activity. The long, straight coast adjoining the Mount St. Elias Range bounds an area with the largest glaciers in the world after those of Greenland and Antarctica; but there are no fiords along this coast except within the triangular basin of Yakutat Bay. Seward Peninsula, near Nome, also has simple, even coasts; it was subject to a glaciation during which glaciers reached sea-level, but without making fiords. On the other hand, there are fiord-like lakes and fiords on parts of the coast which were not glaciated.

Thus Lake Clark, which is long and fiord-like, lies to the south of the non-glaciated Tordrillo Range; and Lake Naknek, which is also described by Spurr as fiord-like, occurs in an area with many lakes and close to the fiord-indented shore of the Shelikof Strait, which is one of the best-established non-glaciated areas in Alaska. These fiords and lakes cannot therefore be attributed to a glacial origin.

The fiords in these parts of Alaska are no doubt smaller than those in the glaciated areas, because the non-glaciated areas were probably regions of low precipitation in glacial times, as they are at present. They would have been less actively attacked by water-erosion in Pliocene times than those areas where the pre-glacial rainfall and the glacial snowfall were both heavier.

7. Evidence of the Plan of the Fiords

The distribution and arrangement of these Alaskan and British Columbian fiords is quite inconsistent with the theory of their glacial origin. The development of the fiords appears quite independent of the glaciation of the country; the direction of the fiords is not simply radial from the chief glacial centres. The channels transverse to the coast might be attributed to excavation by rivers or glaciers flowing seaward from the mountains; but the initiation of the deep channels and straits approximately parallel to the coast is quite inexplicable by either agency. The general plan of the whole series and the detailed topography of special parts of the coast are alike inexplicable on the view that their plan was due to river or glacial erosion. Thus the map by the Geological Survey of Canada of the coast between Portland Inlet and Pitt Inlet shows an arrangement of fiords and straits quite different from anything that would be expected if the valleys had been excavated by glaciers. They resemble a series of intersecting cracks in a broken sheet of glass. (See, *e.g.*, the fiords around Pearse Island, Fig. 59.)

The arrangement of the longer fiord-straits in long-curved series is the more significant as those of Patagonia have the same plan, a fact remarked by Dr. O. Nordenskjöld (**1900**, p. 206) who knows both districts. The direction of the West Fiord of Norway and the straits through the Western Isles of Scotland represent the same plan less well preserved.

8. The Preglacial Age of the Fiord-valleys

The fiord-valleys were in existence before the glacial occupation of parts of the fiord regions; the slopes have doubtless often been smoothed, the spurs that projected into the valleys have been cut back and the floors deepened by glaciers. The fiord-system is, nevertheless, a preglacial feature. "It is scarcely to be doubted," says Gilbert (**1903**, p. 159), "that all these long troughs [the Lynn, Behm, and Portland Canals] were initiated by preglacial rivers." These trough-valleys, he says (**1903**, p. 135), are to be "regarded as pre-existent stream-valleys, only moderately scoured and straightened by the ice which overran and occupied them."

The preglacial age of the fiords in south-western Alaska and their original formation by subsidence were maintained by Spurr, who claimed that in early Pliocene times Alaska was larger and extended farther seaward; and he concluded that—

"The fiords, which are found all along the coast of the Gulf of Alaska, form a direct continuation of the river valleys and without doubt represent submerged portions of them, and since these valleys were excavated during Miocene time it follows that all this belt which is now sea was at that time land" (Spurr, **1900**, p. 247).

Evidence of the preglacial origin of the fiord-valleys is also afforded by the lakes. The frequent association of lakes with fiords has been often advanced as an argument in favour of their both being due to glacial agencies; but in Alaska lakes are abundant in the non-glaciated areas as well as in the glaciated. According to Spurr (**1900**, p. 257), the lake-basins are preglacial. He says that "all the lakes of south-western Alaska, so far as observed by the writer, occupy mountain-valleys which are evidently the ancient river-valleys of the late Miocene."

Some of the lakes were formed by tilting and some by the deposition of alluvial bars. Thus, to the south of the non-glaciated Tordrillo Range is a long fiord-like lake known as Lake Clark. According to Spurr, both this lake and its larger neighbour, Lake Iliamna, are in warped valleys, and are therefore due to the tilting of the land.

The lakes of a second group are due to dams deposited across bays. Thus, in reference to Lake Naknek, which is on the base of the Alaska Peninsula, he says:

"It occupies a deep-cut mountain-valley, and is fiord-like in its form. . . . When the water stood at the level of even the lowest terrace, the lake must have been a fiord connecting with Bristol Bay, and at the same period the other lakes of the peninsula which appear to have the same characteristics must also have been fiords" (Spurr, **1900**, p. 258).

A slight elevation, he continues, would transform many of the bays beside the Bering Sea into lakes.

Though Naknek lake is described by Spurr as fiord-like, it occurs in a district which has not been glaciated. Thus Spurr describes the mountains around the lake as jagged and snow-covered, but he saw upon them "no signs of glaciation" (**1900**, p. 145). He repeats (pp. 254–5):

"The mountains around Naknek Lake are deeply eroded, with no signs of glaciation, the valleys being V-shaped." He continues: "From these facts we see that in the Aleutian Mountains the conditions have been the same as in the rest of southwestern Alaska. In the favorable places glaciers still exist, but it is quite certain, from the topography of the mountains, that in general no glaciers other than those which now survive have ever existed; and in the vicinity of Katmai Pass it seems that some glaciers have advanced while others have retreated since the period of maximum submergence, which is marked by the terraces on the mountains and by the upper limit of stratified glacial drift." [1]

9. The Tectonic Origin of the Fiords

The explanation of these fiords as simply due to glacier corrosion seems to me quite inadequate. That they are due to the action of some tectonic force has been recognised by many visitors to them. Mr. John

[1] J. E. Spurr (**1900**, p. 255). The preglacial age of the valleys of south-eastern Alaska has been already referred to (p. 301).

Burroughs (**1902**, pp. 19, 20) has graphically expressed this view[1]:

"The edge of this part of the continent for a thousand miles has been broken into fragments, small and great, as by the stroke of some earth-cracking hammer, and into the openings and channels thus formed the sea flows freely, often at a depth of from one to two thousand feet."

The Successive Foldings and Earth-movements

The whole fiord-district of Alaska and British Columbia has been subject to a complex series of earth-movements dating from Cretaceous to recent times.

The Cretaceous foldings in Alaska, as pointed out by Messrs. Smith and Eakin (**1911**, p. 30), have no direct effect on the present topography. The existing surface has been formed by denudation since Eocene times. The upland surface was reduced to nearly a plain, but whether this plain was formed near the sea-level and has been uplifted, or whether it was formed at high level is a question that they leave undecided.[2]

Some of the faults in the Norton Bay area have been shown by Messrs. Smith and Eakin to be of post-Cretaceous age, for they cut dykes which have been intruded into the Cretaceous rocks. These authors describe even these later faults as having exercised no direct effect on the topography. (**1911**, p. 89.)

[1] See also Dall (**1870**, pp. 458, 461–3).

[2] They advance several objections to the view that this plain was formed near sea-level and has been since uplifted (P. S. Smith and H. M. Eakin, **1911**, p. 30); their chief argument for that view is the lack of any known process by which a plain surface could be produced at a high level on rocks of different powers of resistance. This argument is, however, discredited by evidence from the high level plains of Africa, western Australia, etc.

The Valleys cut by Preglacial Rivers along Fractures

The folding which formed the chief mountain-chain in Alaska was certainly post-Cretaceous, and mainly happened in the middle of the upper Kainozoic. Thus, according to J. E. Spurr (**1900**, p. 245), the main geographical revolution was later than the Kenai formation, which is of Eocene-Oligocene age; and the movements continued after the Miocene, as beds belonging to that system have been folded. The country, according to Spurr (**1900**, p. 246, and **1898**, p. 259) did not come to rest until late in the Miocene or early in the Pliocene. The country had been uplifted sufficiently for valleys to be carved by rivers during the later Miocene, and a subsequent uplift in the early Pliocene led to the formation of deep canyons, which are often cut on the floors of the Miocene valleys (Spurr, **1900**, p. 246).

Many of the Alaskan fiord-valleys were therefore cut by Miocene and Pliocene river-action after the great middle Kainozoic uplift. The course of the river-cut valleys was doubtless guided by the faults which had produced planes of weakness where denudation was more rapid; and the faults also had a direct influence by vertical displacements.

In the area east of Prince William Sound the country has been shown by Messrs. Moffit and Capps to be intersected by two series of faults crossing at right angles. These faults divide the country into blocks, some of which have moved up, and some down. "In this way," they say, "adjustments of great amount were brought about by many small, widely distributed displacements" (Moffit and Capps, **1911**, p. 70). The evidence for these faults is often obscured, and along the fiords such faults could hardly be recognised; but their recognition by Messrs. Moffit and Capps in the Nizina district renders it probable that intersecting faults may be widely distributed through Alaska, and form planes of weakness along which the fiords have been excavated.

There is conclusive evidence of the submergence of widespread localities around Alaska in recent times, as has been shown by Spurr (**1900**, p. 248). It therefore appears probable that the fiords of Prince William Sound are, as elsewhere, submerged valleys, and that the original valleys, like those of the adjacent rivers, were preglacial in date. Uplifts and subsidences in Alaska appear to have been local and irregular. Thus in the Bering Sea, the Siberian side has been lowered; while on the opposite coast around Norton Sound and Golofnin Sound, at St. Michael's on the southern side of Norton Sound, and about the estuary of the Kuskokwim River in latitude 60° there is evidence of recent uplifting.[1] Some of the earth-movements happened in historic times. In addition to the evidence from Yakutat Bay (see pp. 308–309), Becker (**1898**, p. 19) has referred to uplifts along the Alaskan coast in recent times; he quotes the case of an earthquake in 1868, which is said to have caused an elevation of over twenty feet at Unga (one of the Shumagin Islands, off the south-eastern coast of the Alaskan Peninsula), and of the change which has rendered the Isanotski Strait now impassable.

It follows, from the local character of the movements of elevation and depression around Alaska, that the land has not moved uniformly as one block. Spurr (**1900**, pp. 247, 248) is emphatic that " Alaska, in Tertiary and Pleistocene times, seems to have moved up and down, and to have been warped so often that the erosion of rivers could not possibly reduce the land to a plain, the development of which demands long stability." He insists that the cutting of the canyons in Pliocene times was evidently due to earth-movements, and that

[1] A. H. Brooks (**1901**, p. 63) and G. M. Dawson (**1894**). Stanley-Brown (**1892**, p. 499) has described Pleistocene faults caused by an uplift of 200 to 300 ft. on the Pribilof Islands.

the courses of the rivers "can only be explained by differential movements" (Spurr, **1900**, p. 248). Spurr also explains many of the peculiarities in the arrangement of the Alaskan rivers as due to the tilting of the region (**1898**, p. 275). According to him, north-western Alaska has been uplifted more than the south-eastern district, and he considers that the whole region has probably been affected by broad, gentle warpings. He regards the axes of these warpings as approximately parallel to the Alaska Peninsula. The effect of the tilting of the country on the river-system is considered in a contribution by H. B. Goodrich to Spurr's mongraph (**1898**, pp. 276–89).

Differential Nature of the Movements

These widespread differential movements supply a more natural explanation of the formation of deep internal basins than any form of denudation.

The tilting of valleys must produce basins unless denudation cuts through the rising barriers as rapidly as they are being raised. If tilting be quicker than denudation the formation of basins is inevitable, whereas their formation by any type of denudation is problematical, and, according to many authorities, impossible. That the differential movements caused some of the Alaskan fiords is supported by clear evidence. Mendenhall insists that the final uplift of Alaska was differential, and that the fiord known as Turnagain Arm, south-westward from Cook Inlet, Portage Bay in Prince William Sound, and the valley that connects them, lie along an axis of minimum uplift (Fig. 56) (Mendenhall, **1900**, pp. 333, 334, map xvii. p. 296).

These two fiords, therefore, according to Mendenhall, occur along a depression due to earth-movements, and the same explanation offers the simplest interpretation of many other Alaskan fiords and fiord-straits. They appear to be of tectonic rather than of glacial origin.

G. THE PACIFIC COAST OF THE UNITED STATES

The Ocean old,
Centuries old,
Strong as youth, and as uncontrolled,
Paced to and fro, restless,
Up and down the sands of gold.

LONGFELLOW.

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1. Puget Sound a Preglacial Sunk-land.—2. Sudden Change in the Coast to the South.—3. Small Fiords near San Francisco and Pliocene Fiords of California.

1. Puget Sound a Preglacial Sunk-land

The western fiord-coast of North America extends a short distance southward from British Columbia into the United States, for the basin of Puget Sound presents the essential character of a fiord-area. The general aspect of the country around Puget Sound is well shown in a bird's-eye view by J. P. Kimball (**1897**, pl. xii.), which displays the long, straight, parallel-walled inlets, their angular branching, and their connection by cross-fiords which leave island-blocks separated by a network of channels. Shaler (**1893**, p. 202), in fact, has described Puget Sound as " one of the greatest and most characteristic fields of fiord-topography on the coast of North America." This description Kimball rejects, apparently because he limits the term " fiord " to valleys made by glacial erosion. He shows, however, that the Puget Sound district has undergone repeated oscillations in level between Cretaceous and post-glacial times, and he attributes the origin of the Puget Sound basin to these earth-movements (Kimball, **1897**, p. 309).

Arnold has confirmed the importance of the oscillation of this district; for he shows that one great uplift in the Olympic Peninsula to the west of Puget Sound happened at or near the close of the Miocene; there was another uplift during the late Pliocene; and the mountain-forming movements are still taking place, or have occurred very lately, for folded and tilted Pleistocene clays and gravels occur near Port Angeles (Arnold, **1906**, p. 468). This district has been affected by glaciation, but its influence has been secondary; for Kimball (**1897**, p. 321) ascribes the topography of Puget Sound and the adjacent areas "primarily to fluvial erosion followed by glacial erosion." Hence he considers (p. 316) that "Except perhaps in point of resulting partial submergence, the physiography of that basin and border, as shown in the present paper, presents the widest difference from that of a fiorded or ice-carved coast."

2. Sudden Change in the Coast to the South

This conclusion is based on the view that no drowned valley can be a fiord unless it has been made by ice; and the acceptance of Puget Sound as a true fiord by Dana (**1856**, p. 26), Shaler, Ratzel (**1880**, p. 394), and others seems to be fully justified. South of this great fiord the coast alters its trend, and then, with a suddenness which Shaler (**1893**, p. 202) has described as "revolutionary," and "unequalled for abruptness of transformation in any part of the world,"[1] the coast changes in character and the fiords cease.

The fiord-coast of Alaska and British Columbia cuts across the grain of the country, but is parallel to the great fracture which forms the north-eastern face of the Canadian Rocky Mountains. The Pacific coast of the same region no doubt also lies along a fracture. The mountains of British Columbia form a band between the down-faulted plains of western Canada and the foundered basin of the Pacific. The western mountains

[1] For Bailey Willis's view that the basins in Puget Sound are hollows left empty by melted ice see p. 392.

of Canada have either shared in this subsidence or have been uplifted less than their continuation to the north-west and the south-east, for the mountain-levels in Canada are low compared with the great 18,000 to 19,000 feet peaks of Alaska and with those of the Rocky Mountains and Sierra Nevada of the United States, in both of which the summits rise to over 14,000 feet. The coast-line of British Columbia has a general trend from north-west to south-east, and the fiord-belt ends where the coast leaves this direction and projects across it into the Pacific.

The explanation of this striking change may be deduced from the investigations of Prof. A. C. Lawson on the coast of California, which has a very different geological history from that of British Columbia and south-eastern Alaska. Prof. Lawson has shown that throughout the Pliocene period a vast sheet of sediments was being quietly laid down along the Pacific coast of the United States, which was very similar to that of the present day. The materials were obtained from the denudation of a mountainous country which had been raised by Miocene uplifts. During the Pliocene this region subsided quietly. At the end of the Pliocene a series of local movements raised parts of the area into mountains (Lawson, **1894**, p. 262). Then followed a uniform uplift of the whole region, though naturally attended by some local inequalities. The uplift in northern California was from 1,500 to 2,100 ft. (**1894**, p. 274), and in southern California from 800 to 1,500 ft.[1] Hence, as the last movement along most of the western coast of the United States was an uplift, there are naturally no fiords, although intersecting fissures greatly influenced the geography of the adjacent country. (See, *e.g.*, Becker, **1891**.)

[1] A. C. Lawson (**1893**, p. 157). The uplift of this coast 1,500 ft. after a subsidence of the same amount is also confirmed by Blake (**1898**, p. 165).

3. Small Fiords near San Francisco and Pliocene Fiords of California

In one part of the coast there has been a recent subsidence, the first that occurred after the great uplift. It formed the Bay of San Francisco with the outlet through the Golden Gate, and the only inlets on the main western coast of the United States which have been described as fiords are situated in this subsided area. Lawson, describing Walker Creek, says it "presents all the characters of a fiord, being a narrow tidal inlet with high, precipitous walls on either side" (**1894**, p. 264). Tomales Bay appears from his description to be also fiord-like, for it is a narrow inlet fifteen miles long and less than a mile in average width, so that its ratio of length to width agrees with that of typical fiords. He describes other creeks in the same area as similar, and Rodeo Lagoon, outside the Golden Gate, he calls "an incipient fiord, flooded only in its lower portion" (Lawson, **1894**, p. 267). This development of a series of small fiords in the one part of the coast which has undergone recent subsidence illustrates the dependence of the fiords on earth-movements; and this fact is implied by Prof. Lawson's account of the change in the nature of this coast during recent geological times. At the end of the Pliocene, he says, it was an archipelago; and "A map at the beginning of the Pleistocene would resemble rather that of the present Alaskan shore-line" (Lawson, **1893**, p. 159).

As the coast shows no signs of former glaciation, both its few existing fiords around the drowned area near San Francisco and the long series of fiords that formerly indented the Californian coast were due to tectonic, and not to glacial agencies.

H. THE FIORDS OF PATAGONIA

The mountains opened wide on either hand,
And lo! amid those labyrinths of stone
The sea had got entangled in the land,
And turned and twisted, struggling to get free,
And be once more the immeasurable sea.

MATHILDE BLIND.

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1. The Pacific Coast of South America.—2. The Three Chains of the Andes.—3. The Patagonian Channels and Islands.—4. Baker Channel.—5. Scenery of the Fiords.—6. Thresholds; sometimes absent.—7. Former Westward Extension of Patagonia.—8. Tectonic Origin of the Fiord-valleys by Pliocene Fractures.—9. Preglacial Age of the Fiords.

1. THE PACIFIC COAST OF SOUTH AMERICA

The coast of South America from Panama to Chile is free from fiords and has but few good harbours. This character persists as far south as southern Chile, for, according to W. A. Smith (**1899**, p. 27), "there is no really good landing for steamers" from Valparaiso for 274 miles southward to Talcahuano, though small boats can cross the bar of the Rio Maule. Farther south, however, the coast becomes somewhat irregular. The long and fairly regular coast of Chile is interrupted a little north of latitude 40° S. by Valdivia Harbour. It has a wide entrance, which tapers rapidly inland, and it decreases at the same time from 96 to 36 ft. deep; it is constricted by the Manzera Bank, near which it breaks up into three radiating arms, each of which is long, narrow, and has fairly straight sides, though the shore-line is slightly scolloped. The land around the harbour is high, and, judging from the data on the charts, appears to be a dissected plateau at a level of about 800 ft.

South of Valdivia Harbour the coast is again fairly regular until the entrance to Ancud Gulf. Thence southward the coastal range of Chile is continued as an archipelago. The land has been partially submerged, so that the valleys have been drowned, and the coast is one of the most jagged and irregular in the world. "The coast-line," says Hatcher (**1903**, p. 249), "is seen to be broken up into one of the most complicated systems of deep fiords, inlets, and inland waterways to be found anywhere on the earth's surface." The superabundance of long harbours is an even greater hindrance to the development of the country than their rarity farther north.

2. The Three Chains of the Andes

Southern Chile consists geographically of three main bands, which trend northward and southward parallel to the Pacific coast. To the west is the comparatively low chain of the Coastal Cordillera, which is composed of very ancient rocks, mainly schists and gneisses. To the east of this band is the main valley of Chile, which runs north and south throughout the whole length of the State between the Coastal Cordillera and the lofty Western Cordillera. The Western Cordillera is mainly composed of folded Mesozoic rocks, which are much younger than those of the Coastal Cordillera; these sedimentary rocks are associated with or sometimes completely buried beneath volcanic rocks. Then follows a line of north and south valleys, which are bounded to the east by the second main chain of the Andes, the Eastern Cordillera.

3. The Patagonian Channels and Islands

North of latitude 42° S. the three Chilian mountain-chains are all parts of one connected land; but south of that latitude the geographical character of the country suddenly changes in consequence of a widespread recent subsidence. The Coastal Cordillera is represented by

FIG. 60.—DIAGRAMMATIC SKETCH-MAP OF THE DISTRIBUTION OF THE PATAGONIAN FIORDS AND LAKES.

a chain of islands, and the southern part of the main valley of Chile has been flooded by the sea and is continued as a series of long fiord-straits. Transverse channels go westward to the Pacific along the lines of the valleys and thus convert the former mountains into islands, and the eastern valleys occur as a series of fiords running far inland. Chiloe is the most northern of the islands which represent the southern continuation of the Coastal Cordillera. Its western shore is a rough, straight line; the eastern shore is broken into fiards. W. A. Smith describes the channels between the islands as "Los Canales," or the canals; and the character of the scenery can be realised from his statement that the district to the south of Puerto Moutt resembles that about Rothesay and the Clyde (Smith, **1899**, p. 170). The channel leading to Castro, the chief town of Chiloe, he describes (p. 177) as "the long, winding Estero de Castro, an arm of the sea like a Highland loch."

Chiloe is separated from the mainland by the Ancud Gulf and Corcovado Gulf, which continue southward the main longitudinal valley of Chile between the Coastal and Western Cordilleras; and on the latter, to the east of these gulfs, rise the volcanoes Osorno (7,405 ft.) and Minchinmadiva (8,000 ft.) and Corcovado (7,510 ft.).

The Corcovado Channel opens to the ocean between the southern end of Chiloe and the Guaytecas Islands; an arm continues southward, and contracts into the Moraleda and Rafael Channels; it ends in the Elefantes Gulf against the low Ozqui Isthmus, which connects the Peninsula of Taytao to the mainland.

The Coastal Cordillera is continued between Chiloe and the Taytao Peninsula by the Chonos Archipelago; its northern part is a group of rectangular islands of remarkable regularity. The main channels run north and south, the cross-channels extend east and west, and the seaward side is fringed by numerous small islets. Unlike Chiloe, the outer, or western, side is the less regular.

The southern end of the Chonos Archipelago is close to the mainland, and its last great island is separated from the peninsula of Taytao by the Ortuza Channel, which runs west-south-westward.

Then the island line is interrupted by the broad Gulf of Peñas, to the north of which the land shows a trend to the south-south-west.

South of the Gulf of Peñas the meridional trend is resumed, and the line of the Coastal Cordillera is continued through Wellington Island. The valley between this island and the mainland begins as the narrow Messier Channel. Its shores are very indented, many fiord-like channels go off to east and to west, and the coast projects in many headlands and is fringed by numerous islets.

The Messier Channel narrows to the south and passes through the English Narrows and the Indian Reach; thence one channel, Escape Reach, continues southward, while a strait between Exmouth Promontory and Saumarez Island leads to the mouth of Eyre Sound. Eyre Sound opens south-westward to Wide Channel, which continues in the same direction to Concepcion Channel; it leads south-south-westward through Concepcion Strait to the Pacific between the Duke of York Islands and Hanover Island.

Concepcion Channel at its northern end is joined at right angles by Trinidad Channel, which passes the southern side of Wellington Island, and leads from west-north-west to east-south-east; this direction becomes conspicuous in this part of Patagonia, for it occurs also in Falcon Inlet, a branch of Eyre Sound, in St. Andrés Bay, which opens nearly opposite though a little to the south of Trinidad Channel, and also in Pitt Channel and Innocentes Channel on the two sides of Chatham Island.

The main geographical lines then bend from a meridional to a south-south-easterly direction. This change in direction of the longitudinal channels is accompanied by the bending of the cross-channels. The cross-fiord of Peel Inlet runs almost due westward, though its inner end to the west of Mount Stokes (6,400 ft.) runs from north to south. The lower end of Peel Inlet trends slightly to the south of west; east of Hanover Island it opens to a series of straits, which have about the same degree of easterly trend.

Hanover Island is bounded to the south by Nelson Strait, on the southern shore of which is Queen Adelaide Archipelago. To the north-east of its main island the main straits are crowded together, and they converge to a centre near Mount Burney in the north-western part of King William IV. Land. There are six important channels. Cutler Channel and Smyth Channel, on the two sides of Rennell Island, both trend from north-west to south-east; Collingwood Strait trends from north-north-west to south-south-east; then, to the east of the Andes, the Canal de las Montanas penetrates the mainland on a course to the north by west; the next strait to the east begins at the eastern foot of the same line, which trends from north to south, and Kirk Strait leads to channels which go north-eastward.

This complex of fiords is connected to Collingwood Strait by Union Sound, and it continues inland to Last Hope Inlet, so called because it was the last hope of its explorers of discovering a sea-channel across Patagonia to the Atlantic. This long fiord is on the same north-west to south-east line as Pitt Channel, which is continued as Trinidad Channel to the south of Wellington Island.

In southernmost Patagonia the dominant geographical elements trend more strongly eastward. The Strait of Magellan begins between King William IV. Land and the Isle of Desolation, and extends to the east of south-east, while the tendency to adopt a course due east and west is shown by the strait known as Sea Shell Channel, between the Isle of Desolation and Santa Ines Island ; the same direction holds in the Gulf of Xaultegua and the isthmus between it and the western end of Otway Water. Useless Bay and St. Sebastian Bay, which deeply indent the northern part of Tierra del Fuego, are on nearly the same line.

Magellan Strait continues farther to east-south-east, until it is suddenly bent northward along the eastern side of Brunswick Peninsula ; but the south-eastern channel continues as the fiords between Dawson Island and Tierra del Fuego, the closed gulf known as Admiralty Sound, and as various channels. The dominant direction in this area soon becomes that from west to east ; it is found in the straits, Darwin Sound, and the Beagle Channel, in the trend of the mountains, and in the extension of the land to its end in the jagged coasts of Staten Island.

4. Baker Channel

The longest of the Patagonian fiords are the fiord-straits which extend for 300 miles parallel to the coast. There are, however, some important transverse fiords ; the best known is Baker Channel, which was explored by the Chilian gunboat the *Magellanes*, and has been described by Dr. Hans Steffen (1904). Dr. Steffen accepts the Baker Fiord as entering the sea at Bahia Tarn, in the south-eastern corner of the Gulf of Peñas. But it is also allowable to regard Baker Fiord as beginning from the Messier Channel and passing through the Somerset Channel, to the south of the Baker Islands, thence extending eastward to the south of Isla Merino Jarpa, and then bending south-eastward to the mouth of Rio de la Pascua.

It is, in general, parallel to the Canal Martinez, which starts from Bahia Tarn, on the northern side of the Baker

Islands, and extends inland to the Estero Michell and the valley of the Rio Bravo. These two parallel fiords are connected by five cross-channels along strike-valleys between large islands. The most notable feature of the Baker Fiord is its depth. It is the deepest known cross-fiord in the world, being 4,081 ft. (1,244 metres) deep; and the Messier Channel, opposite the mouth of Baker Fiord, is the deepest longitudinal fiord, with the depth of 4,252 ft. Baker Fiord has a compound basin, divided by three highly raised thresholds. The section along the middle line of the fiord is shown in Fig. 61, of which the eastern part is copied from Steffen; the western end

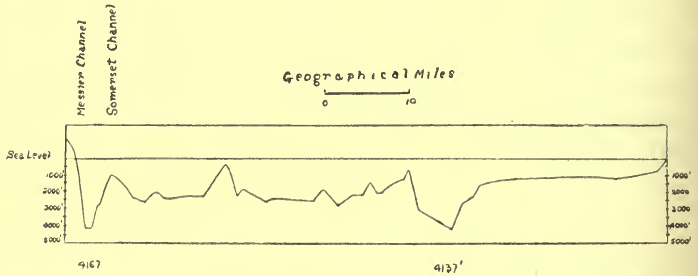

FIG. 61.—SECTION ALONG THE BAKER FIORD.
(Depths in ft.)

crosses the 4,167-ft.-deep Messier Channel, and passes to the north of the locality where the *Condor* found no depth at 4,252 ft. (1,296 metres).[1]

The fiord, considering its length and that it cuts across rocks of varying strength, is fairly regular in width. Its length is given by Dr. Steffen as 120 km. (75 miles), and its average width is from 2½ to 3 miles. The arrangement of the fiord and its branches shows the influence of two series of parallel lines, of which the more important trend from west-north-west to east-south-east. In the

[1] Steffen (**1904**, p. 144). The Admiralty Chart records the maximum depth of Messier Channel as 680 fathoms. The Sogne Fiord is the second deepest cross-fiord.

western half of the fiord are two series which Dr. Steffen describes as crossing at right angles; one series trends from north-west to south-east, and the other from south-west to north-east.

Dr. Steffen (**1904**, p. 142) describes the fiord as similar in aspect to the Norwegian fiords. The slopes are not especially steep, and the adjacent land usually rises to heights over 3,000 ft.[1] The fiord is apparently confined entirely to massive crystalline rocks, mostly granite; clay slates occur to the east, but Dr. Steffen never found them *in situ* on the shore of the fiord.

The origin of its "deep" seems difficult to explain by glacial erosion. Had its floor been scooped out by ice it is difficult to understand why the ice should have suddenly acquired such digging power in the basin containing the deepest depression; and why it should have lost strength, and then regained it at intervals along the channel. The shallow depths of the inner branches of the fiords are attributed to sedimentation from the rivers and glaciers.

Dr. Steffen refers to the deeps as subsidences and trough-formations (*Einsenkungen und Muldenbildungen*), and concludes that their occurrence at the intersection of the concordant and transverse valleys indicates that they are primarily of tectonic origin (**1904**, p. 144).

5. Scenery of the Fiords

Many of the Patagonian inlets are most typical fiords, and they often have such parallel and steep walls that the name "canal" seems quite appropriate.

The artificial aspect of some of the passages is remarked by Anderson Smith (**1899**, pp. 154, 155), who, leaving the Palena River, passed "through the canal, wondering if this region has not once been under human care, and this an artificial cutting, after all."

[1] The Admiralty Chart records heights on opposite sides of Baker Fiord as 3,429 ft. and 3,058 ft.

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These Patagonian fiords have been well described by Sir Martin Conway, who compares them to the fiords of Norway. His account shows how well the Patagonian fiords reproduce the typical features of the Norwegian fiords.

"Even more magnificent is the scenery of the labyrinth of fiords leading from Smyth Channel to Last Hope Inlet, where the cliffs are precipitous, the summits of the peaks generally buried in a dark roof of cloud, which sheds a mantle of majestic gloom over the deeply lying channels of the sea. At the very head of Last Hope Inlet stands Mount Balmaceda. The snow-field resting in its lap pours down a splendid ice-fall to the waters" (Conway, **1902**, p. 134).

"Messier Channel is the name of the northern reach of the long submerged valley, or rather succession of valleys, which flank this part of the continent of South America, and along which we were to steam during the next few days to the Straits of Magellan. It lies between the mainland and the closely packed archipelago of islands fringing the coast. From its entry at the Gulf of Peñas to its exit into Magellan Strait, a distance of 360 geographical miles, following the windings of the channel, the open sea is only once visible. Different reaches of it have different names, but hereafter I shall, in accordance with common usage, speak of the whole as Smyth Channel, though that name properly belongs only to the last reach at the south.

"There are two other inland passages between a mainland and a continuous, or almost continuous, string of islands which may challenge comparison with Smyth Channel. These are the Alaskan and Norwegian inland steamboat routes. The Alaskan I have not seen, but the consensus of competent opinion agrees that it is inferior in point of scenery to the Norwegian channel, which I have traversed four times, between Bergen and the North Cape.

"I shall confine myself, therefore, to a comparison between the Norwegian and Smyth Channel, and I have no hesitation in asserting that the Chilean waterway is, on the whole, less splendid than its northern competitor. The points of similarity and contrast between the two are worth nothing. In both the mountains, alike of the mainland and the islands, are similar in character. They are very ancient ranges, formed of the hardest rocks—granite, gneiss, and so forth. They have been exposed through countless ages to the forces of denudation, carved into deep valleys by water action, then rounded and polished up to their very summits by a great ice-sheet, which has now withdrawn from all but the highest elevations. Finally, both have been depressed till the valleys and the bases of the hills are deeply submerged. Both are now rising once again. Thus there is little to choose between the Norwegian and Chilean waterways in the matter of form, except near Magellan Strait, where, as will be seen, some bold and splendid snowy peaks arise; but these belong rather to the Magellan district. If, however, they are to be reckoned as one of the scenic assets of Smyth Channel, they may be set off against the mountains of Lofoten, and to them they must yield the palm of beauty.

"In respect of width—of apparent as distinguished from navigable width—Smyth Channel is astonishingly uniform; it is more like a wide river than a sound. There are a few broad reaches and two notable narrows, but there is none of that frequent change of breadth which gives such variety to the Norwegian passage; nor are there so many of the far-stretching vistas that excite the expectation or stimulate the memory of the North Cape passenger. To the credit of Smyth Channel, on the other hand, must be reckoned the dense velvet-textured forest mantle that drapes the shoulders and forms the skirts of the hills, covering even the smallest islands and reaching to the very margin of the channel. The trees often actually overhang the water, where the high-water level cuts off the foliage in a sharp horizontal line, so that the branches just touch the surface of the flood, whilst at the ebb a boat can be rowed beneath the thick arboreal roof. . . .

"At the other side of Orlebar Island is the narrow entrance to far ramifying Calen Inlet, the biggest Patagonian fiord, which cuts right back through the Cordillera almost to its eastern foothills. But nothing would lead a voyager down Messier Channel to expect the existence of this recondite labyrinth, so numerous are the branch waterways, short and long, that turn off on either hand (Conway, **1902**, pp. 141–4).

The South American Pilot describes the Patagonian channels in general as having the character given by Sir Martin Conway to special members of the series. Thus it summarises the general features of the whole line of channels from the Strait of Magellan to the Gulf of Peñas as follows : " The general features of these channels are high, abrupt shores, with innumerable peaks and headlands remarkably alike in character ; their bold, rugged heads giving an appearance of gloomy grandeur rarely seen elsewhere. The shores are generally steep-to." [1] The same authority records Picton Channel as one mile wide by twenty long. The straight, featureless walls of these fiords are shown in the description of the southern and eastern arm of the Gulf of Peñas. " They are merely deep and narrow arms of the sea, running between steep-sided mountains. The shores are rocky, affording neither coves nor bights, nor even shelter for a boat, and are entirely unproductive, for not a seal or bird was seen, and the shores were destitute even of shell-fish." [2] The parallelism of some of the channels is referred to in the account of the Guaytecas Islands—which are said to " preserve a remarkable parallelism in an east and west direction." [3]

6. Thresholds ; sometimes absent

The Patagonian Channels agree with fiords in their great depth (*ante*, p. 336) and the frequent presence of thresholds. Many of the Patagonian fiords are, moreover, basins separated from the sea by comparatively shallow thresholds ; and this fiord-characteristic was

[1] *The South American Pilot*, Pt. II., p. 192, 10th ed. (1905).
[2] *Ibid.* p. 265.
[3] *Ibid* p. 282.

first discovered in Patagonia by Captain Cook (see *ante*, p. 62). The thresholds may be illustrated by reference to Alert Harbour on Indian Reach, which consists of a small double basin separated from the outer fiord by a threshold of ten fathoms deep. Brazo de Norte is also a deep, but shallow-mouthed fiord.

The Patagonian fiords supply, however, cases showing that sometimes at least the threshold is a bar of sediment which has been piled across the mouth of the fiord by currents. Thus, Laura Harbour (Admiralty Chart No. 558, 1835), in lat. 54° 7′ S., and 73° 15′ W., has depths within of 132 ft.; but a shoal has grown half-way across its mouth; and Port San Miguel, on the Strait of Magellan (Admiralty Chart No. 556), is nearly closed by some parallel shoals.

Thresholds, moreover, are not present in all Patagonian fiords; thus Mayne Harbour, lat. 51° 18′ S., Port Grappler, 49° 25′ S., Isthmus Bay, 52° 9′ S., and Smyth Harbour (Admiralty Chart No. 1306), all deepen regularly seaward, and in this respect agree with the ordinary definition of rias.

7. Former Westward Extension of Patagonia

The fiord region of Patagonia occurs along the continuation of the Chilian Coastal Cordillera, which is composed of ancient rocks that disappear eastward beneath the higher and younger Cordillera of the Andes. This coastal chain is probably a fragment of a land which once extended far westward into the Pacific. The site of this land is marked by the submerged Patagonian Platform, which extends beneath the Pacific far northwestward. According to Karl Burckhardt, fragments of this ancient land can still be found in the gravels of western Chile. East of Valparaiso and south of Santiago there are vast deposits of a conglomerate composed of porphyritic pebbles, which are replaced eastward by sand. Burckhardt believes that these materials came from the west, and as they are traced eastward the pebble-beds pass into sand, as the fragments were worn finer during their longer journey from their western source.[1]

8. Tectonic Origin of the Valleys by Pliocene Fractures

The fiord district has the unmistakable geographical character of a dissected plateau. Thus Wehrli's section[2] across southern Chile in lat. 41° S. through Lake Nahuel Huapi represents the coast-hills as a flat-topped plateau. That the northern part of the Patagonian Archipelago is also a broken-up plateau is evident from the accounts by Darwin, as well as from the work and charts of later explorers. Darwin's descriptions of Chiloe shows that, although the island has high rocky shores, its surface is fairly level. He says that "the land is hilly, but not mountainous, and is covered by one great forest" (**1845**, p. 273). In a ride along the eastern coast he found that "at first, the country consisted of a succession of hills and valleys; nearer to Castro it became very level" (p. 292); he speaks of his traverse from Castro across the island to the west coast as over "undulating, woody country" (p. 294). He enjoyed one extensive view over the great forest, "a rare thing on this road"; and then he saw, "over the horizon of trees, the volcano of Corcovado" and other peaks of the distant Andes (p. 296).

The impression that Darwin gives of Chiloe is confirmed by a later visitor, W. A. Smith, who shows that other islands of the Chilian Archipelago have a fairly level average surface, though it has been rendered undulating by denudation. Thus Smith (**1899**, p. 127)

[1] K. Burckhardt, *Traces Géologiques d'un Ancien Continent Pacifique*, Rev. Museo de la Plata, vol. x., pp. 177–92, pl. i. (1902).

[2] *Rev. Museo de la Plata*, vol. ix. 1899, pl. opp. p. 242.

reports that, during the survey of Chiloe, a high tower had to be erected above the level of the trees. He described (p. 173), the land near Quicavi as generally about 200 to 300 ft. high, and the opposite Islas de las Chauques as several hundred feet high; to the south is a long, low, flat island and two smaller islands of similar elevation (p. 174).

The sketches on the Admiralty Charts also represent the islands as flat-topped plateaus. Thus Chart No. 1289 shows that the island of Chiloe has a long, level summit, though with three low peaks at one point; and the surface of the Peninsula of Tres Montes, further to the south, is represented on Chart 1325 [1] as a long, flat plateau.

The fiord region of Patagonia is therefore a plateau country which has been fractured by the foundering of the old land that once extended to the west of the present coast. Further evidence of the westward extension of the country is given, according to many authorities, by the valleys which cross Patagonia eastward to the Atlantic. Some South American geographers agree that the rivers which carved out these valleys once rose to the west of their present sources; and these rivers were beheaded as the land was cut backward by the swift rivers that flow westward to the Pacific. This view was adopted by Moreno, but denied by others, as by Hatcher.

The fiord-valleys themselves appear to be primarily of tectonic origin. No doubt they were once occupied by ice which straightened and enlarged them, and thus are regarded as of glacial origin by Dr. O. Nordenskjöld (**1900**, pp. 206–209). But the valley-system is probably of tectonic origin, and is of preglacial age. This conclusion is adopted by so distinguished an authority on Patagonia as Dr. F. P. Moreno (**1899**, p. 249). He says, "All the transverse depressions of the Patagonian plateau correspond to large ancient fiords, the remains of veritable tectonic fractures, very probably produced

[1] South America, W. Coast, Sheet III.

by tertiary granite eruptions" (p. 354). Regarding Lake Viedma he remarks that "This lake also occupies a tectonic depression" (p. 262), and the general fiord-straits he assigns to "upheavals and submergences connected with the tectonic movements which have formed the present Andean Cordillera, and to which movements must be ascribed the fractures which gave the Austral region such a characteristic aspect" (p. 249).

The fiord-valleys themselves resemble fractures. Thus, M. L. Gallois (**1901**, p. 241) refers to the southern fiords as "Long, narrow canals, which seem to correspond to fractures (*cassures*) which have dug their way into the mass of the continent."

The date at which this region was fractured, according to Dr. J. B. Hatcher, was the late Pliocene, and the formation of the fiord-valley was connected with the uplift of the Andes. "The birth of the Andes," says Hatcher (**1903**, p. 174), "took place at the close of the Pliocene." He describes the region of the Patagonian Andes as having been in the Miocene and early Pliocene "a broad, but little elevated plain, with numerous and extensive marshes, but no real mountains then existed where now are the Andes" (p. 235). The country was then submerged, and "with the close of the Pliocene the final emergence of this region began, and that the principal elevation, if not the actual birth, of the southern Andes dates from this period" (p. 235).

According to Hatcher, the recent uplift of the fiord-area varied in amount in different places. He claims to have absolute proof that the elevation along the Andes in northern Patagonia was at least 5,000 ft., and that it diminished to the east and south; and he explains the irregular depth of some of the channels as directly due to the varying degree of submergence (Hatcher, **1903**, pp. 291–294).

T. G. Halle has also recently advanced evidence of great oscillations in the level of the Patagonian fiord-area in recent geological times; he even accepts repeated movements since the glaciation of the area, and remarks that "The complicated changes of level which would result from the foregoing explanation are of a somewhat startling nature" (Halle, **1910**, p. 110).

9. Preglacial Age of the Fiords

The main fiord-valleys are probably not only correctly assigned to earth-movements, but, according to leading authorities on the geology of the area, the fiord-valleys are preglacial in date. Thus, according to Hatcher (**1903**, p. 292), the valleys were formed during late Miocene and early Pliocene times. "Both Otway and Skyring occupy the bottom of great preglacial depressions," says T. G. Halle (**1910**, p. 102).

Quesnel, who has carefully studied the glaciers of the Patagonian Andes, concludes that the lake-basins and the trans-Andine valleys were preglacial in origin. "They are," he says, "to be considered as valleys of erosion of preglacial age, probably formed, as the land rose, after the last mighty Pliocene transgression" (Quesnel, **1910**, p. 89). He shows that the ice, even at its greatest extension, did not reach the western shore of western Chiloe; hence it can hardly have formed the deep western fiord-straits or hollowed out the deep basins. If the lake-basins and valleys of the Andes are not due to glacial action, it is impossible that the deep submarine trenches of western Patagonia should have had such an origin.

The Patagonian fiords, therefore, occupy a series of valleys which, according to leading authorities, are of a tectonic origin and occupy old preglacial valleys in a fractured plateau-land.

CHAPTER XV

THE FIARDS OF NORTH-WESTERN AUSTRALIA

And the tide flows over the shingle,
  Flows and ripples and moans,
Then whispers through meshes of sea-weed,
  Whispers in silvery tones . . .
Whispering, whispering, whispering
  Over the slippery stones.

And I love that whispered message
  Though it calls on me to roam
Over the smiling water far,
  Over the sobbing foam.

W. A. Osborne.

Australia is, after Africa, the most fiordless of the continents. It lies in the tropics and in the warmer part of the temperate zone. The most striking feature in its geographical structure is the absence of any modern chain of fold-mountains. Many of its older Palæozoic rocks have been intensely contorted, crumpled, and over-folded; but its modern folds are monoclines due to subsidence and some local gentle folds. There is no fold mountain-range of recent date in Australia. The main outlines of the geographical relief of Australia are due to vertical earth-movements; and most of these were probably subsidences.

The shores of Australia are often deeply indented, and the inlets are best developed upon the eastern coasts, such as Sydney Harbour and the estuary of the Derwent in Tasmania. Sydney Harbour has many points of resemblance in structure to the föhrden of Schleswig. The harbours of eastern Australia and south-eastern

Tasmania are drowned river-estuaries; they are rias, and not fiords.[1]

Spencer Gulf on the southern coast is long and narrow, and is separated from St. Vincent Gulf by the L-shaped Yorke Peninsula; it is a drowned rift-valley, but not a fiord.

The most fiord-like coast in Australia is that of the province of Kimberley in the northernmost part of Western Australia. It is very indented, and resembles in several respects the ria-coast of south-eastern China. Most of the northern coast of Western Australia, from the North-west Cape eastward, though jagged in detail, follows a long, even course. The nature of the coast changes suddenly with the northward projection of Dampier Land, at the south-western base of which is Roebuck Bay. This bay runs inland, north-eastward, and parallel to the general line of the coast; it is protected to the north-west by a peninsula, off which is a long, narrow depression known as the Roebuck Deep. This deep trends from north-west to south-east; its maximum depth is 294 ft.; and it is enclosed on all sides by depths of no more than 60 ft.

A slight elevation of the land would convert the Roebuck Deep into a fiord-like basin with a narrow, shallow entrance. On the eastern side of Dampier Land is the broad King Sound, which breaks up inland into a series of narrow inlets; its mouth is partially enclosed by a chain of islands including the Buccaneer Archipelago. The seaward passage between Sunday Island and the Buccaneer Archipelago is only 120 ft. deep, although much of the basin inside is 164 ft. deep. Thence north-eastward the coast is indented by a series of long channels running south-eastward and giving off branches at right angles to their main course. The general trend of the coast in this part of Australia follows the same two directions.

[1] For the indentations on the Queensland Coast cf. E. C. Andrews, *Proc. Linn. Soc. N.S. Wales*, vol. xxvii., pp. 146–85 (1902).

The most fiord-like of all the inlets is the entrance to Prince Regent River on Brunswick Bay (Fig. 62). It is a long gulf, which extends forty miles inland. It consists of two outer basins, of which the larger is St. George's Basin, and it is continued inland as a long, narrow estuary. The course of the south-western shore is straight, except for one sharp bend at the junction of the St. George's Basin and the Prince Regent River. A series of narrow branches stretches from the outer basin south-westward at right angles to the trend of the main channel. On the north-eastern side are a few branches which extend at right angles to the main length of the inlet. The depth increases steadily seaward to 198 and 240 ft. near the mouth, which is partially closed by islands; outside them the depth is less, and a line outside the mouth of the bay ranges from 72 to 108 ft.; and it is not until three miles further out to sea that the depth of 180 ft. is again reached. In my "Australasia"[1] this gulf was described as having the character of a

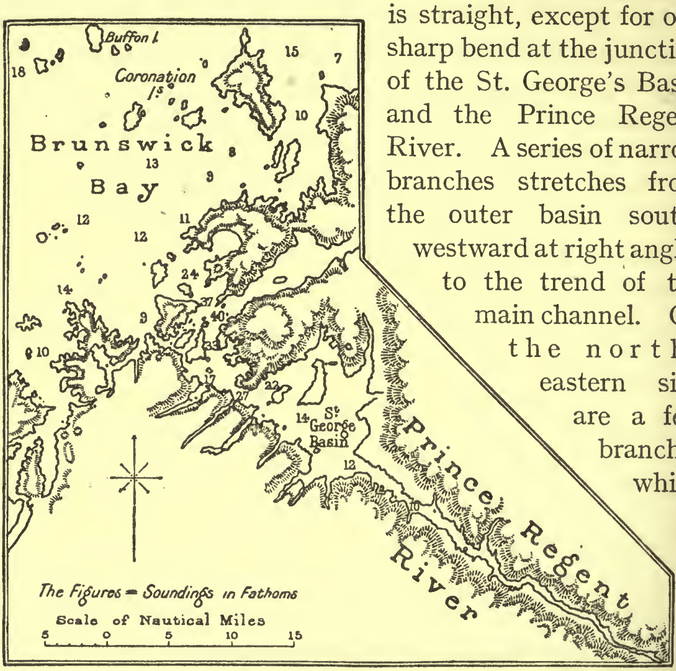

FIG. 62.—FIARDS OF NORTH-WESTERN AUSTRALIA.

[1] Stanford's *Compendium of Geography*, vol. i. pp. 85–6 (1907).

fiord. As it is a long, deep inlet, with often straight sides and rectangular branching, as it shows a striking parallelism in its elements, as its mouth is crossed by a threshold, it certainly has many of the properties of a fiord. It may prove, however, owing to the gentleness of the slopes beside it, to be a fiard rather than a fiord. In any case, these inlets are not true rias, as they are deeper within, and have well-developed thresholds.

This part of the coast of western Australia ends to the north-east with a sudden bend from Cape Londonderry south-eastward to Cambridge Gulf, which is a long, deep, Y-shaped inlet, and, though tapering near its mouth, has a fairly uniform width. Near the seaward end its course is almost from north to south, but inland the main branch bends to the south-south-west and then to south-west, and becomes approximately at right angles to the directions of the chief fiord-like inlets along the Kimberley coast.

The existence along this coast of inlets which, whether fiords or fiards, belong to that group of inlets is significant, as there are several reasons for the belief that a former land which connected this part of Australia to Timor and the Malay Archipelago has foundered beneath the sea. The trend of the inlets is approximately parallel to the longer sides of the great deep, over 20,000 ft. in depth, lying to the south-west of Timor and the south-east of Java. The lines of weakness along which these Australian inlets run are probably tectonic in origin, and connected with the formation of the adjacent ocean deep.

CHAPTER XVI

THE FIORDS OF NEW ZEALAND

My basking sunfish know it, and wheeling albatross,
Where the long wave fills with fire beneath the Southern Cross.
KIPLING.

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1. Distribution of the Fiords.—2. Geology; the Fiord District a dissected Plateau.—3. Three Types of Fiords.—4. Walls.—5. Hanging Valleys.—6. Depths.—7. Thresholds and Glacial Erosion.—8. Glaciation of New Zealand.—9. Reduced Claims for the Influence of Glacial Agents.—10. The Fiord-valleys Preglacial.—11. Their Tectonic Origin.—12. Summary.

1. DISTRIBUTION OF THE FIORDS

THE south-western coast of New Zealand is broken by a group of sounds which are famous for their supreme beauty and are of special geographical interest, as in them some essential characteristics of fiords reach their extreme development. Owing to the geological structure of that corner of New Zealand, and the recent date of its last earth-movements, which may indeed be still in progress, the fiords lie between majestic precipices, which, thanks to the wet climate and the special character of the New Zealand flora, are draped, wherever plants can get a foothold, with vegetation of tropical luxuriance.

The fiords are fourteen in number [1] and open to the sea at intervals along some 120 miles of coast from the latitude of 44° 30′ S. to 46° 10′ S. The fiord country

[1] The sounds on the southern shore of Cook Strait may once have been fiords, but they are usually regarded as rias, a view adopted by P. Marshall (**1905**, pp. 72–73), and the author (**1907**, p. 564).

extends inland to the 168th meridian. Its eastern border passes along Preservation Inlet, the southernmost of the fiords, and thence north-eastward to Lake Manapouri, past the long, straight, eastern shore of Lake Te Anau and down the Hollyford River through Lake Mackerrow to Martin's Bay. The block of mountainous country between this line and the western coast includes all the typical fiords. The Palæozoic rocks, of the Kakanui series, to the east of Preservation Inlet, include several fiord-like lakes, Lake Poteriteri, Lake Hauroko, and Lake Monowai; fiord-like also are the well-known "Cold Lakes" of New Zealand, to the east and north-east of the region of the sounds.

FIG. 63.—DISTRIBUTION OF NEW ZEALAND FIORDS.

The sounds of south-western New Zealand are, for fiords, comparatively short, but they are narrow and have exceptionally high walls. They lie along two series of intersecting lines. The first series trends from between north-north-west to south-south-east and north-west to south-east. This series embraces the most northerly of the fiords, including Milford Sound, George Sound, Charles Sound, Nancy Sound, Thompson Sound, and Doubtful Sound. The fiords of the second series trend from between west-south-west to east-north-east and south-west and north-east, though some aberrant

FIG. 64.—MAP OF MILFORD SOUND, NEW ZEALAND.

members of the series lie about east and west. This second series contains Bradshaw Sound and the inner so-called "Foot Arm" of Nancy Sound, Breaksea Sound, Wet Jacket Sound, Dusky Sound, the two branches of Chalky Inlet, and Preservation Inlet.

Some of the fiords have reaches belonging to both series. In such cases the fiord may be simple and zigzag in course; or it may have an L-shape, like Nancy

Sound, in which a short branch, the "Foot Arm," projects like a foot from a leg; or by the intersection of the channels, the land may be broken up into islands such as Resolution Island, which is separated from the mainland by the Acheron Passage between Breaksea Sound and Dusky Sound.

These New Zealand fiords, therefore, include both the straight, simple type like Lyse Fiord, and the intersecting series of fiord-straits forming groups of angular islands like those near Trondhjem.

2. Geology of the District

The somewhat triangular tract of fiord country is composed of the most ancient rocks of New Zealand. They are the members of the Manapouri System, which are regarded as Cambrian by some authors; for instance, by Professor J. Park[1]; but, according to the older view (still adopted, for example, by Dr. Marshall, **1905**, p. 382), they are Archean. As the rocks include syenitic gneiss, mica-schists, and hornblende-schists, it seems safer to regard them as Archean until there be more definite evidence of their Cambrian age.

The Fiord District a Dissected Plateau

The fiord country is a deeply dissected plateau which may have been above sea-level since Jurassic times. Its surface was formerly a pene-plane, but the country is now intensely rugged and mountainous; that it is an old plateau has been shown by relief-diagrams.[2] That this district has the typical characteristics of a dissected pene-plane—viz. numerous parallel ridges, along whose crests the summits all reach one straight line and no single mountain rises much higher than the rest—is apparent

[1] J. Park, *Geology of New Zealand* (**1910**, p. 29). This work includes (pp. 409–64) a valuable bibliography of New Zealand geology.

[2] See, for example, diagram in Marshall (**1905**, p. 103).

from the description by Anthony Trollope quoted on page 483.

This old plateau has been affected by repeated variations in level. Hutton, in his *Geology of Otago*, has given a diagram (pl. ii. p. 85) to represent the great uplifts of the district in the Eocene and Pliocene periods and their separation by an interval of deep subsidence broken by a minor Miocene uplift. The effect of these oscillatory movements must have been the rending of the country by intersecting faults and fractures.

The level of this fiord country is high. The ground rises steeply from the sea to heights of usually over 3,000 ft. The old plateau-surface is lowest near Preservation Inlet, and it is well shown in photographs [1]; further north the plateau is higher, but it is less conspicuous from the coast. Inland the level rises gradually to mountains of some 5,000 ft. to over 6,000; the higher peaks appear in the north, where Castle Mountain, to the north-west of Lake Te Anau, rises to 6,872 ft., and Tutoko Peak, to the north-west of Milford Sound, reaches the height of 9,042 ft.

The coast has been described by Sir George Bowen as bounded by a "sea-wall of steep and rugged cliffs" (in *Trollope*, p. 681); but the late Prof. F. W. Hutton (**1875**, p. 79) described the seaward shore as a series of steep slopes and as marked by an absence of high cliffs. He inferred therefrom that the land was still moving upward or downward, as otherwise the surf would have cut the land backward into well-developed cliffs. This view is also adopted by Dr. Marshall (**1905**, p. 77).

3. Three Types of Fiords

The fiords of south-western New Zealand may be divided into three main types. The first group includes simple fiords, which are long and narrow; they may be

[1] *E.g.* Andrews (**1906**, fig. 2, p. 26).

unbranched, and slightly bent, as in Milford Sound, or bent at sharp angles such as Bligh Sound and Nancy Sound; or they may be branched, such as Charles Sound.

The second group consists of fiords which belong to a network; such are Thompson Sound and Doubtful Sound beside Secretary Island, and Breaksea and Dusky Sounds beside Resolution Island.

The members of the third group are less uniform in width; they are wedge-shaped, and have many small islands at their mouths; such are Chalky Inlet and Preservation Inlet.

4. Walls

The New Zealand Fiords are remarkable for the exceptional steepness of their inner walls and the size of the facets which end many of the spurs.[1] The sea-coast is bounded by slopes rather than cliffs; but within the fiords the banks become steeper until they rise in lofty precipices, that are all the more impressive as they are straight and spurless. The walls have been well described and illustrated by Mr. E. C. Andrews (**1906**, pp. 26–38), who represents the fiord-valleys as canyons from 5,000 to 6,000 ft. deep; and he says their majesty is so continuous that it becomes almost monotonous.

He also describes the bases of the cliffs (Andrews, **1906**, pp. 26, 27) as being rectilinear, as if the spurs that must once have projected from them had been cut off.

"The idea," he says, "suggested from a study of these forms is that of a former series of overlapping spurs which have been subjected to some mighty force, whose maximum strength had been exerted along the lower and central valley-channels, causing the planing off of spur-ends in some cases, and utter shrivelling up of spurs against the canyon walls in others" (Andrews, **1906**, p. 27).

[1] Speight has referred to the faceted spurs as evidence of the enormous power of glacial excavation (**1910**, p. 258).

The remarkable straightness and steepness of the walls of the New Zealand fiords are shown in many well-known photographs; and their canyon-like structure is all the more striking owing to the extreme wetness of the climate. The mean annual rainfall is probably over 200 inches, as it is 228 inches at Puysegur Point, near the southern end of the fiord-coast. As this heavy rainfall has not yet widened the canyons into ordinary valleys, they must be comparatively young, though the hardness of the rocks has helped their resistance to the attack of the weather; for to the east and south-east of the fiord district, in areas composed of softer Palæozoic beds, the valleys are wider and have gentler slopes. Hence Lake Wakatipu, though doubtless occupied by ice at much the same time as the fiords, lies in a basin and not in a canyon.

Owing to the slight cutting backward of the walls of the canyons, the lateral streams leap in high waterfalls directly into the sounds. Thus, the Bowen Falls discharge into Milford Sound from a broad, hanging valley over a cliff 550 ft. high. The volume of the water is sometimes so great that steamers approaching the foot of the falls are swept back by the eddying outrush. The Sutherland Fall descends usually in three leaps, but sometimes, it is said, in one, from a height of 1,900 ft., and it is claimed to be the highest waterfall in the world; it occurs on the wall of the valley, which continues inland from the head of Milford Sound.

5. Hanging Valleys

Hanging valleys are also extremely well developed in connection with the New Zealand fiords, and are especially well shown at Milford Sound. They are geologically of historic interest, as the now popular theory that hanging valleys are due to the over-deepening of a main valley by glacial erosion was first advanced to explain these New Zealand examples. Sir James Hector advanced this hypothesis in a report [1] published by the Provincial Government of Otago in 1863. Hector described Milford Sound as "a chasm that was in past ages ploughed by an immense glacier"; and he continues, "The lateral valleys join the main one at various elevations, but are all sharply cut off by the precipitous wall of the sound, the erosion of which was no doubt continued by a great central glacier long after the subordinate and tributary glaciers had ceased to exist."

6. Depths

The New Zealand sounds are also typical fiords owing to their considerable depth. Milford Sound, according to the Admiralty Chart,[2] reaches the depth of 1,284 ft. Its floor shallows to 360 ft. near its inner end, and it has a threshold of about the same depth across its mouth. Subsequent soundings have increased the recorded depth. Thus, according to Andrews's section across the sound, reproduced as Fig. 65, the depth of 1,500 ft. occurs opposite the Lion Rock, only fifty yards from the shore. Most of the sounds have depths of over 600 ft., and depths of over 1,200 ft. are met with in several, as in Breaksea Sound.

The basins, moreover, so far as the soundings are available, are flat-floored, as is well shown in Andrews's section (Fig. 65).

7. Thresholds and Glacial Erosion

All the sounds occupy basins. Thus, Hutton [3] remarked that the sounds "universally become shallower at their entrance into the sea." The New Zealand sounds,

[1] Most of it was republished in *Journ. R. Geog. Soc.*, vol. xxxiv. pp. 96–111 (1864).

[2] No. 2,589, 1872.

[3] F. W. Hutton and G. H. F. Ulrich, *Report on the Geology and Goldfields of Otago* (1875, p. 5).

in fact, supply the most regular series of fiord-thresholds in the world. Thus Milford Sound is only 360 ft. deep at its mouth. George Sound increases steadily in depth from 138 to 636 ft. near its mouth, where it quickly shallows to 234 ft. Charles Sound increases steadily from 60 ft. to 1,128 ft. and then at its mouth decreases quickly to 228 ft. Nancy Sound is somewhat less regular; its "Foot Arm" sinks to 426 ft. and is therefore deeper than the upper part of the main channel. The sound itself then deepens steadily from 288 to 756 ft. and is crossed at its mouth by a threshold of only 240 ft. deep. Breaksea Sound is also less regular than most, as its upper part, the Vancouver Arm, appears to be deeper than the main channel. The maximum depth of 1,260 ft. is reached opposite the mouth of the Acheron Passage, after which the floor rises seaward to a threshold of 630 ft. The Wet Jacket Arm is a basin descending to over 672 ft. and separated by a threshold of 324 ft. from the Acheron Passage, which, opposite its mouth, is 624 ft. deep. Dusky Sound, fronting the mouth of the Acheron Passage, has a depth of 972 ft., while its mouth is only 216 ft. deep.

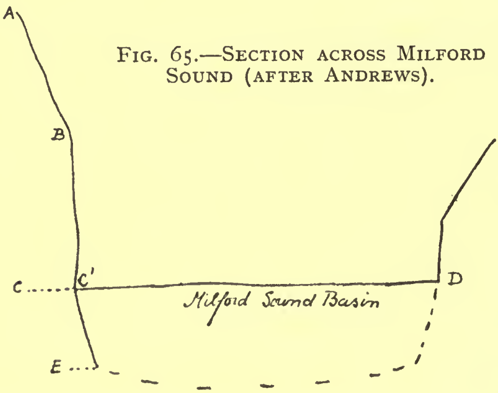

FIG. 65.—SECTION ACROSS MILFORD SOUND (AFTER ANDREWS).

The thresholds are so well developed that Dinse (**1894**, p. 220) has selected the New Zealand fiords as the most typical simple fiord-basins in the world. The great depth of the inner basins is attributed by Andrews to the varying powers of glacial erosion; he considers that the extent to which glaciers excavate their beds varies with their rate of flow. Basal erosion is increased where the speed is raised by the narrowing of the channel or by the increase in the volume of ice; but, where the glacier moves more slowly, the channel is left shallower. On that hypothesis, as the valleys widen at their mouths, the glaciers should have less excavating power there, and the floor should accordingly be left as a raised threshold. This explanation seems to me inadequate. The deepening of Milford and Charles Sounds, for example, progresses with fair regularity from the head to the inner sound; nor does there appear to be any reason, judging from the maps, why in George Sound, Charles Sound, or Nancy Sound, the pace of the ice-stream should have been accelerated at the places of the greatest depth. Nancy Sound, for example, is shallower where the "Foot Arm" branch is joined by a tributary from due south; and there seems no reason why the velocity should have reached its maximum close to the mouth. Charles Sound, again, is Y-shaped, and the depth is only 300 ft. at the confluence of the two arms; whereas near the mouth, at a point where the channel is a little above its average width, the depth is 1,128 ft.; and there is no indication of any lateral glacier having entered the valley at that locality. The apparent discrepancies between the theory and the facts recorded on the maps may be due to the incompleteness of the maps; but, as the theory fails for other areas where the evidence is more complete, I am sceptical of its application to the New Zealand fiords, especially as a simpler explanation of the thresholds is available. This coast is swept by a strong current, and in Westland, the next province to the north, the rivers are all blocked at their mouths by alluvial bars; and the drift of the shingle is there so powerful that many of the rivers, such as the Totara River and the series of streams that discharge through the outlet from Lake Mahinapua, have had their mouths pushed miles northward. This fact is illustrated by a map prepared for a New Zealand Geography in 1904.[1] The same process has probably been at work off the south-western coasts of New Zealand. The ice from the fiord probably melted rapidly when it reached the sea, and all the interglacial material was therefore deposited as a bank of moraines forming a threshold across the mouth of the fiord. This bank may have been rounded and smoothed over by the action of tide and current; and it may have been raised by the addition of shingle which was washed along the coast by the current and collected in the sheltered water within the mouth of the sound.

The nature of the New Zealand thresholds is still uncertain, for the fiords have not been sounded adequately. The regularity of the thresholds suggests that they may be banks of sediment due to the piling up of moraine matter and coastal shingle near the mouth of the fiords. This view of their origin is, however, rejected by Prof. Marshall (**1905**, p. 73). The thresholds may be rock-barriers raised by tilting of the coastal area; for, as remarked on page 354, the uplift of the coast is indicated by the raised beaches and the nature of the present shore. The great size of the thresholds appears to favour the rock-barrier explanation, but their bulk does not fully disprove their sedimentary structure; for the shore accumulations along the coast to the north of the fiord district are colossal, and the basins of the fiord-like lakes to the east have been closed by the joint action of warping and the deposition of gigantic moraines. According to Hutton (1875, p. 7), "the arms of Lake Te Anau and Manapouri exactly resemble the sounds on the west coast." The basins of these lakes are usually wider than the western sounds, which is a natural consequence of the fact that their walls are built of

[1] J. W. Gregory, *Imperial Geography*, Standards III., IV., Christchurch, N.Z. (**1904**, p. 71).

weaker rocks. The nature of these lake-basins has recently been discussed by A. E. Kitson and E. O. Thiele (**1910**, pp. 540, 541, 545, 549), who conclude that Lakes Tekapo, Pukaki, and Ohau, the three chief lakes on the three branches of the Waitaki River, are all moraine-dammed.[1] They describe the enormous thickness of some of the moraines in the valleys of that district.

The flatness of the fiord-floors may also be regarded as a feature due to ice-action; but many lakes with equally flat floors are certainly not due to glacial erosion. Thus Prof. Marshall, who is one of the advocates of the view that ice has played the leading part in modelling the New Zealand fiords, has published a section across Lake Taupo showing that it has a remarkably flat floor with steep sides.[2] I found it to be a typical subsidence cauldron. It occurs in the northern island in an area that, according to most New Zealand geologists, lay outside the area of the former glaciation.

8. Glaciation of New Zealand

The chief existing problem in reference to the glaciation of New Zealand is the former extent of the glaciers. According to Prof. James Park (**1910**, p. 14), the glaciers covered the whole of the South Island and most of the southern part of the North Island; but, according to the map by von Haast (**1879**, pl. ii. p. 370) the glaciers that flowed down the eastern slopes of the New Zealand Alps did not reach the sea. It was only in the extreme southern part of New Zealand, at the mouth of the Taieri River (lat. 46° 10′ S.) that undoubted moraines occur at sea-level on the eastern coast.

In a traverse of New Zealand and from Canterbury to Westland in 1904 I saw no evidence of the former occupation by glaciers of the Canterbury Plains in the

[1] This view has also been supported in regard to Lake Pukaki by Dr. J. M. Bell (**1907**, pp. 183, 184).

[2] Marshall (**1905**, fig. on p. 169).

eastern lowlands of New Zealand (Gregory, **1907**, p. 600), and the conclusion as to the restricted range of the glaciers is also adopted by Dr. Marshall (**1905**, p. 160).

If Prof. Park's view be correct, the advocates of the glacial origin of the fiord-valleys are faced with the difficulty of the absence of fiords on the eastern coast. Moreover, the New Zealand glaciers are, at the present time, best developed in the Alpine region around Mount Cook; and it is probable, from the great size of the moraines around that district, that the ancient glaciers attained their maximum thickness and development in the same area. Nevertheless, the western coast near the chief glacial centre is straight and unbroken, instead of being fiord-indented. The glaciers in that area have flowed down steep valleys on both sides of the Alps, and they have left these valleys with steep parallel sides. One of the most remarkable is the Franz Joseph Glacier, which at the present time descends only to some 700 ft. above sea-level. This glacier has not worn out for itself a deep basin, though near the end of the glacier the valley is crossed by a rock-barrier which it has not been able to wear away.

9. Reduced Claims for the Influence of Glacial Agents

That the fiords of the south-western coast of New Zealand have been occupied by ice is undoubted. There is, however, a strong conflict of opinion as to whether the ice has played a primary or a secondary part in their formation.

Von Haast appears to have regarded the ice as almost solely responsible for the formation of the fiord-valleys. He recognised that the fiord district was a dissected plateau, and that the early depressions on it were often along faults and fractured folds (Haast, **1863**, p. 130); but he thought that the old depressions were largely obliterated, and he says that glaciers "soon formed for themselves channels in the plateau-like mountains" (p. 131).

Sir J. Hector was of much the same opinion. He described Milford Sound as "a chasm that was in past ages ploughed by an immense glacier" (**1864**, p. 100), and in recent years this view has been reaffirmed by Prof. Marshall (**1905**, p. 74) in his statement that probably glaciers "are responsible for the excavation of all the West Coast Sounds."

Nevertheless, according to most later geologists, the ice played only a subordinate part in the formation of fiords. The recent paper by Mr. E. C. Andrews, who is an enthusiastic advocate of glacial erosion, illustrates the recent tendency to attribute reduced importance to glacial erosion in connection with these fiords. Thus he says that, though the region of Lakes Te Anau and Manapouri has been intensely glaciated in recent times—

"It is difficult to assign the exact share that earth-movements and erosive activities have had in producing this magnificent topographical feature, but it is evident that corrasion [1] has had only a minor share in producing the total result."

"The beginning of the fiords which break its western and northern walls may also have been in heavy cross-faulting, but it is certain that the fiords have been intensely glaciated during the recent Ice Age, and that the long and profound cañons discharging into the fiords may be easily explained by erosive processes alone" (Andrews, **1911**, p. 135).

He repeats that—

"In some cases, for example, Dusky Sound, Doubtful Sound, Lake Manapouri and Lake Wanaka, it is highly probable that the basins have originated in heavy faulting action with the production thus of senkungsfelder, and

[1] He uses "corrasion" in Powell's sense; *vide* p. 397.

that the senkungsfeld valleys have in later time been modified and extended headwards as cañons, first by ordinary streams and then by ice-action. . . . Some of the lake and sound basins, such as those of Wanaka, Hawea, Wakatipu, Manapouri, Te Anau, Doubtful, Breaksea, and Dusky Sounds are situated also where one could not expect them to be, if they had been the products of stream corrasion, and their maximum depths, moreover, occur in places where the maximum stream scour could not have taken place" (Andrews, **1911**, p. 136).

10. The Fiord-valleys Preglacial

The secondary importance of glacial action in the formation of the fiords is a natural deduction from the demonstration of their preglacial age, a view maintained by Hutton (**1875**, pp. 10, 77, and 83 n.). The fiord district was raised into a plateau in Eocene times and early Kainozoic denudation carved out a series of great valleys, some of which were subsequently filled, or partially filled, by sediments. Hence, when the glaciation began toward the end of the Kainozoic era, the glaciers found valleys already in existence and deepened them by removal of the soft and decayed materials upon their floors. The passage of the ice down the valleys no doubt modified their form; any projecting spurs from the sides would have been worn back, and sinuous river-valleys would have been converted into broad, trough-shaped, glacially moulded valleys. The valleys, however, were in existence before the advent of the ice, and New Zealand rivers are capable, without its aid, of forming trough-valleys.

11. Their Tectonic Origin

Owing to the preglacial age of the fiord-valleys, glacial excavation cannot explain their distribution or origin, and the view that they are due to tectonic causes has been growing steadily in recent years. I maintained in

1907 that the theory of the glacial excavation of the fiords is unsatisfactory, and that they occur "along a series of regular intersecting tectonic fractures" (Gregory, **1907**, pp. 564, 595, 596).

Percy Morgan (**1908**, pp. 455, 456), of the New Zealand Geological Survey, a year later attributed a moderate influence to glacial action and explained the U-shaped valleys of southern New Zealand by glacial excavation along stream-valleys, along fault-lines, and along trough-faults.

An interesting summary of the recent literature on the subject has been given by Kitson and Thiele, and they conclude (**1910**, p. 551), that the "Waitaki basin is due to preglacial erosion, faulting, with probably some warping, modified by glacial action."

The tectonic origin of the fiords has been recently advocated by Speight. He accepts Andrews's view that they are old river-valleys modified by glaciation, but he recognises that the original course of the valleys was dependent on lines of fracture in the earth's crust.[1]

Thus, in reference to my suggestion that "fiords always occur in fractured tablelands,"[2] he says, "It is extremely likely that this is the case here, although there is no positive evidence of their [the fractures] presence" (Speight, **1910**, p. 256). He points out the difficulty of explaining otherwise the course of the Wet Jacket Arm. He says the soundings in it do not indicate that it was formed by the lowering of a divide by ice-erosion. "It

[1] The lake-basins of Otago have also been frequently assigned to earth-movements, as by McKay (**1884**, p. 80). He attributes them to fractures due to a lateral thrust caused by the subsidence of the land east of New Zealand. Prof. J. Park (**1910**, pp. 230, 231) accepts some of the smaller lakes as "exaggerated tarns" scooped out by ice on the floor of fault-valleys; in some cases he describes the fault as determining the course of the preglacial valley and the rock-basin as due to excavation by ice. The origin of Lake Wakatipu he assigns to the powerful faults that traverse it, and considers that a lake occupied part of the valley in preglacial times.

[2] J. W. Gregory (**1908**, p. 53).

can be most easily explained as being the result of a cross-fracture" (Speight, **1910**, p. 256). He also regards the orientation of these valleys as probably dependent upon fracture-lines which were due to the great earth-movements in this district, such as the enormous fault which forms the eastern boundary of the fiord district.

The dominant influence of faults on New Zealand geography was first recognised by A. McKay in 1891. His views were long ignored and even ridiculed, but they have gained more general recognition in recent years. In a remarkable memoir McKay (**1891**) showed that the South Island of New Zealand is traversed by thirteen major faults; several of them have had an important influence on the fiord area. Thus its eastern boundary, along Lakes Te Anau and Manapouri, is along the Te Anau-Hollyford fault, which, according to McKay (**1891**, p. 23), is probably of very recent date. He attributes the abruptness of the western slopes of the New Zealand Alps to the Motueka Fault, which traverses the fiord region, where various branches of the fiords and the peninsula portion of Resolution Island are parallel to it. The main coast-line of the fiord region from Cascade Point to Doubtful Sound is probably along a parallel fault-plane. Nearly at right angles to this great fault are the Waihemo and Waiholo faults, which are parallel to Charles Sound, Doubtful Sound, and parts of other fiords.

Many of the fiord-channels are parallel to the great faults, but the direction of the fiords is not solely determined by the major faults. A map by Dobson published in 1879[1] shows that the main topographic features of the Southern Alps are arranged along radial lines which converge to a point off Cliffy Head in Westland Bight, the wide bight on the western coast of the South Island. Dobson's radial lines and McKay's faults are shown on

[1] Republished in von Haast (**1879**), opposite p. 176. A copy of it on a smaller scale is given on the map illustrating Kitson and Thiele's paper (**1910**).

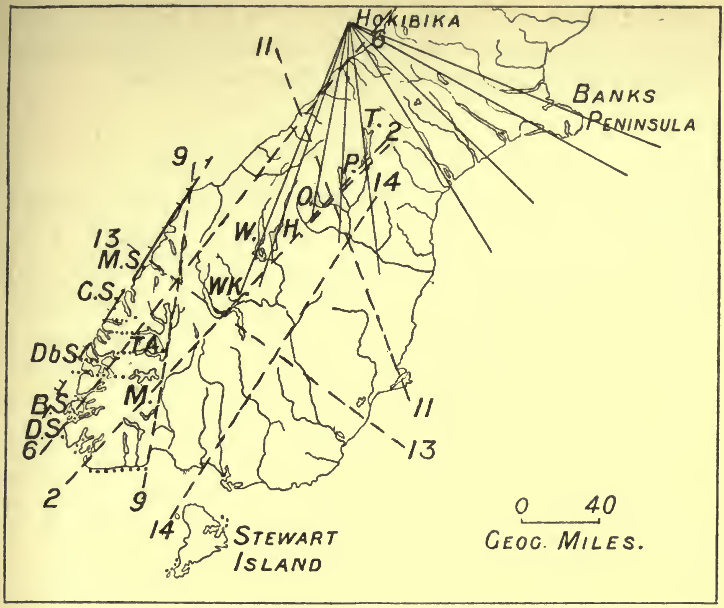

FIG. 66.—THE FAULT-SYSTEM OF SOUTH-WESTERN NEW ZEALAND.

——— Dobson's Radial Topographic Lines from a centre W.S.W. of Hokitika.
- - - - - Major fault-lines of McKay (the Nos. are those of McKay's memoir).
⊥⊥⊥⊥⊥ Fault along the fiord coast (after Park).
. . . . . . Conspicuous east-west lines.

B.S.—Breaksea Sound.
D.S.—Dusky Sound.
Db.S.—Doubtful Sound.
G.S.—George Sound.
M.—Lake Manapouri.
M.S.—Milford Sound.
H.—Lake Hawea.
O.—Lake Ohau.
P.—Lake Pukaki.
T.—Lake Tekapo.
T.A.—Lake Te Anau.
W.—Lake Wanaka.
W.K.—Lake Wakatipu.

a sketch-map (Fig. 66), with the fault along the western coast of Otago that has been added by Park (**1910**, p. 265).

The distribution of the fiords is apparently due to faults combined with a network of intersecting fissures caused by the stretching of the country during the last great uplift. Many of the fissures thus produced naturally occur along the faults as they took advantage of these lines of weakness; and, as the intervening belts were traversed by cross-fissures, the country would have been broken up by a network of fractures, and these tectonic fissures were enlarged by the various agents of denudation into the valleys of the existing fiords and lakes.

12. Summary

Hence the fiord district of New Zealand is an ancient plateau which has undergone extreme oscillations in level, involving great uplifts in the Jurassic, Eocene, and Pliocene. These uplifts occasioned a network of faults and fractures; and the foundering in recent geological times of the land to the west of New Zealand probably refractured the fiord area. The fiord-valleys, and the Alpine lake-basins, which doubtless had the same origin as the fiords, are preglacial in age. They have been modified by the glaciation, but their tectonic origin is now being generally admitted.

CHAPTER XVII

THE FIORDS OF ANTARCTICA AND SOME SUB-ANTARCTIC ISLANDS

Beyond this flood a frozen continent
Lies, dark and wild, beat with perpetual storm
Of whirlwind and dire hail, which on firm land
Thaws not, but gathers heap, and ruin seems
Of ancient pile, or else deep snow and ice;
. . . . the parching air
Burns frore, and cold performs the effect of fire.

MILTON.

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1. THE UNEQUALLED GLACIATION OF ANTARCTICA

THE continent of Antarctica is covered by the greatest ice-sheet in the world, and from its inland-ice colossal glaciers flow outward to the sea. The glaciation of Antarctica is unrivalled in extent; hence, if fiords be formed by ice-erosion, all the coasts of Antarctica should be indented by fiords. These should be well exposed, as in various parts of the continent the glaciers have been for some time in retreat. The valleys thus left empty have been straightened in their course, their spurs have been flattened, and the adjacent peaks have been faceted; the valleys, therefore, show characteristic signs of ice-action. An illustration of this may be seen in a photograph of the King Oscar Coast by Dr. O. Nordenskjöld (**1911**, p. 77), where a series of peaks have been faceted into pyramids as well developed as the Dreieckhorns beside the Aletsch Glacier.

2. Its Fiordless Coasts

The coast of Antarctica as a whole is, however, free from fiords. Thus Lieutenant Mulock's charts of the coast of South Victoria Land show that there is not one fiord along its whole length of over 7° of latitude.[1] The coast projects in headlands separated by broad, open bays, such as Lady Newnes Bay and Terra Nova Bay, and smaller harbours such as Tucker Inlet or Granite Harbour. Biscoe Bay, in King Edward VII. Land, on the opposite side of the Ross Sea, is also a wide-mouthed bay.

The coast of Wilkes Land is still little known, but it is probably similar to the southern coast of Australia, so that it may have many open bays with possibly some deep gulfs corresponding to Spencer Gulf in South Australia. Such a gulf in a glaciated country would be generally claimed as a fiord, and any counterpart in Wilkes Land to that submerged rift-valley would naturally be regarded as a fiord.

The Fiords of Graham Land

The only known part of Antarctica which has a fiord-indented coast is the region of Graham Land, where the numerous off-lying islands are separated by straits which are fiord-like in character. They are best developed on the northern and western coasts facing Drake Strait and the South Pacific. The Charcot Expedition reports the existence of large fiords along the Pacific coast to

[1] G. F. A. Mulock, *National Antarctic Expedition* (1901–1904). Charts: Roy. Geog. Soc., London, 1908.

the south-west of Graham Land. It is, however, only in north-eastern Graham Land that the coasts have been explored in sufficient detail to throw any light on the problem of fiord-formation ; and the channels there are not typical fiords.

The main channels are a series of straits parallel to the main coast ; they include Bransfield Strait between the South Shetlands and Graham Land, and the Gerlache Strait between the latter and the Palmer Archipelago. On the southern side of this part of Graham Land the coast occurs in long, curved, open bays.

Nordenskjöld, however, regards some of the inlets in this district as fiords. He says that Gerlache Strait may be regarded as a fiord running parallel to the coast. Dr. Gunnar Andersson has shown that it was once filled with ice, and Nordenskjöld has remarked that the ice has moulded the form of the strait. But, he adds, it is, however, almost impossible that these valleys could have owed their origin exclusively to the work of ice (**1911**, p. 184).

3. The Fiord-straits of Graham Land Tectonic in Origin

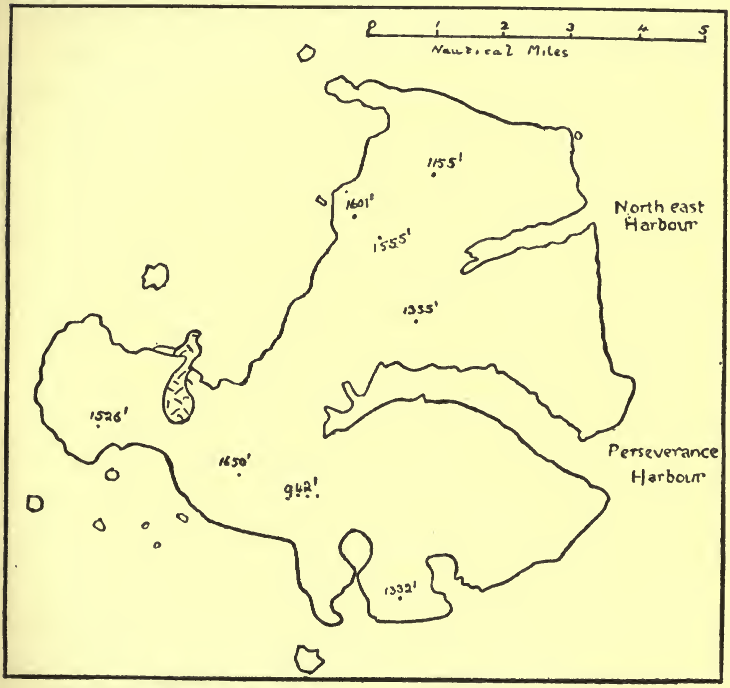
J. Gunnar Andersson (**1906**, p. 62) in his memoir on the geology of Graham Land, states that " the large Bransfield Strait is a tectonic basin." Dr. O. Nordenskjöld (**1911**, p. 184) also explains this channel as a sunk-land, and says no other explanation is possible. He accepts the Gerlache Strait as nearly allied in origin. Gunnar Andersson (**1906**, p. 62) regards the Crown Prince Gustav Channel, the narrow Admiralty Sound, and Sidney Herbert Sound as valleys of erosion made " in very late Tertiary or early Quarternary times " ; he adds that, during the glaciation, the ice " continued the dissecting work carried out before by running water and other sub-aerial agents " (Andersson, **1906**, p. 63). He therefore regards them as preglacial in origin though modified by ice. His conclusion that the chief valleys were preglacial in origin naturally followed from his evidence that the elevation of the country was much greater in preglacial times. The straits of Graham Land, according to Dr. Nordenskjöld, may have originated like the longitudinal canals of Patagonia, as a kind of step-fracture (*Staffelbruch*) due to a derangement (*Zerrung*) connected with the folding of the area. He attributes their present form to ice, but adds it is not yet certain that these valleys did not receive their full development from tectonic forces connected with the disturbances of the earth's crust during the glacial period.

It is significant that the one coast in Antarctica which is fiord-like in character is that facing the fiord-coast of Patagonia; and the Graham Land region has probably shared its recent oscillatory movements. So far as is at present known, the remaining coasts of Antarctica, in spite of their intense glaciation, are free from fiords.

4. The Sub-Antarctic Islands represented by Kerguelen Land

On the other hand, the islands in the seas around the Antarctic area have well-developed fiords. Thus South Georgia, in the south Atlantic, has a series of fiords which, though their actual length is short, are long in comparison with the width of the island.

Campbell Land, to the south of New Zealand, in latitude 52° S., is of interest from its position between New Zealand and the opposite coast of Antarctica. It is a small island about eight miles across, and is deeply indented by two fiord-like harbours, of which Perseverance Harbour nearly bisects the island. Prof. Marshall (**1909**, p. 685) describes their valleys as showing features which are usually the result of glaciation, and he concludes that glaciers once existed on the island. The arrangement of the two harbours suggests, however, that they were probably formed by denudation along a couple of rifts, when the land extended further to the north-west, an extension indicated by the outcrop of a mass of gabbro on the western coast. Campbell Island shows that the process of fiord-formation extended south of



Gabbro area on western shore. Heights in ft.

FIG. 67.—CAMPBELL ISLAND (AFTER MARSHALL).

New Zealand, although not as far south as the opposite coasts of Antarctica.

The archipelago of Kerguelen Land is the best known of the smaller islands with fiord-coasts in the southern hemisphere. It is situated in the Southern Ocean in approximately 50° S. and 70° E. It consists of about 130 islands and 160 rocks. The largest island is 85 miles long and 70 miles wide, but the area of land is only 2,050 square miles, as all its eastern plains have been flooded by the sea. The chief island has been reduced to a somewhat L-shaped form; but the inner coast-line is exceedingly irregular, and the base of the L forks at its eastern end into two peninsulas. According to the Rev. A. E. Eaton (**1879**, p. 1), one of the naturalists

Fig. 68.—Kerguelen Island.
Altitudes (in ft.) from German Antarctic Expedition.
Soundings (in fathoms) from Challenger Expedition Report.

with the Transit of Venus Expedition of 1874–5, "no part of the interior is more than ten or twelve miles from the sea." [1]

Kerguelen was discovered in 1773 by a French expedition under de Kerguelen. He sailed along part of the coast, but did not even anchor. The first landing

[1] As Kerguelen has the largest and best-known of the fiord-systems on the Sub-Antarctic islands, it may be considered as a representative of this group.

was in 1776 by Captain Cook, who proved that it is a group of islands, and not a projection from the Antarctic Continent; he named several of the harbours, including Royal Sound and the Prince of Wales Foreland. The archipelago has since been frequented by whalers and sealers, and has been visited by numerous scientific expeditions, including that of Sir James Clark Ross, the *Challenger* in 1874, the British and German expeditions for the observation of the Transits of Venus in 1874 and 1882, and the German South Polar Expedition in 1901–3.

Distribution of the Fiords.—The most striking feature in the map of Kerguelen is the contrast between its eastern and western sides. The western coast is long and comparatively even. The land rises from it to a highland covered by the Richthofen Ice-sheet, so named by Dr. E. Werth of the German South Polar Expedition. The island is very mountainous. The chief mountains are Mount Ross (6,120 ft.), the highest in the island, which stands on a projection on the southern coast, Mount Richards (4,000 ft.), which rises above the northern part of the Richthofen Ice-sheet, and Mount Crozier (3,250 ft.), which stands on the isthmus connecting the eastern peninsula with the mainland.

The eastern coast is extremely intricate, and is fringed with islands and skerries, and is penetrated by a series of inlets which have been generally described as fiords. Thus, according to Sir John Murray—

"The whole coast is broken up by deep sounds or fjords, which resemble closely in form the fjords of Norway and other parts of the world. They are long channel-like excavations of the coast line, occupied by arms of the sea, often shallower at the mouths than nearer to the upper extremities, and bounded on either hand by perpendicular cliffs" (Murray, **1885**, p. 332).

Christmas Harbour is described by Sir John Murray as "a small example of one of the Kerguelen fiords; it is a deep inlet with dark frowning cliffs on either hand at its entrance" (p. 332). Renard also accepts the inlets as fiords. He says:

"Numerous deep gulfs penetrate it, cutting the coast line into long narrow fjords. These are similar in all essentials to those of Norway; they are bounded by cliffs rising perpendicularly, and shutting in an arm of the sea often narrowed at its opening. Royal Sound and Rhodes Bay present classic examples of these extraordinary sinuosities of the coast-line" (Renard, **1889**, p. 110).

According to the Rev. E. A. Eaton, "The coast on all sides is exceedingly intricate and abounds in large inlets and narrow fiords, which run far inland at frequent intervals between ranges of precipitous hills" (**1879**, p. 1).

Dr. Werth describes the inlets in the district around the station established by the German South Polar Expedition of 1901–3, as föhrden rather than as fiords (**1908**, pp. 142–4). His photographs of Royal Sound (plate xii. fig. 2) and of West Bay (plate xvii. fig. 1) show that some of the inlets are unquestionably of the fiard type. Others, however, owing to their form, the precipitous nature of their walls, and the height of the adjacent land, may be accepted as true fiords. Thus "Greenland Harbour [p. 340] is a fiord seven miles in length and a little over a mile in breadth" (Murray, **1885**, p. 340). Cumberland Bay, near the northern end of Kerguelen, is about fifteen miles long by one and a half broad, and is strikingly fiord-like owing to its long, straight, parallel sides.

Geology and Recent Earth-movements.—The geological structure of Kerguelen is still imperfectly known. It consists mainly, or perhaps entirely, of volcanic rocks and of sedimentary rocks composed of volcanic debris. The mountains include volcanoes with well-preserved craters; others are remnants of broken-up sheets of lava. Basalt is the chief rock, but some of the older lavas consist of trachyte and phonolite. A few non-volcanic rocks have also been discovered. Sir Joseph Hooker found at Christmas Harbour some beds of impure lignite, or brown coal, and the silicified trunks of some coniferous trees. These deposits are interstratified with the lavas, but their fossil-wood unfortunately gives no precise information as to the age of the rocks. Eaton (**1879**, p. 2) reported the occurrence of limestones and of a fossil shell, but nothing definite is known about either. Among the rocks collected by the German Transit of Venus Expedition near Mount Crozier, Roth (**1875**) identified mica-diorite, red porphyry, and a dolomite similar to that found in association with crystalline schists; but, as Renard (**1889**, pp. 139, 140) suggested, these old rocks may have been brought to Kerguelen by floating ice. The reported "schistoid rocks" and "slates" associated with the coal-beds have been shown by Renard to be only trachytic lavas (p. 117).

The plutonic rocks and the dolomite determined by Roth may, however, have come from the older rocks which form the sub-volcanic platform. If so, Kerguelen Land has been built up by a group of volcanoes resting on a plateau of continental rocks. This view is not improbable, as the archipelago is the summit of a submerged plateau. The fiord district of Kerguelen is only a higher though shattered plateau, of which the structure is still manifest, as around Royal Sound. The existence of the lower submerged plateau is proved by the soundings (Philippi, **1908**, p. 190). Thus, according to Renard—

"The actual island is only the skeleton, one might say, of a great region on which the phenomena of oscillation and denudation have left a profound imprint. The deep-sea soundings in the neighbourhood of the land lead inevitably to this conclusion, as they show the portion above water to be the summit of a great submarine plateau." [1]

[1] Renard (**1889**, p. 110). The same view is expressed by Sir J. Murray (**1885**, p. 347).

The fiords are probably due primarily to this oscillation, though the geology of Kerguelen is still too imperfectly known for a final opinion on the question. Dr. Werth (**1908**, p. 142) claims that the depressions on the surface of Kerguelen are due to erosion, and not to tectonic causes.

The Present Topography Preglacial.—The Kerguelen glaciers were formerly more extensive. That the ice did not completely cover the highest peaks is indicated by their irregular forms, as in the jagged rocks on Mount Ross, which Eaton (**1879**, p. 2), described as "aiguilles," and are well shown in a photograph by Werth (**1908**, pl. xvii. fig. 2). Mount Crozier (3,250 ft.) probably also rose above the ice, for Eaton describes some of its peaks as "singularly picturesque, bristling with pinnacles, needles, and castellated towers of rock" (**1879**, p. 2).

The glaciers were, however, once much larger and Dr. Werth attributes the formation of the valleys to erosion by the glaciers of past ages. The evidence for this conclusion is not convincing, especially as the late Emil Philippi, who also visited Kerguelen with the German South Polar Expedition, has pointed out that the valleys and the existing topography were preglacial (**1908**, p. 193). He says: "In my opinion, the ice found the existing topography already essentially there and did not make it." The glaciers are at present best developed along the western coast, which is comparatively free from indentations. It has only two or three small fiords. The shore at the foot of Mount Ross, the highest mountain in Kerguelen, is also even, for it is gently scolloped and not indented. The fiords do not, therefore, occur in the areas where glacial action doubtless lasted longest and the ice was thickest.

Evidence of the Plan of the Fiord-valleys.—The best test of the origin of fiords is the plan of their arrangement, which does not agree with what might be expected if they were due to glacial excavation. Thus, on the northern part of the eastern coast the most conspicuous inlets, such as White Bay and London Water, trend northward. Further down the eastern coast the islands, the numerous promontories from the Bismarck Peninsula, the adjacent inlets and fiords, all trend west and east. Yet further south, while the two chief peninsulas project eastward, the main fiords and valleys trend to the south-east.

The eastern fiords have, therefore, a somewhat fan-shaped or radial arrangement. The eastward trend of the fiords from Whale Bay to Irish Bay might be explained as due to the action of ice flowing eastward from the ice-sheet around Mount Richards; but the ice from the eastern side of the mountains in the south-western part of the mainland might have been expected to flow north-eastward. The valleys in that district run across the probable line of ice-movement. The land is there crossed by six parallel valleys which trend from west-north-west to east-south-east. The first, proceeding from the west, is the glacier-filled valley at the head of Swain Bay; then follow the two valleys, which have been named by Werth the Second and First Parallel Valleys; next is the Enzensperger Valley, with its chain of lakes; then the American Valley, which leads from Hillsborough Bay past Mount Crozier to Royal Sound; and finally the Studer Valley on the other side of Mount Crozier. Dr. Werth's map of the glaciation of Kerguelen represents the former glaciers as having passed down these valleys; but the course of the glaciers was probably determined by the previous existence of the valleys. It appears most improbable that the two parallel American and Studer Valleys, one on each side of the long narrow ridge of Mount Crozier, should have been excavated by ice flowing from Hillsborough Bay to Royal Sound. It appears difficult to understand why ice should have forced its way right across the eastern peninsula, close beside Mount Crozier, which is one of the highest mountains on Kerguelen, while it had an easy outlet to the sea to the north-east.

The general plan of the Kerguelen valleys does not seem to be the work of glacial erosion. Their arrangement suggests that they are due to fault-action and excavation along lines of weakness due to earth-movements. There appears clear evidence of repeated movements of elevation and depression of the country. Studer (**1878**, pp. 346, 347) recorded evidence of a slight recent uplift; and though Dr. Werth and Philippi saw no raised beaches on the Gauss Peninsula, they found recent shingle and sea-shells up to the height of over 300 ft.; they remark, however, that the materials may have been carried inland by seagulls or sea-elephants (Philippi, **1908**, p. 200). The fiords and fiards give clear evidence of recent subsidence. During the earth-movements parallel and radial rifts were probably formed in the basalt sheets. Some blocks collapsed and preglacial streams appear to have excavated valleys along the lines weakened by fracture. The glaciers have doubtless enlarged and modified the valleys they entered; but the arrangement and forms of the fiords are probably both of tectonic origin.

PART III

THE ORIGIN OF FIORDS

CHAPTER XVIII

SUMMARY OF THE ESSENTIAL CHARACTERISTICS OF FIORDS

These iron-rifted cliffs, that o'er the deep,
Wave-worn and thunder-scarred, enormous lower,
Stand like the work of some primeval Power,
Titan or Demiurgos, that would keep
Firm ward for ever o'er the bastioned steep.

AUBREY DE VERE.

1. Characteristics used in Definitions of Fiords: (*a*) Shape and Dimensions; (*b*) Thresholds; (*c*) Hanging Valleys; (*d*) Parallelism; (*e*) Restriction to High Latitudes; (*f*) The Fiord-valley and Fiord-trench.—2. Definition Accepted.—3. Transition from Fiords to Allied Inlets.—4. Transient Nature of Fiords.—5. The Essential Features of Fiords.—6. The Fiord Problem.

1. CHARACTERISTICS USED IN DEFINITIONS OF FIORDS

(*a*) *Shape and Dimensions.*—The account in the previous chapters of the chief fiord districts of the world shows that the name "fiord" has been used for arms of the sea of very different kinds. There is no agreement as to the precise definition of fiord, though it is generally agreed that fiords are narrow arms of the sea which are bounded by steep walls. The definition by Hahn (**1883**, p. 137), that fiords are "long, narrow arms of the sea mostly bounded by steep, high walls," includes the characteristics which have been accepted by most subsequent authors. But in regard to the other characteristics opinions have differed greatly. Peschel, in 1866 (see, **1870**, pp. 8, 9), laid stress on the facts that fiords are usually at a high angle to the coast, and he attached especial importance to their groupal habit. Le Conte[1] in his definition that fiords are "half-submerged glacial valleys" insisted on their glacial origin, whereas Hahn (**1883**, p. 141) had been emphatic that some fiords had certainly never been occupied by ice. He states that "Fiord coasts can occur where glaciers were never present" (**1883**, p. 153).

Various mathematical attempts have been made to distinguish between fiords and allied arms of the sea, of which the most precise are those of Schwind (**1902**), for the rias coasts and that of Jordan (**1903**, pp. 16–50), for the föhrden coast of Schleswig and eastern Denmark; but, though their figures illustrate the extreme irregularity of such coasts, the attempts at numerical distinctions have not proved very helpful.

(*b*) *Thresholds*.—It has often been proposed to regard the existence of a shallow mouth separating a deep basin from the outer sea as an essential characteristic of a fiord; the presence of such a threshold was first claimed as an invariable rule by Leipoldt in 1879 (in Peschel, **1879**, p. 480). The truth of this "law" has been denied by both Dinse and Nordenskjöld, though they both admit the general truth of the principle. Dinse (**1894**, p. 215) restates it in the form that "before all fiord districts there is a shallow sea, whose limited depths offer a striking contrast to the considerable subsidences within the fiord-broken zone."

The presence of a threshold is a usual but not a constant characteristic; but the existence of this barrier would only be of much geological significance if it were made of solid rock; and in many cases it is admittedly only

[1] I. Le Conte, *Elements of Geol.*, p. 597, 5th ed. (**1903**).

a bank of sediment. This opinion of the nature of thresholds is essential to the view held by von Richthofen (**1886**, p. 302), of the origin of fiords. Prof. Herbertson (**1910**, p. 39) describes fiords as usually growing shallower at the mouth " owing to the presence of a submerged terminal moraine." The alluvial composition of the threshold of Yakutat Bay is recognised by so eminent a glacial-erosionist as Dr. G. K. Gilbert (**1903**, p. 50).

Ratzel (**1880**, p. 393) thought that far too much weight had been attached to variations in depth. On the other hand, Dinse claims that the presence of an undulating floor which gives rise to a series of basins and thresholds is " the most weighty criterion of fiords " (**1894**, p. 235); but he admits that in some cases this characteristic may not be apparent, as the whole floor may have been levelled by deposits of sediment.

(*c*) *Hanging Valleys.*—Hanging valleys have also been claimed as essential to fiords. Thus, Hubbard (**1901**, p. 336) advanced two definitions, of which the shorter adopted the descriptive view that a fiord is a " long, deep, uneven-floored arm of the sea " ; but in his longer definition he adds that their tributaries join from high-level valleys.

(*d*) *Parallelism.*—Parallelism among the lines of a fiord district was proposed as a leading characteristic by Ratzel (**1880**, p. 395). " A pervasive parallelism," he says, " runs through the direction of the elements of a fiord coast, especially in the peninsulas, isthmuses, islands, rocks, bays, and straits, and it persists for considerable distances." Dinse (**1894**, p. 207) has remarked that this parallelism is not always present; and, as a slight extra submergence would give many a fiord-reach, which now has straight, parallel sides, a very sinuous shore, it is not likely to be an absolute characteristic ; but even in the cases of Norway, western America, and Scotland, which are cited by Dinse, there is often a very significant parallelism.

(*e*) *Restriction to High Latitudes.*—The restriction of fiords to high latitudes has been very commonly asserted among recent definitions. Thus, Richter (**1896**, p. 185) accepted, as the four essential characteristics of fiords, the presence of steep walls, of basins on the floor, a trough-like form, and a groupal distribution in the cooler halves of the temperate zone.

Prof. Günther (**1899**, vol. ii. p. 660) regards fiords as restricted to the Polar and sub-Polar regions; but he combined both the glacial and tectonic theories, for he says that the valleys had been preformed by breaks in the earth's crust, and that these valleys had been subsequently filled by ice.

Dr. Otto Nordenskjöld (**1900**, p. 213) adopted a very similar position. According to his definition, fiords occur in groups; many of their lines are approximately parallel; they are uniform in width for long distances, and the width is not affected by the junction of their tributaries. The length in a true fiord is from 5 to 40 times its width, and they are found only in mountainous regions. He has repeatedly declined to accept any valley outside a glaciated area as a fiord (e.g. Nordenskjöld, **1900**, p. 216); but he recognises that the valleys (p. 221) are preglacial, and that their basins are often due to the deposition of moraines; and he also accepts the tectonic explanation in part, as he says (p. 223), that the disruption (*Zerkluftung*) of the crust is essential to the formation of deep fiord-basins.[1]

Supan (**1911**, p. 801) referred to the constant association of typical fiords in areas of massive crystalline or Palæozoic rocks, and says that fiords in the strictest sense are limited to the higher latitudes.

(*f*) *The Fiord-valley and Fiord-trench.*—In the preceding series of definitions fiords are regarded as arms of the sea; but the term is used by some authors for the valley containing this inlet, and thus includes the extension of

[1] See also the definition by Prof. Penck quoted on p. 58.

valleys inland far beyond the shore. The term has been extended in the other direction, as by Warren Upham (**1890**, p. 565), to a submarine valley, and thus to parts of the open sea. Thus the trench on the floor of the Atlantic Ocean opposite the Hudson River, New York, is often called a fiord.

The term "ria," which was introduced in order to secure greater precision in the nomenclature, is also indefinite; it was introduced by von Richthofen for a series of estuaries in contradistinction to fiords; but this distinction has proved difficult, and Gulliver (**1899**, p. 220) regards all arms of the sea as rias; according to him, fiords are one class of rias.

It seems most desirable to limit the term "fiord" to arms of the sea. The valley containing the fiord may be continued inland and both parts form the "fiord-valley." If the fiord-valley extend seaward the submarine part may be called a fiord-trench, using the term "trench" for a narrow depression on the sea-floor, as recommended by the International Geographical Congress.

2. Definition of Fiord

A fiord may, then, be defined as an arm of the sea, which lies in a long, deep valley, with steep parallel or subparallel walls, and has a comparatively even floor, so that the fiord-valley is trough-shaped. The fiord may be straight and unbranched. If bent it is usually bent at sharp angles, and the branches, if any, are also straight and usually pass off at similar angles, so that throughout the fiord and its branches there is a well-marked parallelism. The branches of the fiord or of the fiord-valley often unite, enclosing angular islands or block-mountains. Fiords are limited to highlands, and apparently always to districts that have the structure of dissected plateaus.

The fiords, though their floors are fairly level, with usually gentle slopes, are divided into basins by raised barriers or thresholds. These thresholds may consist of banks of moraine matter, of shoals deposited opposite the mouths of rivers, or by tidal currents across the mouth of the fiord, or of rock-barriers. The existence of these barriers would alone be sufficient to prove that the fiords are not excavated by the sea. The sea has entered pre-existing valleys on the sinking of the land.

3. Transition from Fiords to Allied Inlets

Fiords are drowned valleys, and they are related to the other varieties of drowned valleys, known as rias, fiards, and föhrden. The efforts to establish a sharp distinction between fiords and other arms of the sea have failed, for these different geographical forms are not separated by absolute distinctions. Fiords pass gradually into fiards and föhrden, and through them into rias; and there has been no general agreement as to where the divisions between these types should be drawn. "The sea-lochs of West Scotland are typical fiords," says Prof. Herbertson (**1910**, p. 39); but, according to von Richthofen (**1886**, p. 301), they are a type intermediate between fiords and rias; many of them are fiards.

4. Transient Nature of Fiords

Fiords, in fact, are only a stage in the evolution of one kind of arms of the sea, and not a final geographical product. A ria, on the other hand, is a finished article which may be permanent until some deep-seated geographical change has disturbed the geographical stability of its neighbourhood. A fiord is essentially unstable and short-lived; and the fiord-stage is one through which many valleys have passed. A further subsidence would turn many fiords into fiards. Thus, for example, the middle part of the Sogne Fiord is a typical fiord; but if the country were flooded by the sea to a greater height,

FIG. 69.—SOGNE FIORD.

Showing the fiard-like form that would be caused by submergence to 2,000 ft. The area of the present fiord is shown by full lines; the enlargement by submergence to the 2,000 ft. contour is shown by the area marked by broken lines.

then, as is shown by Fig. 69, the submergence would convert the fiord into a fiard.

5. THE ESSENTIAL FEATURES OF FIORDS.

The most frequent distinction that has been proposed between fiords and rias is that fiords are limited to high latitudes [1] by their glacial origin, whereas rias may be formed in any climate. This character would not separate fiords from fiards, as they generally occur in adjacent areas; while it would exclude from the category of fiords those of Dalmatia, Greece, and Asia Minor, and it would

[1] It should be remembered that unquestioned fiords range to the moderate latitudes of 48° in the northern and 42° in the southern hemisphere.

preclude the valleys of Sinai being regarded as fiord-valleys.

Fiords, it is true, are most abundant in the higher latitudes of the countries in which they occur, since the fiord-oscillations were in the main confined to two circumpolar belts.

Fiords, moreover, are limited to highlands, and to those which are or have been in the condition of plateaus. They do not occur in areas where the existing geographical features are due to folding; but they are numerous and are well-developed in districts where fold-mountain chains have been worn down into plateaus, and also, as in Patagonia and Alaska, on the plateaus bordering fold-mountain chains.

A final point in connection with the distribution of the fiords is their groupal habit. A ria may be separated from its nearest neighbour by a thousand miles of coast; but fiords occur in crowded groups, which are usually arranged in a long, curved band, as in Norway, Alaska, and Patagonia.

The essential features of the valleys in which the fiords lie are fivefold: (1) The walls are high, steep, straight, and generally parallel. (2) The valleys bend or branch at regular angles. (3) The plan of the branching is that of a network, and not the tree-like, dichotomous subdivision which is characteristic of all river-systems except of those with the trellis-like plan due to excavation along powerful joints. The branches of adjacent fiords are often in the same straight line, and when connected at their heads they form a fiord-strait. Where the fiords do not extend all the way up the branch-valleys there is usually a low pass, and these deeply cut valleys divide the country into angular blocks, which appear very conspicuous in hill-shaded maps of Scotland and Scandinavia. The heads of the fiords are often so near together that boats can be drawn across them, and such portages may be available for heavy fishing-boats and were used by the Vikings; they are known in Scotland as "tarbets," and as "haulovers" in Kerguelen. (4) The parallelism which is so conspicuous in the walls of the fiords is also shown in the trend of the adjacent valleys and the lines of islands which skirt the shores. (5) The floors of the valleys are often crossed by barriers which break up the fiord-valleys into a series of basins, and there is often an especially well-marked shoal or threshold at the mouth of the fiord.

6. The Fiord Problem

The main problem regarding fiords is the origin of these remarkable networks of regular, narrow, parallel-walled, straight-sided, angular valleys, their deep basins and their shallow mouths.

CHAPTER XIX

THE FORMATION OF VALLEYS

Thy dells by wintry currents worn.
R. Bloomfield.

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1. Fiords are Drowned Valleys.—2. Three Classes of Valleys: Valleys of Deposition.—3. Classification of Rock-ruptures.—4. Tectonic Valleys.—5. Valleys due to Denudation.—6. Nomenclature of Processes of Denudation.

1. Fiords are Drowned Valleys

Fiords are valleys of which at least the lower ends have been drowned by the sea. Hence the origin of fiords involves that vexed question, the formation of valleys. The old cosmographers failed to recognise that in time "every valley shall be filled and every mountain and hill shall be brought low," and attributed valleys to violent disruptions; but more careful observation showed that most valleys are due to excavation by rivers, which wash away decayed rock-material and slowly saw their way through hard rocks. It was found that most of the chief valleys of western Europe and of eastern North America had been excavated by rivers, and the conviction was gradually established that all valleys, and even all the great hollows on the earth's surface, had been scooped out by the denuding action of various natural forces. The accumulation of geological evidence from western America, Africa, and Australia has corrected the tendency to refuse to other forces any important share in moulding the surface of the earth; and it is now recognised that valleys are due to earth-movements as well as to excavation.

2. Three Classes of Valleys: Valleys of Deposition

Valleys may be classified, according to their mode of origin, into three chief classes, due respectively to denudation, deposition, and to earth-movements. Valleys due to deposition are relatively unimportant. Such valleys are caused when the growth of two banks of talus, or gravel, on the sides of a basin or valley has advanced so far that only a narrow space is left between them. The most remarkable of such valleys of accumulation are the submarine trenches found off the mouth of some rivers, such as the Congo and the Hudson. These submarine canyons have been regarded as evidence of a great subsidence of the adjacent country in recent times. There is no evidence that the mainland beside the river Congo has undergone any such subsidence; though its former continuation westward has sunk beneath the Atlantic and the submerged canyon, or "trench," may be the result. It is, however, possible, as maintained by Dr. J. Y. Buchanan, that the submarine continuation of the gorge of the Congo,[1] was formed by the deposition of the silt brought down by the river on either side of its mouth, while the main channel was kept clear by the current. If so, this fiord-trench (*vide* p. 385) would be a colossal example of such channels as that opposite the mouth of the Rhone in Lake Geneva, and those through the shoals off the Essex coast.

The formation of some fiord-basins by deposition instead of by excavation has been claimed by Mr. Bailey Willis for Puget Sound. This fiord consists of a network

[1] This trench was first described by E. Stallibrass ("Deep-sea Sounding in Connection with Submarine Telegraphy," *Journ. Soc. Teleg. Eng.*, vol. xvi. (1887), pp. 479–511, pl. C.). The observations in 1899 by Capt. H. E. P. Cust (*African Pilot*, Part II., 6th edition, 1910, pp. 180, 181), show that the Congo trench is filled with almost or quite stagnant water and its floor is covered with deep mud containing much vegetable matter; and these facts are weighty objections to Dr. Buchanan's explanation.

of channels which is well represented diagrammatically in his plate (**1898**, plate vi.). The maximum depth is 918 ft., though the mouth of the sound is only about 276 ft. deep. The deep basins, according to Willis, are hollows in glacial drifts; and he denies that they were formed by erosion, and considers that they are the actual spaces that were occupied by the ice. As the glaciers melted, their included material was deposited on the floor and on the surrounding slopes, and thus built up the basins; while the hollows are "the casts of glacial tongues" (Willis, **1898**, p. 119).

3. The Classification of Rock-ruptures (Lithoclases)

The most famous classification of rock-ruptures is that proposed by Daubrée in 1882. He adopted the term "lithoclase," from the Greek words *lithos*, a rock, and *klasis*, a fracture, for all the various kinds of planes which divide rock-masses into blocks. He divided lithoclases into three main divisions, distinguished by size. The first division he called leptoclases (from *leptos*, small) and it comprises the dividing planes which divide rocks into small blocks; these leptoclases he subdivided into two sections: (*a*) synclases are those due to internal contraction, either by cooling, as in the columnar jointing of lava, or by drying, as in the cracks formed in aqueous rocks; (*b*) piesoclases are due to external agents, such as pressure, or the alternate expansion and contraction with changes of temperature which cause the innumerable small cracks across such rocks as granite; slickensides (smooth surfaces caused by earth-movements), and various concretionary structures, such as cone-in-cone structure, are also included as piesoclases.

The second division, diaclases, are larger and more regular than leptoclases; the common joints of stratified rocks are the typical representatives of this division.

The third division, paraclases, are long, divisional planes, which are often miles in length; their typical representatives are faults.

Daubrée's terms have not been generally accepted, as the first classes, leptoclases and diaclases, are defined as differing in size instead of in origin.

Rock-ruptures may be classified as follows:

I. (1) Joints—fissures due to internal contraction.
 (*a*) Joints due to solidification.
 (*b*) Joints due to contraction on drying.

II. Disruption-clefts due to external tension.
 (*a*) Torsion clefts in intersecting series, which cross at regular angles and usually at about 45° to the direction of strain.
 (*b*) Tension clefts, gaping cracks which may occur singly, or in parallel series on the sides of arch-like upfolds, or in networks on the sides of dome-shaped upfolds.

III. Rifts due to differential movements.
 (1) Slip-faults. (See Fig. 79*c*.)
 (2) Trough-faults.

IV. Earthquake fissures.

V. Crushed zones, bands of rock shattered by earth-movements and subsequently removed by denudation.[1]

4. Tectonic Valleys

Valleys due to direct earth-movements are known as tectonic valleys. Of these there are two kinds, those

[1] The German terms "Spalt," "Riss," and "Kluft" are used indefinitely. A Kluft may be either a joint (diaclase) or a fault (paraclase). Generally speaking, a Spalt is a small cleft, but when used in combination, as in "Dislocation-kluft," it may mean a fault. "Kluft" is the convenient German equivalent for joint, "Verwerfung" for fault, and "Spalt" for crack. "Kluft" is connected with our word "cleft," and "Spalt" with "split." "Riss" is a tear or rent, and is thus used for a crevasse and a fissure.

formed by direct displacements and those formed as clefts or fissures.

Earth-movements and rock-ruptures have both a direct and an indirect influence on the formation of valleys. They may merely guide the agents of excavation. Thus, some valley-systems are due to the folding of the earth's crust, which has raised soft bands to the surface, where they are worn into valleys, while the harder rocks resist and remain as ridges.

The faulting of the earth's crust also produces bands of weak and shattered rocks which are easily washed away and thus many valleys have been worn out along fault-lines. Joints have a somewhat similar effect. They are produced by slight internal movements in rocks when they contract during cooling or drying. Joints generally occur in intersecting series, which form angular networks. The joints act as lines of weakness, and valleys are worn out along them (see p. 459). Such valleys, though their directions have been determined by earth-movements, are valleys of excavation. Tectonic valleys, on the other hand, are the direct results of the earth-movements themselves. Thus, when rocks are folded by lateral pressure, the upfolds form hills and the troughs, or downfolds, form valleys; and some of the greatest valleys in the world occupy the trough-like downfolds. Faults or movements of blocks of the earth's crust along fracture-planes also produce important valleys. A single fault will produce only a mountain-block with a down-throw plain at its foot. A single fault combined with tilting, however, may produce a fault-valley (Fig. 79*b*). A parallel series of faults with the movements always in the same direction produce a terrace-like, or step-like structure. A pair of faults may lower a strip of land between two areas, that remain at their original level; and a pair of trough-faults produces a rift-valley (Fig. 79*a*).

The most remarkable of all the rift-valleys is that which runs from the Jordan through the Red Sea and down eastern Africa to Lake Nyasa. Part of the valley of the Rhine, Spencer Gulf in South Australia, and many valleys in volcanic districts are also rift-valleys.

5. Valleys due to Denudation

Valleys formed by excavation no doubt are the most numerous class of valleys, for they include the ordinary valleys of most of the settled districts of the world. Some of them may have been rift-valleys of which the walls have been completely worn away, and then it may be impossible to distinguish a rift-valley from one which has been excavated along a pair of trough-faults.

Valleys due to excavation may be classified according to the agent which has made them. They are due to the wind, to the sea, to rivers, and to ice. Wind-worn valleys are characteristic of arid regions, and they have no importance in reference to the origin of fiords.

Valleys worn out by the sea are relatively unimportant, though there is no doubt that in many cases the sea, in its attack upon a rocky coast, excavates valleys by eating away the softer bands of rocks or widening cracks into gorges.

The inlets on the coast of Brittany have been attributed by Rutimeyer (**1883**, pp. 21–24, 141–3, etc.), to marine erosion, and his conclusions have been endorsed by Umlauft (**1883**, p. 230), and Prof. Vallaux (**1903**, pp. 29, 30). Daly (**1902**, p. 263) has described cases in Labrador. Cases, in fact, must be known to nearly every one who has examined sea-worn, rocky coasts. The late Prof. O. Krümmel, the well-known oceanographer, advocated the view (**1889**) that tidal coast-erosion plays a more important part in the formation of inlets and channels than is usually recognised. Marine erosion of valleys is, however, insignificant in comparison with the abrasion or backward cutting of the coast, and the fiords, with their deep and quiet waters, cannot have been worn far into the land by the action of the surf.

Rivers are the most effective and frequent agents in excavating valleys, for they act in nearly all climates and parts of the world, and their activity is ceaseless. Evidence of the erosive power of rivers is given in most text-books of geology, and owing to the solvent action of the water, the chemical activity of the included gases, and the rasping effect of the sand and stones carried along their beds, rivers are the most powerful of all agents of denudation.

Glaciers are the last of the eroding agents appealed to in the formation of valleys; that they are powerful instruments in the excavation of valleys appeared to follow from the striking analogy between rivers and glaciers. For glaciers are simply rivers of ice. Like rivers, they lie in valleys, down which they flow; and as glaciers are usually armed on the sides and sole with dirt and rock-fragments, they must have a file-like effect upon the rocks with which they come in contact. The analogies between glaciers and rivers all suggest that glaciers have great powers of valley-erosion; but, as the problem of glacial erosion is one of the most vexed questions in current geology, it requires special consideration. (Chapter XX.)

6. Nomenclature of Processes of Denudation

During recent years there has been a tendency among British and American authors to give different meanings to the terms used for the processes by which valleys are excavated. The wearing away of the surface of the earth is known as denudation (*denudo*—I make bare), a term proposed by Lyell in 1833. A strict interpretation of his definition would limit it to the action of running water; but it has been since used as a general term for the laying bare of fresh surfaces of the earth and removal of the loosened material.

Many American authors have followed Dr. G. K. Gilbert in the use of "erosion" instead of "denudation"; but, since "erosion" is derived from *erodere* (to gnaw out), most British authors from the time of Lyell have applied this word to any process which gnaws away the earth's surface, and have adopted the term "transport" for the removal of the loosened materials. According to this use, erosion and transport are both included in denudation.

The excavation of valleys includes two processes: deepening by digging away the floor, and widening by cutting back the sides. The distinction between these two processes is often so helpful in considering the geographical evolution of a country that different terms have been proposed for them. "Erosion" is, then, used for the general wearing away of the earth's surface and the widening of any valley, and "corrosion" or "corrasion" for the deepening of any valley-floor. This distinction was first clearly stated in 1875 by Powell,[1] who then pointed out that, where erosion is more powerful than corrosion, valleys become wider and their sides more sloping.

The term "corrasion" was introduced into current geology by Powell, and though in one place he distinguished corrasion as due to running streams, and erosion as due to rain, he did not maintain that distinction; for his "base level of erosion" is largely due to rivers, and in his index he refers to erosion by streams. The term "corrasion" was extended by Gilbert in 1877 to the work of all running water; but it has been generally restricted to basal as opposed to lateral excavation. Powell practically used it in that sense, for he attributed canyons and water-gaps to corrasion, and "the general surface-features of the landscape" to erosion. He

[1] J. W. Powell, *Exploration of the Colorado River of the West and its Tributaries* (Washington, 1875), p. 205.

appears to have overlooked the difference between the verbs *radere* and *rodere*; for he used "corrasion" for deep gnawing into a surface and "erosion" for the more general scraping down of the surface. Powell had some precedents for this use of the term "corrasion," but they were due to misinterpretation or to misprint of "corrosion." The word "corrasion" comes from the Latin *radere*, "to scrape," and *cum* (in composition *con* or *cor*), "together," and thus means collecting, as illustrated by the sentence "Wealth corraded by corruption," which means to gather a pile by innumerable corrupt acts. Sir Thomas Brown in 1646 had used "corrasion" in the sense of scraping, a process which reduces instead of increases the inequalities of a district. But "corrasion" has been also used as meaning corrosion, and it was adopted by Powell in this sense. Penck and many other authors, British and foreign, have therefore used "corrasion" as an erroneous variant of "corrosion."

"Corrosion" comes from the Latin *corrodere*, compounded of *rodere*, to gnaw, and *cum*, a prefix which is here used to give intensity to the simple action expressed by the verb. It is, therefore, appropriate for that process of eating into a country which forms canyons. The prefix *cum* in its form *cor* is used with its primary meaning of "together" in the word "corrosion," but in its secondary, or intensive meaning in "corrasion" as used by Powell.

Corrosion has been sometimes restricted to the process of solution. The essence of corrosion is, however, the etching or eating of a surface either mechanically or chemically.

During recent years the use of "corrosion" for basal excavation, as distinct from the use of "erosion" for lateral excavation, has not been so general as formerly; the retention of both terms would be convenient.[1]

[1] A fuller consideration of this subject, with references and examples, was given in a paper "The Terms 'Denudation,' 'Erosion,' 'Corrosion,' and 'Corrasion.'" in *The Geographical Journal*, vol. xxxvii. pp. 189–95 (**1911**).

CHAPTER XX

THE PROBLEM OF GLACIAL EROSION

Had I but the torrent's might.

GRAY.

1. THE ORIGIN OF LAKE-BASINS AND EFFICIENCY OF GLACIAL CORROSION

THE origin of lake-basins and fiords by glacial corrosion is one of the most disputed questions of contemporary geology. The question was raised in 1827 when Esmark (**1827**, p. 120) explained the precipitous nature of the cliffs on the islands of Gulé (61° N.) and Inner Lulé as due to glacial action. He remarked: "I can explain this phenomenon in no other way than by supposing, that large masses of ice, pressing through the sound, have cut these precipices lying parallel to the direction of the sound." This suggestion appeared to be supported in **1849**, when Dana pointed to the close connection of fiords with formerly glaciated areas. The main controversy dates from the famous memoir by Sir Andrew Ramsay in **1862**, in which he claimed that many lake-basins have been hollowed out by glacial action.

Sir Andrew Ramsay's paper offered a very attractive explanation of the difficulty presented by many Alpine lakes and fiords. Their basins are often surrounded by hard rock; yet they are often of extraordinary depth. The floor of Lake Garda, for example, descends 911 ft.

below sea-level; and one puzzling feature in the form of these basins is that they are often deepest in the upper part and shallow instead of becoming deeper towards the lower end, as is the case with ordinary river-valleys and estuaries. These deep, shovel-shaped basins, if entirely enclosed by hard rock, cannot have been excavated by river-action unless the country has been tilted. Some of these basins may be river-valleys of which the mouths have been blocked by banks of sediment; but this explanation is inapplicable to lakes in which the floor lies far below sea-level.

At the period of Ramsay's paper the appeal to earth-movements to explain the surface-features of the earth's crust was unpopular. It was regarded as unnecessary, and as almost an unfair invocation of an extraneous agent. As lakes are especially common in glaciated areas and as there is clear evidence of the glacial occupation of these lake-basins, Sir Andrew Ramsay concluded that the basins must have been worn out by ice, and that the great depth of the upper parts of the basins was due to the ice there having had greater corrosive power owing to its greater thickness and weight.

Ramsay's theory was rejected by many of the most clear-sighted geologists of his time, such as Lyell; but its agreement with the views of so distinguished a physicist and mountaineer as Tyndall upon the great extent to which the Alpine valleys had been excavated by glaciers, and its own attractive simplicity, have always secured for it wide support. The theory has also had the warm advocacy of Dr. Russell Wallace, who claims (**1905**, vol. i. p. 412), that he gave in 1867 the first detailed explanation how glaciers wear out their basins by grinding due to unequal pressure.

The balance of opinion was at first opposed to Ramsay's theory. Rutimeyer, in a classical paper on the formation of the Alpine valleys and lake-basins, maintained in 1869 that ice has a protective instead of a denuding effect; he pointed out that the Swiss lakes lie along the great structural lines of the Alps (**1869**, pp. 40, 41); he therefore attributed their basins to tectonic causes and the tilting of ancient valleys that had been worn out along lines of weakness. He explained hanging valleys and truncated spurs as due to successive deepening of valleys by water-action, and showed that the Alpine lakes, and even different parts of one lake, are of various ages. In an interesting map he showed the different elements in the Alpine lakes and the changes that have taken place in many of the Alpine valleys through the diversion of their waters by the now familiar process of river-capture.

Rutimeyer's view [1] that the valleys are not caused by the glaciers, but that the valleys cause the glaciers which occupy them was strongly supported by Dr. Pfaff (**1874**, pp. 333, 336). Two years later Prof. Judd (**1876**, p. 15) rejected the attribution of lakes to glaciers with the remark that the " agency in question is as unnecessary as it is hypothetical."

A similar controversy to that over the Alpine lakes has taken place over the Great Lakes of North America, including Lake Superior and its neighbours. They have been claimed as due to glacial erosion by Newberry (**1882**, p. 92), Gilbert, and others. Newberry's paper called forth promptly the protest by Lesley that the glaciers which occupied Lakes Erie and Ontario " left them everywhere precisely in the topographical condition in which it found them, merely scratching their rock exposures. . . ." (p. 101).[2]

[1] Rutimeyer's view of the origin of lake-basins has been in the main supported by Heim and Bonney, while their glacial origin has been maintained by Penck, Davis, O. Nordenskjöld, and others. Glacial erosion and the formation of lake-basins has a voluminous literature, which has been well summarised by Sir Henry Howorth in **1905** (chap. viii. pp. 376–458), and by Culver in **1895**.

[2] These great lake-basins are now generally regarded as due to the tilting of old valleys, a view first suggested by H. Y. Hind, in 1859. A summary of the earlier literature on this problem is given by A. N. Winchell (**1897**) and by J. W. Spencer (**1898**).

In recent years the arguments for and against the efficiency of glacial erosion have been well presented by eminent authorities. Prof. Penck has stated the evidence in favour of the view that glaciers have taken a leading part in excavating the Alpine valleys; the great book, *Die Alpen in Eiszeit*, written by him in conjunction with Prof. Bruckner, is universally recognised as one of the standard works on Alpine geography and glacial problems. Prof. W. M. Davis has given his high authority to the school of advanced glacial erosionists, and advocated its view in a series of memoirs (**1909**) characterised by his usual insight into physiographic problems and illustrated by his graphic and instructive sketches. Prof. W. H. Hobbs (**1911**), after a discussion of recent observations on existing glaciers, has warmly championed the efficiency of what is known as "glacial plucking" in deepening the upper ends of valleys and forming rock-basins.

On the other side, Prof. Bonney has repeatedly stated the difficulties in the glacial-erosion theory and advanced strong evidence to show that glaciers have very limited powers of eroding hard rocks and have really a protecting influence on the beds beneath them; and he has recently restated some of the arguments with the high authority of a presidential address to the British Association.

Dr. G. F. Becker (**1891**, p. 65) declares that the extensive erosion of solid rocks by glaciers is opposed by "overwhelming evidence." Prof. Heim asserts that "glacier erosion is almost nothing (*fast verschwindend gering*) in comparison to erosion by water" (**1885**, p. 366), and he heads one section of his discussion of the question "the stagnation of valley-formation during glaciation" (p. 397). Prof. Fairchild has discussed the whole question in a paper entitled, *Ice-erosion a Fallacy*. He concludes:

"The quite unanimous testimony of geologists who are most familiar with living glaciers is to the effect that they do almost no erosional work, or scarcely more than sufficient to attest the fact of their presence. . . . We have no evidence that any glacier has ever carved its own valley, nor have we any proof that any glacier has greatly deepened the valley it has occupied. . . . The glacier cuts faster at the sides and is prohibited from rapid bottom-cutting by every known factor and principle of glacier mechanics" (Fairchild, **1905**, pp. 31, 41).

Prof. Garwood explains many of the features often attributed to the erosive action of glaciers as due to the protective action of ice and snow, while the Alpine valleys were being enlarged by rivers during interglacial periods.[1]

It has been claimed that this controversy has been between the physiographers and the experts on glaciers. The physiographers, it is said, have been driven to attribute to glaciers great powers of erosion in order to explain otherwise puzzling physiographic features. Their position, according to Prof. Fairchild (**1905**, p. 47), shelters "behind a bulwark of analogy and assumption"; and many of the men who have had the most prolonged personal experience of glaciers have been most emphatic in assigning to glaciers a protective rather than an eroding effect. But this classification of authorities is only partly correct. The experts have been distributed between the two sides. Thus, amongst mountaineers, Tyndall was a great champion of glacial erosion and Whymper denied it. Amongst Alpine geologists, Bonney and Heim are opposed by Penck and Bruckner. And the physiographers are not all on the side of extreme glacial erosion.

At different periods in the controversy the value attached to the chief arguments has varied greatly; but there has been no real approximation between the two

[1] Prof. Reusch has advocated the same view for some of the Norwegian valleys. Prof. Bonney has recently (**1912**, pp. 191-6, and especially p. 192) advanced strong grounds for the belief that the Alpine valleys had been cut nearly to their present depths in preglacial times.

sharply conflicting schools. Any tendency to compromise has, perhaps, been all the more sternly resisted because the question at issue is one not of absolute fact, but of degree. There is no doubt that glaciers sometimes act as agents of erosion, and that under certain conditions their influence must be to some extent protective. The difficulty is in estimating the relative effect of these two processes.

Glaciers are undeniably agents of erosion. Glaciers are rivers of ice, and they flow down their valleys like streams of water. They therefore necessarily, like rivers, act as agents both of transport and denudation. They pick up loose material from their beds or from their banks, and carry it away ; and, as this material naturally collects most along the margins and the lower layers of the glacier, this rock-arming inevitably helps to wear away any rock-surfaces over which it flows.

The milky colour of glacier-streams has often been quoted as a proof of the rapidity of glacial abrasion [1] ; but much of this fine material is probably derived from the grinding of the rocks which have fallen on to the glacier from adjacent cliffs and from the mud washed down into it by rain and by water from melted snow. Heim, moreover, has shown that the amount of sediment discharged from glaciers is less than that carried away by streams during ordinary subaerial denudation. After a careful discussion of the amount of sediment carried by glacial streams and quotation of many measurements of the amount of sediment which they carry, Heim (**1885**, pp. 362, 363) concludes that " the transport of sediment and mud by glacial streams is very much

[1] The oft-quoted estimate by Dollfus-Ausset (*Mat. Ét. Glac.*, vol. i. p. 276), that the Lower Aar Glacier denudes its bed ·6 mm. per annum or one inch in 150 years, or two and a half times as quickly as river erosion, is defective since it omits the contributions of sediment from the lateral streams and from the subglacial river, and as the measurements were made when the streams were most active; also in other respects this estimate is unsatisfactory.

smaller, indeed quite insignificant (*geradezu verschwindend*), compared with that of ordinary streams and rivers" (Heim, **1885**, p. 365).

An ice-covering has unquestionably a double effect. A stagnant sheet of snow protects the rocks underneath it, much as the bed of a lake is protected by the water above it. On the other hand, a swiftly flowing glacier, like a rapid river, acts as a powerful agent of lateral erosion, and in places also of corrosion.

2. The Formation of Rock-basins

A river cannot corrode its bed much deeper than the level of its mouth, and thus it cannot dig out large basins. A river cuts a trench, the floor of which has a general fall from the source of the river to its mouth. Rivers can only form comparatively small and shallow basins. Below a powerful waterfall the water may deeply corrode its bed even in hard rocks; and the accumulation of the loose material in the quieter water beyond the fall may convert the bottom of the gorge into a shovel-shaped basin. The most remarkable instance of a basin excavated by a waterfall is that below the falls of Niagara. Rivers also deepen their beds where they pass over a band of soft rock; for rivers often consist of a succession of pools separated by shallows, where the channel is crossed by a bar of hard rock. River-basins are also formed where a stream escapes from a narrow channel or rushes over a rock-barrier or weir, for the scour of the eddying water excavates a "wash-out" basin in the softer rocks below.[1]

These river-formed basins must be comparatively shallow, and there is no known cause of a river cutting out rock-basins which, like Lake Morar in western Scotland, are very deep in comparison with their length.

[1] Prof. Suess has referred to the analogy between such a wash-out basin, which is called a "kolk"—the usual German word for an eddy—and those attributed to glacial erosion.

But that great rivers may excavate fairly deep hollows in their channels is shown, for example, by the Irrawadi, which, 600 miles above its mouth, is in places 160 ft. deep, so that its bed is there only 140 ft. above sea-level.

Glacial Corrosion.—But the power of rivers to excavate basins below sea-level is very limited. A glacier is free from such narrow restrictions as a river, for it acts as a mop as well as a file. The lowest ice of a thick sheet is gradually pressed into any underlying soft or loose material and removes it, particle by particle, frozen into the ice. Loose, decomposed rock-material below

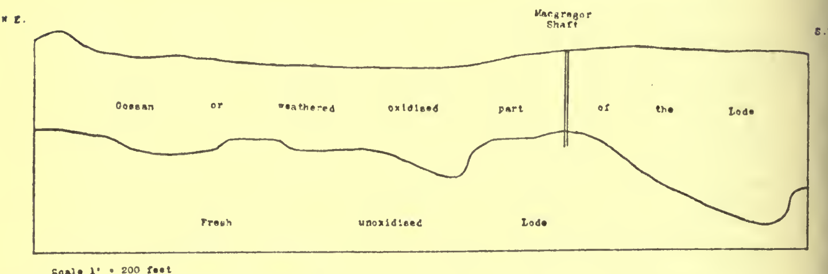

FIG. 70.—SECTION ALONG PART OF THE BROKEN HILL LODE (BLOCKS 10–12).

Showing the irregular junction of the oxidised or weathered with the unaltered lower part of the lode. Glaciation would leave the rise of unoxidised rock around the Macgregor shaft as a threshold. Scale 1 in. = 600 ft.

the ice may therefore be gradually mopped up and removed.

The depth to which rocks decay under the influence of the atmosphere and of the waters which soak downward from the soil is very irregular. This fact is best shown in mining operations. The upper part of a mineral lode is usually decomposed to an iron-stained mass, known to miners as a "gossan," and due to the action of the atmosphere and rain-water. The depth to which lodes are thus altered is very irregular. Deep basins occupied by oxidised material are separated by projecting ridges of hard, fresh lode-matter. This fact may be illustrated by the section along part of the Broken Hill lode in New South Wales (Fig. 70); the area of unweakened rock near the Macgregor shaft would remain after glaciation as a threshold between two rock-basins.

When a glacier flows over decomposed weathered material it may remove this grain by grain and leave a series of basins separated by bars or thresholds of rock.

A glacier may corrode basins deep below sea-level. If a glacier flow out to sea, the ice displaces the water and flows on, wearing away the sea-floor. A glacier 800 ft. thick may displace the water from a bay and flow on in contact with the sea-bed to a depth of 700 ft. and even more, if all the ice be compact and the lower layers be weighted by earth and rocks. This ice, flowing seaward, would continue to corrode its bed; but, as its weight is reduced by melting, it would gradually lose this power and the ice would therefore tend to excavate a basin shallowing seaward.

Glaciers can also excavate deep basins by means of pot-hole action. The cutting down of hard bars of rock by rivers is largely due to the formation of pot-holes. A stream rushing across a rocky shallow, or falling over a series of ledges in a cataract, has an irregular eddying motion; a boulder, being swept into one of these eddies, will be spun around upon the underlying rock, and a pot-hole gradually formed.

Pot-holes generally occur in groups, and a hard bar of rock in a river-bed is thus riddled with holes. These are enlarged until their walls are so thin that they are worn away or are broken down by boulders which are rolled along the river-bed during floods. This process of pot-hole formation plays such an important part in denudation that Geinitz has proposed for it the special name of "evorsion."

Rivers, however, can only drill pot-holes at a comparatively shallow depth, and cannot thus burrow into rock much below sea-level. There is no precise limit to the depth of pot-hole formation beneath a glacier. The water formed by the melting of the surface of a glacier flows over it in streams which plunge down crevasses as "glacier-mills." A boulder swept into this mill is swirled around on the bottom with terrific force and thus drills into the underlying rock. Such glacier-mills are often fairly constant in position, for they occur where, owing to some variation in the course of the glacier, crevasses are kept always open.

Groups of these subglacial pot-holes occur together, and the destruction of their walls forms a rock-basin the depth of which is not subject to the same restrictions as is that of pot-holes drilled by river-action.

The famous glacier-garden at Lucerne is a well-known instance of a rock-surface which has been pitted by pot-holes. The numerous giant-kettles in Norway are deep, well-like pot-holes that have been formed below glaciers; and G. K. Gilbert has published photographs showing the extensive erosion of hard rock in the Sierra Nevada by a series of glacial pot-holes (**1906**).

"A lake-basin," said Belt (**1864**, p. 464), "is an immense pot-hole in which the "mass of ice that filled it took the place of the moving stone." Some small lake-basins may have been formed by the enlargement of pot-holes.

Pot-hole formation is, however, due to the action of water; though they are sometimes secondary glacial effects, as the ice contributes the vertical pipe which directs the water and gives it its great boring power.

3. The Criteria of Glacial Erosion

The general agents which are most important in destroying and wearing away rocks are the sea, rivers, wind, and ice; and each of these four agents has its own particular methods of attack, and imparts characteristic forms to the materials affected. The contrast between the different forms due to each of these four agencies is well shown by the forms of the smaller boulders and pebbles made by them. The pebbles selected for the comparison should be of some hard and fairly homogeneous material, such as a quartzite, in which the form is not determined by any special planes of weakness. Hard pebbles which have been sufficiently attacked by the sea to have acquired the characteristic form of beach-pebbles are somewhat bun-shaped. They are circular in plan, rounded above, and have a flat base. Their flat base is the result of their continually spinning around and around, as they are washed backward and forward by the tide. River-pebbles, on the other hand, are usually egg-shaped, since they are rolled along by the river, and always travel in the same direction. Wind-worn pebbles have flattened surfaces like the facets of a gem. They are often shaped like the ordinary ridge-tent, with a triangular cross-section. In most localities where the wind has one prevalent direction, the windward side of the pebbles is worn away by this natural sand-blast, and the sand-grains falling over the crest down the lee side, also flatten that. The base may be flattened by the pebble being turned over on to one of its flat sides. In a locality where the winds are especially variable in direction or diverted or deflected by cliffs, the upper face of the pebbles may be worn on three or more faces, so that the pebble becomes pyramidal. The form that may be described as tent-shaped is, however, more commonly taken by pebbles that have been worn by prolonged sand-blast action.

The form of ice-worn pebbles is well shown on those that occur in boulder-clay. They have flattened faces and straight edges, and thus have some resemblance to wind-worn pebbles; and the "Dreikanter," or faceted stones due to wind-action have been regarded as evidence of glacial origin. The typical form of a glaciated boulder is one with a series of flattened faces meeting at irregular angles. Such boulders have often been compared to the worn blocks of sandstone used by masons for smoothing slabs of marble; and the number of the polished faces depends upon the number of positions in which the block of stone has been held by the glacier while abrading its bed.

The characteristic feature of the ice-worn pebble is its faceted as well as its scratched surface.

In the attempt to distinguish between the various agents of denudation, especial search has been made for reliable criteria of glacial action. Ice-scratched rocks, *roches moutonnées*, and far-travelled erratics give unmistakable evidence of the work of ice. Some other geographical features, including the overdeepening of valleys, the existence of hanging valleys and cirques, the smooth relief of a land in which all the hills have been rounded and the peaks blunted, large bare surfaces of fresh rock, beds of contorted drifts, and tumultuous deposits of boulders, sand, and clay, are often due to glacial action ; but each of these features is also produced by non-glacial agencies, and therefore their evidence alone is not conclusive.

Valleys may be overdeepened by faults, or by corrosion by the main stream, while the tributary valleys are left undeepened owing to the comparative feebleness of their streams. Hanging valleys may be formed by the sea cutting back a cliff, by a river wearing away its banks or overdeepening its bed, and by faults. A country may acquire a gently undulating subdued relief owing to the action of wind and the changes of temperature between day and night ; and bare rock-surfaces can be formed by the solution of rocks, such as limestones, which contain very little insoluble material, or by sand-erosion in arid climates. Cirques are an effect of the shattering of cliffs by frost, and though they are no doubt often formed on the edge of ice-sheets owing to the constant freezing and thawing of the water in the clefts and pores of the rock, they are also formed in arid regions by the sudden changes of temperature at sunset ; other cirques appear to be certainly due to many waterfalls cutting back the edge of a cliff. Tumultuous deposits of stones and earth are formed at the mouth of narrow gorges and as talus banks at the foot of cliffs. Some contorted drifts are due to land-slips and to the settlement of deposits as they sink owing to the solution of underlying rocks, or the shrinkage of beds by loss of water.

4. Spur-truncation and Glacial Facets

In recent years great importance has been attached to the truncation of hill-spurs into faceted ends, as indications of glacial erosion. A glacier flowing down a valley presses against the spurs from the sides and wears them away. A river, on the other hand, usually tends to lengthen the spurs, as the force of the current is deflected by them and impinges with full force on the bank opposite them. The material obtained by erosion from one spur is often deposited in the quiet water at the next bend of the river. Owing to the less plastic nature of ice, a glacier is deflected less readily than a stream of water. It bears with persistent pressure against any projecting rock-spurs and wears them away like a grindstone.

The toe of the spur is thus cut away; and a spur between adjacent gullies or tributaries, instead of passing downward into the floor of the valley by an even, continuous slope, ends with a steep, triangular face which resembles the facet of a gem. These faceted spurs are well developed in many glaciated areas. As the facets of a gem are due to artificial grinding, so these glacial facets are often due to abrasion by glacier-ice.

Such triangular facets, in 1878, were exemplified by Studer in Kerguelen.[1] Spur-truncation as a glacial result was also clearly recognised by Prof. Chamberlin in 1883,[2]

[1] Studer (**1878**), p. 341. He there described a "dreikantigen Gebirgstock" in the Studer Valley.

[2] *Third Ann. Rep. Geol. Surv.* (1883), p. 305.

but prominent attention was first directed to the importance of this process by Prof. W. M. Davis in 1906. (See **1909**, pp. 624, 625.)

I was first impressed by the value of this character as a possible test of ice-erosion in 1895 on the Aletsch Glacier, where these faceted spurs are magnificently shown on the ridges that run eastward from the Aletschhorn, each of which ends in a facet. The triangular faceting there is so conspicuous that it is expressed in the place-names. The highest peak of the group between the Aletschhorn and the Aletsch Glacier is known as the Dreieckhorn. The southern ridge in the same group, the Olmenhorn, ends eastward in a face as triangular as that of an artificial pyramid; and to the north of it are four spurs each of which ends above the Aletsch Glacier in a triangular facet. These four spurs are known respectively as the First to Fourth Triangles (Beim 1ten Dreieck, Beim 2ten Dreieck, Beim 3ten Dreieck, Beim 4ten Dreieck). Looking across the Aletsch Glacier from the Eggishorn, it appears obvious that these triangular facets were due to the glacier having cut away the lower ends of the spurs at a time when it was much thicker than it is to-day.

Similar faceted spurs occur in most glaciated countries. Photographs show that they are magnificently developed in the Himalaya and the adjacent mountains. In Scotland they are conspicuous along most of the valleys which were occupied by large valley-glaciers.

All stages in the process of spur-truncation can be seen in Scotland, from the mere cutting off of the toe of a spur, as in Binnem Mor (Pl. VII. Fig. 1), or until, as in Glen Lyon near the Bridge of Balgie, all the lower part of the spur has gone and the rest is left as a rock-gable projecting from the wall of the valley; and finally, as on the long sweep of the eastern wall of Glen Orchy, four miles to the east-north-east of Dalmally, the spurs have been completely worn away and the wall of the valley has an

Photo by H. MacRobert.

FIG. 1.—FACETED SPURS OF BINNEM MOR. (*Vide* p. 412.)

Photo by Rev. A. E. Robertson

FIG. 2.—BEN NEVIS SEEN ACROSS GLEN NEVIS,

In which the spurs have been almost completely removed by ice-erosion. (*Vide* p. 413.)

almost artificial regularity.[1] The southern wall of Glen Nevis, at its entrance near Fort William, has similarly had all of its spurs removed, but the streams are beginning to corrode the face and cut the ice-smoothed wall into a new series of buttresses and gullies (Pl. VII. Fig. 2).

The long, straight, regular lines marked along many of the valleys on the contoured maps of Scotland show how often the valley-sides have been smoothed by the glacial removal of the spurs.

Spur-truncation is, however, not necessarily a glacial effect. Spurless valley-walls occur in mountain regions that have not been glaciated (for examples see pp. 445, 447). Spurs are cut back by torrential rivers or by rivers which are subject to frequent floods. Thus Fig. 71, copied from the India Office map of Burmah on the scale of 1 inch to the mile, shows that the Irrawadi has truncated the spurs of its valleys, leaving long, spurless walls and triangular faceted surfaces, which are essentially the same in form as those so often found in glaciated valleys. Recent glacial action cannot be assumed in the lowlands of Burmah. Spur-truncation by rivers may also be illustrated by reference to the photographs and series of maps of the Ohau River by Adkin (**1911**, pl. xvi. maps pp. 499–517), in a part of

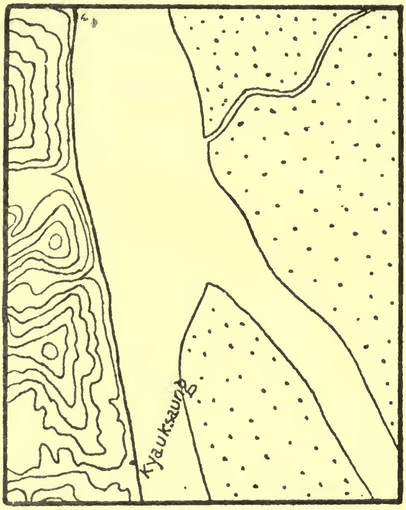

FIG. 71.—TRUNCATED SPURS.
Beside the Irrawadi River (scale 1 mile to inch, 1909).

[1] The significance of this feature was recognised in Glen Lochy by Blanford (**1900**).

the North Island of New Zealand where there is no satisfactory evidence of glacial action. The truncation of spurs in the Crazy Mountains, Montana, beyond the glaciated area, has been described by Mansfield (**1908**, p. 562).

Spur-truncation is also produced by faulting, as has been shown in the sketches from the Great Basin of the Western United States by Prof. Davis (**1909**, pp. 745–48), and in several localities in Dalmatia. The upper part of the fiord of Cattaro lies in a long north-and-south valley, from which the spurs on the eastern sides of the valley have practically all been destroyed by fault-action, while on the western side of the valley the destruction of the spurs by faults can be seen in various stages of operation.

5. Trough-valleys

River-cut valleys are usually sinuous, with curved, rounded banks due to the successive gulleys and spurs; the complete removal of the spurs from a valley leaves it with long, even walls, like a trough; and such spurless, trough-shaped valleys have been frequently claimed as a characteristic product of glacial erosion. The smoothness of their walls, which are free from the alternation of gulleys and buttresses characteristic of deep mountain-valleys in areas which have not been glaciated, are due to the file-like action of ice. A glacier is a flexible rasp, so that its abrasion of the underlying rocks at first gives them a rounded, hummocky surface.[1] Ice, therefore, which has flowed over a rocky surface removes the loose material; and when only slightly worn the hard rocks below produce the rounded hummocks known as *roches moutonnées* (from *moutonner*, to curl). They were so named by de Saussure[2] from their resemblance, as they occur

[1] In that, as in some other respects, the action of ice is similar to that of sand-erosion in the desert; and it is not surprising that the land-forms in arid tropical regions have been often regarded as evidence of former glacial action.

[2] De Saussure (*Voyages dans les Alpes*, § 1061).

one after another down a hillside, to the rounded curls of a lawyer's wig.

The rock-thresholds across fiords and the irregular ridges which occasion the innumerable lakelets in land surfaces that have been swept by ice are evidence of slight glacial corrosion. But even the most flexible rasp must tend to wear the top of ridges more than the sheltered depressions between them. Hence prolonged glacial activity upon a rock-surface planes down the *roches moutonnées* and leaves level, smooth surfaces, which Whymper (**1871**, p. 146) has called *roches nivelées*. It has therefore been often claimed that *roches moutonnées* give evidence of the effective resistance of hard rocks to glacial erosion. The planing action which forms *roches nivelées* would not help a glacier to excavate rock-basins. "Glaciers striate and polish, but never excavate rocks," declared Murchison (**1870**, p. 327). "The glacier planes, though with varying force; it cannot dig," said Prof. Bonney (**1873**, p. 383), and Gurlt (**1874**, p. 149) insisted that the action of glaciers is to plane surfaces, and not to erode them.

This planing action is well seen on a larger scale where an ice-sheet has acted on a widespread country; it wears down the tops of the ridges more quickly than it deepens the intervening valleys. The long, level tops of the ridges in the fiard country in south-eastern Sweden illustrate this process.

A hillside due to ordinary denudation is typically curved, with the concavity downward, and the slope gradually decreases to a low, toe-like projection. In many glaciated districts the slope is swollen and is convex. The slope is gentlest above, and may end below in a steep slope or cliff. This sudden steepening of the gradient is due to the cutting off of the toe of the slope by glacial erosion.

Penck (**1909**, vol. i. p. 289) has published a view of the Zillerthal which shows that these betroughed valleys occur in the Alps ; and the trough-like form of the Rhone valley above Martigny is probably due, at least in parts, to the removal of the lower spurs by the old Rhone glacier, though Prof. Bonney reminds us of the important fact that this valley coincides with a band of comparatively soft rock.

Trough-shaped valleys may be formed by non-glacial agencies, and the difficulty of distinguishing between a river-cut gorge and a glacially corroded valley may be illustrated by reference to the Naerodal, one of the branch-valleys of the Sogne Fiord in Norway.[1] It is in places a very deep gorge, which shows the overlapping profiles (Fig. 19) of a river-cut ravine. It has been occupied by ice, which rounded off the spurs. If the ice had flowed along this valley for a long time, or if the valley had happened to coincide with a band of softer rock, the spurs would have been removed and the whole gorge might have been attributed to glacial erosion. The main work, however, has apparently been done by the river, and the glacier may not have deepened the valley in the slightest degree.

A fairly straight river-cut gorge may therefore be converted into a trough-shaped valley by a very slight amount of glacial excavation. And valley-walls may be steepened by river-action where some geographical change, such as uplift of the district or increased discharge, gives a river increased powers of corrosion.

6. Glacial Plucking in Canyon Formation

The trough-like form of certain glacial valleys is an important difference between some of those that have been occupied by glaciers and the majority of ordinary valleys. A second difference is that typical river-cut

[1] I have not seen this valley, and only know it by the excellent photographs which have been published of it.

valleys are more or less wedge-shaped; the river begins with small streams which excavate correspondingly small valleys; and, as the stream gains in volume and strength by the junction of tributaries, the valley also is enlarged. But many of the trough-like fiord-valleys, and some mountain-valleys in glaciated countries, begin at once broad and deep. Willard Johnson has aptly described these valleys as being "down at the heel"; and he felt, during his survey of some of these valleys in the Sierra Nevada in western America, unable to explain this feature except by glacial action.

This type of valley, however, may be formed in different ways: it may result from waterfall action combined with landslips, where a sheet of hard rock overlies softer beds. It may be also due to floods, as shown by Andrews (**1908**) in New South Wales. And valleys, which suddenly become deep and broad, like a trough, have been adduced by Kjerulf (**1881**, pp. 4–9) as a land-form which cannot be due to glacial action. Willard Johnson's study of some of these trough-shaped canyons in the American Nevada shows that their two ends had been formed by different processes. The lower part of the canyon is admittedly due to river-action; but the upper part, including the sudden descent to the deep floor, he assigns to glacial action. Glaciers still nestle in some of the mountain hollows around the upper ends of these canyons, and Johnson was lowered down the crevasse between a glacier and the rock-wall beside it. He has described his observations in a passage which has been often quoted. He found that the rock beside the ice consisted of blocks which had been loosened along the joint-planes; and, by the freezing of water in the cracks, these blocks of rock were being gradually forced outward so that they would be frozen into the ice and then removed (Johnson, **1904**, pp. 573, 574).

This process of glacial plucking has been alternately advocated [1] and denied. It appears to take place to some extent, and the conditions of the Sierra Nevada would seem to be particularly favourable to its action. The Sierra Nevada is an elevated mountain-region, which has been subject to great and repeated earth-movements, so that the rocks have been deeply riven by cracks and joints. Hence the glaciers find the rock-walls loosened and the conditions especially favourable for ice-plucking.

The canyons in the Sierra Nevada were at first attributed to glacial action, and especially to plucking; but they are now generally regarded as due in the main to tectonic agencies. Thus the famous canyon of the Yosemite was at first confidently attributed by Le Conte [2] to glacial erosion. Whitney, on the other hand, explained it as a rift-valley, and his view has been adopted by I. C. Russell (**1899**, p. 351). According to Becker, it is due to the removal in preglacial times of a band of shattered rocks. He says (**1891**, pp. 68, 69) that ice cannot have excavated it, as the moraines are of trifling extent, and it occurs upon a system of fissures, which he describes as widely distributed through the Sierra Nevada of western California. The rocks there, especially the granite, are intersected by systems of fissures, of which the two most important trend from north-north-west to south-south-east, and from east-north-east to west-south-west; there are also vertical partings running north-north-west.[3] He has shown that these fissures are fault-planes, though the movements along them were often only an

[1] Its importance was perhaps first clearly maintained by Le Conte, who called it rough-hewing (**1875**, p. 137). Johnson described the process (**1899**, p. 112), and showed that it was a result of "vigorous weathering" due to sharp variations in temperature.

[2] J. de Conte, *Elements of Geology* (1878), p. 14.

[3] The influence of the joints on the formation of the Yosemite Canyon has been recognised in a recent paper by Mr. Johnson, though, on the evidence of the hanging valleys, he refers the canyon to glacial over-deepening along the joints (**1911**, p. 899).

inch or two in amount. Becker thinks that the fissures are so numerous that the average distance between them is only about 5 ft.; and in every case the movement was downward on the southern or western side of the fault. He holds (**1891,** pp. 50, 51, 52, 54) that these fissures are preglacial and are probably Pliocene in age, and that this wide network of fissures was made by the upheaval of the northern part of the district owing to its being lightened on the removal of material by denudation. He maintains that the canyons of the Sierra were "established long before glaciation began, and probably during the warm and no doubt very wet Pliocene epoch" (Becker, **1891,** p. 68).

Lawson (**1904,** pp. 328, 337, 365) proved that the long, straight, trough-shaped canyon of the Upper Kern River, farther south in the Sierra Nevada, is a rift-valley, and is due to faults having engulfed narrow, wedge-shaped, orographic blocks. A glacier occupied the upper part of the canyon, and, according to Lawson, cut back the walls to the extent of four inches! (**1904,** p. 349). In a subsequent paper he further showed that the valley of the Middle Kern River was on the same line of rift, and was also determined by a north-and-south crustal fracture (Lawson, **1905,** p. 409).

The age of these rifts was preglacial. Russell (**1889,** p. 351) was emphatic that in the Sierra Nevada the amount of ice-erosion in comparison with the size of the canyons was very slight, and "that the excavation of many of the valleys of the Sierra Nevada began long previous to the Quaternary, and are in fact relics of a drainage-system which antedates the existence of the Sierra as a prominent mountain-range."

Russell has extended the range of these tectonic, preglacial valleys into the northern continuation of the Sierra Nevada—the Cascade Range. In this area the valleys have been glaciated, so the evidence of their age is less obvious; but to the east of the Cascade Range the country was only slightly glaciated, and gives clearer evidence. Thus the great canyon of the Kieger River, in the Stein Mountains, continues for twenty miles below the lowest sign of glaciation, and Russell (**1905,** pp. 83–5) maintains that neither this canyon itself nor its hanging valleys can be due to glacial erosion. He says that, from analogy, the canyons in the glaciated mountains to the west of the Stein Mountains were probably also preglacial, and he claims that the mountains of the Pacific Cordillera of the United States were deeply sculptured by streams before the glacial period, and "that certain of the glaciated hanging valleys are not due, either wholly or in a large measure, to differential ice-erosion" (Russell, **1905,** p. 90).

That rocks are torn in blocks from their beds by the ice is supported by testimony from most glacial fields. I have repeatedly seen traces of it in Scotland, and a photograph of a limestone pit at Lugton, published in **1907,** No. 2 (Pl. II.), shows some blocks of Carboniferous Limestone which had been torn from their bed by a glacier, and carried a few feet and then piled up against a step in the rock. Prof. Penck has described an instance from the Zillerthal of blocks which had been torn from their bed and carried a short distance down the valley; and one of the blocks could be fitted into the socket from which it had been extracted. He concludes (**1905,** p. 6) that "plucking forms the most important part of glacial erosion."

Instances have been described by Prof. Chamberlin (**1897,** p. 236) from the Bowdoin Glacier in Greenland, by Daly from Aillik Bay, Labrador,[1] by Reusch (**1901,** pp. 141, 142) from the Eidfjordvandets in Norway, where, however, the blocks are torn from a wall of fissured rock. Displacements of material by ice-ploughing in soft beds has also been described, as by Sardeson (**1905**).

Roches moutonnées often have one side rough, while

[1] In Grenfell (**1909**, p. 120).

the side which had the full pressure of the ice exerted against it was smoothed and rounded. Penck (**1905,** p. 6) therefore called the rough side, the "lee side," and the other the "push side"; Shaler had previously described this roughness as due to the tearing away of rock-material, and had called the polished face of the *roche moutonnée* the "scour side," and the roughened, or lee side, he called the "pluck side."

7. "Corries" or "Cirques"

The agency of plucking has been especially adopted to explain those rounded, arm-chair-like depressions which occur upon the sides of many valleys. These are some of the most typical of mountain features in glaciated highlands, and have distinct names in most mountain regions. They are known as "corries" in Scotland, "cirques" in the French and "kare" in the German Alps, "cwms" in Wales, "coombes" in southern England, and "botner" in Norway.

The two characteristic features of a corrie or cirque are a steep, curved rock-wall and a flat floor, so that the shape resembles that of half an amphitheatre. There is often a small lake or tarn upon the floor. Corries may occur upon the sides of a valley or at its head. They are generally limited to high levels, and are best developed in, and sometimes as in the mountains of the western Balkans are restricted to, the zone above the old glacial line. Some corries, however, occur in Scotland low on the valley-sides.

Corries have unquestionably been formed by the cutting backward of the rock-wall. They were attributed by Prof. Bonney (**1871**) to the action of waterfalls on a series of convergent streams; and Sir Archibald Geikie (**1901,** p. 183) gave the same explanation. But, since Willard Johnson's invocation of plucking, they have been frequently claimed as glacial features due to the erosion of the wall and the corrosion of the floor by glacial plucking.

Corries have been often formed on hillsides just above the edge of large sheets of snow or ice, and are rather a meteoric than a glacial effect. They are not due to direct glacial abrasion, but to the shattering of rocks by frost. Slight changes of temperature at 60° F. have no appreciable effect on rocks; but an equal range of temperature at the freezing-point of water has a strong disruptive effect by freezing and thawing the water in the crevices of the rock. Corries are formed in arid tropical countries by sudden change of temperature at nightfall, combined with the action of the wind in grinding away fallen rocks and removing the debris as dust. Such corries have been described by Prof. Walther (**1891,** pp. 401, 402) and are illustrated by an example from Birket Qarun

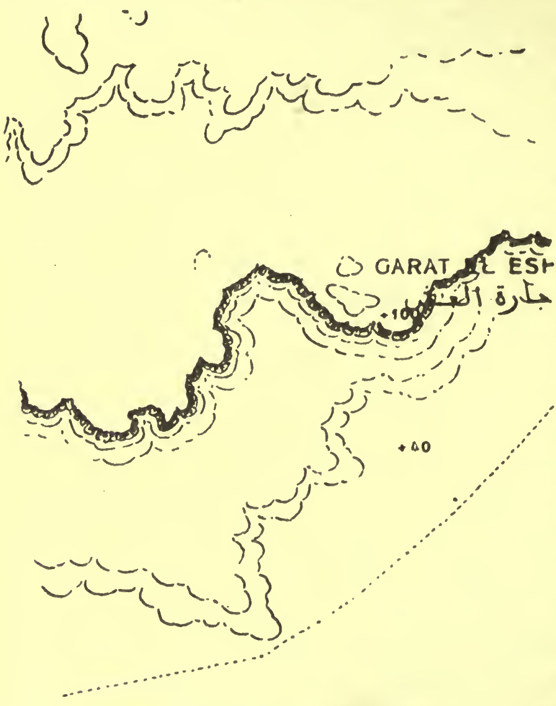

Fig. 72.—Cirque in Lower Egypt.
After Map of Egypt, Sheet III., II., S.W.

to the south-west of Cairo (Fig. 72). A patch of snow or a small glacier lying on the floor of a depression on a mountain-side is in an extremely favourable position for rending the adjacent rock by frost-action. The temperature of the rock in contact with the snow or ice will be kept near the freezing-point, and at least once a day the water in the rock would be frozen and thawed. The constant freezing and thawing beneath a thin bed of snow would stir up or force aside loose material beneath it; they thus produce the beautifully developed columnar joints which are so conspicuous in Spitsbergen on mud-flats that have been recently covered by snow. Beneath a thick glacier the change of temperature must be insignificant; but any exposed rock-surface upon its margin would, during the summer, usually rise above 32° in the day-time and fall below it at night. Hence in such positions the rocks are shattered and the fragments or joint-blocks are gradually forced apart. A block may fall out, or may be pushed out, by ice formed behind it; or, if frozen to the glacier, it may be plucked out. Hence the base of a cliff on the edge of a glacier is gradually cut backward. A gully containing a bed of snow or ice upon its floor would thus be slowly enlarged into the flat-floored, arm-chair-like depression known as a corrie or cirque.[1]

Prof. Hobbs has described the formation of hollows on open hillsides by the destructive effect of the continual freezing and thawing beneath sheets of snow. Snow may remain in hollows on slopes turned away from the midday and afternoon sun and thus last till late in the summer; and the continued freezing and thawing that take place beneath it gradually disintegrate the rock beneath. Prof. Hobbs calls this process "nivation."[2] The action appears to be generally confined to

[1] Some authorities regard cirques and corries as distinct varieties.

[2] This term was distinguished from glaciation by Matthes in 1900 (*21st Ann. Rep. U.S. Geol. Surv.*, pt. 2, p. 183), in describing the cirques of the Bighorn Mountains, Wyoming.

soft rocks, and it should be most powerful on those which are slightly permeable, but slowly absorb water on the surface. Shale or clay, covered by a thin patch of snow, would be thus slowly shivered and the debris washed away by rain or blown away by the wind after the last of the snow had melted away.

The recession of the walls of a cirque by frost is, however, in a wet climate, alone insufficient to form a cirque; for the fallen material must be removed or the talus would shelter the base of the cliff, and the floor must be protected from the action of streams, which would otherwise cut through it and form a funnel-shaped gully instead of a cirque. Both these functions may be served by the glacier on the floor of the cirque. It carries away the fallen rocks and deposits them at the end of the glacier as a moraine; and, if sufficiently thick, it protects the bed from frost, streams, and atmospheric decay, and it therefore keeps a flat floor.

The formation of cirques by the combined action of frost on the walls and the protection of the floors by ice was clearly explained by Prof. Cole (**1895,** p. 56). Of the higher Alps, he says: "Here frost-action and the battering of mountain-winds are the active agents in cutting back the walls of rock, and vertical cliffs of semicircular form result whenever one part gives way more readily than another." He describes the formation of a small glacier on the floor of this hollow and explains how "the ice thus protects the hollow, keeps it clear, and smooths and striates its floor." Richter (**1896,** pp. 152–64), a year later, advanced a similar explanation of cirques or botner of Norway, and since then it has been widely applied.

In the northern hemisphere the hollows on the northern side of a mountain-range are enlarged into normal cirques, while those on the southern side are developed into funnel-shaped gullies; for here, owing to the greater power of the sun on the southern and south-western slopes, snow and ice soon disappear from the depressions; the floor being thus left unprotected, streams cut them away. Thus on the south-western side of the Dent du Midi there is a series of funnel-shaped gullies, which on a northern face would have been cirques.[1]

8. U- and V-valleys and Glacial Base-level

The shattering of rocks by their being alternately heated during the day and chilled at night also takes place beside glaciers. This process widens the valley at the base, and thus gives it a U-shaped cross-section; whereas the deepening of a mountain-valley by rivers gives them a V-shaped form.

This U-shape is increased by the truncation of the rock-spurs. It is, however, important to remember that glacial valleys are by no means always U-shaped in cross-section. Prof. Bonney has pointed out that the Saas valley, although a typical Alpine glacier-valley, is shown, by sections drawn to true scale across and along it, to have the shape of a widely open V. Prof. Bonney (**1902**, pl. xxxv. fig. 3) has given two sections to illustrate the difference between his own and Prof. Davis's conceptions of the form of the typical glaciated valley. Prof. Bonney represents his (fig. 73 *b*), as a V-shaped trench on the bottom of a broad open valley, whereas Prof. Davis represents it (fig. 73 *a*), as a U-shaped, or flat-floored trough.

Most of the higher Alpine valleys seem to have the V-shape shown by Prof. Bonney. Thus, to quote the last Alpine valley which I have closely examined (January 1912), the valley of Morgins—a branch of the Champery

[1] Corries, it must be remembered, are of at least three distinct types. There are frost-formed corries, like the Great Corrie of Balglass, on the Campsie Fells; secondly, corries which are preglacial hollows on the sides of valleys, and sometimes even almost on their floors, which have been rounded by ice flowing down the valleys; (3) corries which have been cut by the action of a series of convergent waterfalls, as suggested by Professor Bonney. The smaller corrie of Balglass affords an example of this process in operation.

a.

b.

c.

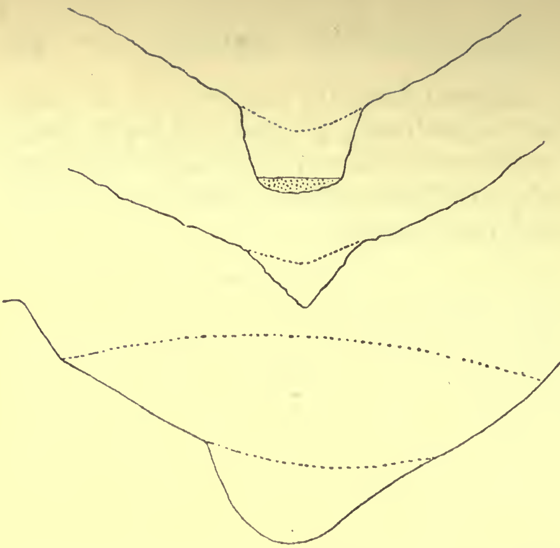

Fig. 73. Transverse Sections of V- and U-Valleys.

a. Prof. Davis's view of a glaciated valley according to Prof. Bonney.
b. The typical form of an Alpine glaciated valley after Prof. Bonney.
c. The form of an Alpine glaciated valley according to Prof. Penck.

d.

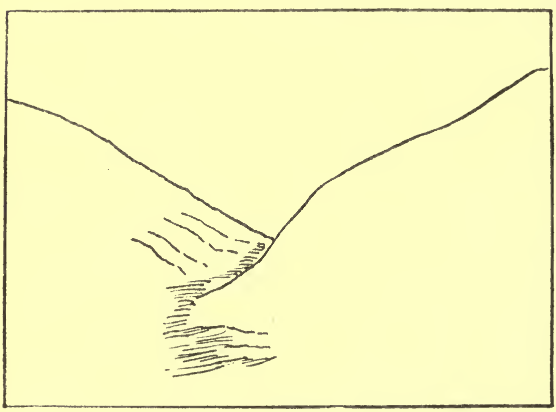

Fig. 73 *d.* Section across the Val de Morgins.

Representing a typical Alpine glaciated valley.

e.

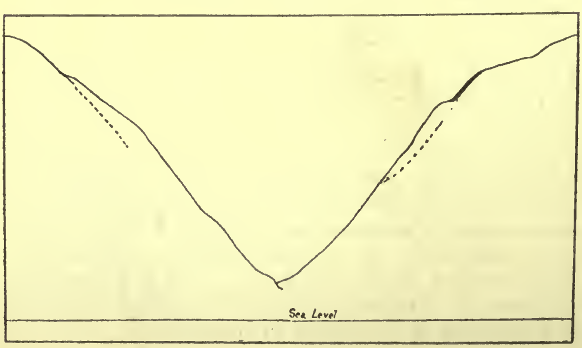

Fig. 73 *e.* The V-shaped Cross-section of the Continuation of the Hardanger Fiord-valley, looking up the Valley to the Buarbrae from Sandvedvandet.

Valley which joins the Rhone Valley at Monthey—has been glaciated to its floor; but, as shown by Fig. 73 *d*, it agrees essentially with Prof. Bonney's representation of the form of the Saas Valley; and many cross-sections of Norwegian fiords (see, *e.g.*, Fig. 73 *e*) have the same V form. The part of the Rhone Valley near Morgins, on the other hand, corresponds with the ordinary idea of a U-shaped valley; and the form here must be due to the truncation of the spurs as the valley is crossing the strike of the rocks.

The V-shape of the trench on the floor of a broad old glacier-filled valley implies that the main deepening during glacial times was due to the action of a stream beneath the glacier, as is well shown, *e.g.*, in the gorges below the ends of the Rosenlaui and Lower Grindelwald Glaciers. The narrow notch on the floor of the wide valley is admittedly due to water-action.[1] When a valley occupied by a glacier has a steep gradient and a free outlet for its drainage, subglacial corrosion appears always to form a " V " valley. Where, however, a glacier flows down a valley with a gentle gradient, or where it has reached base-level, then its tendency is to attack its walls rather than its floor.

The difference between the forms of glacial and river-cut valleys appears to be often over-estimated, for under similar conditions both rivers and glaciers produce either U-shaped or V-shaped valleys.

A mountain-stream has usually greater powers of corrosion than of erosion, and it therefore produces a V-shaped trench; but in the lower parts of the valley, where the widening by erosion is greater than the deepening by corrosion, the valley acquires a U-shaped form. There is the same difference between the forms of an upland and a lowland glacier-valley. Valleys that have been occupied by ice are no more necessarily V-shaped

[1] By Prof. W. M. Davis (**1900**), and by Reusch in his instructive sections across the upper part of the Laerdal (**1901**, p. 170).

than are river-made valleys. They are V-shaped where corrosion is in excess of erosion and are U-shaped where the influence of erosion exceeds that of corrosion.

A glacier, in fact, has, like a river, a base-level of corrosion. A glacier may, in special circumstances and by pot-hole action, hollow a deep basin below its bed, although the floor of the valley is at its base-level. Thus, if a stream from a lateral valley flow on to a glacier the water will fall through crevasses and pipes on to the floor of the main valley and excavate a series of pot-holes, which will in time excavate a basin on the main valley-floor; but except in such special cases, the chief abrading influence of the glacier is lateral at any part of its course where it has reached its base-level; and it thus wears its walls into long, straight, spurless sides. This limited corrosive influence of a glacier after it has reached sea-level is well shown, for example, in the valley at Sligachan on the eastern side of the Coolins of Skye.[1] In the upper part of those mountains there are magnificent glaciated valleys with V-shaped cross-sections. Most of the ice from the eastern sides of the Coolins flowed northward down the Sligachan Valley, the lower part of which is but little above sea-level. The glacier has there spent its rock-cutting powers in wearing back the sides of the valley. Hence this valley, no doubt, had formerly the sinuous course of an ordinary river-valley around the ends of the spurs which must once have projected into it from both sides; but these spurs, as illustrated by the western face of Marsco, have now been worn back and faceted, and the valley has a straight, trough-like form. Its floor, though covered by a litter of morainic material, shows so many exposures of rock *in situ* that the glacier left it as an irregular rocky plain, and did not excavate it into a basin with a floor lower than the outlet.

The contrast between the lateral and basal abrasion

[1] The glaciation of the Coolins has been described by Harker (**1901** and **1904**).

by glaciers is well shown by the contrast between the effect of an ice-sheet moving over a high plateau and that of a glacier flowing from it on to the adjacent lowlands. The surface of a plateau may be nearly all at the local base-level. During the passage of the ice across the plateau it flowed around the old ridges, cut off their ends, and widened the gaps through them ; but it has never, in any case which I have examined, excavated deep basins. The effect of a glacier under such conditions is mainly levelling and planing. It wears away the rocky projections in its course instead of deepening the depressions into basins. This fact is well shown in central Scandinavia, as on the plateau of Jemtland to the east of the Norwegian frontier at Storlien. The hills, which lie to the south of the railway, have had their spurs cut back and faceted by the ice flowing westward ; and the summits have been rounded and lowered by the passage of the ice-sheet across them. When the ice entered the valleys to the west the confinement in the narrow channel concentrated the attack of the ice on the walls, and thus the spur-cutting was increased in vigour ; but in the upper parts of the valleys corrosive abrasion was effective and the valleys have narrow floors and are V-shaped. In the lower parts of the valleys, near the coast at Trondhjem, corrosion appears to have been relatively insignificant, and the effect of the glacier was to widen the valleys into a U-shaped cross-section and to give them a straighter course.

The contrast between the planing effect of a high ice-sheet and the formation of trough-valleys in the lowlands is well shown along the railway from the plateau of central Scandinavia near Röros to Trondhjem. Röros is on the high plateau of central Norway at the height of 2,060 ft. above sea-level. It stands on a wide plain surrounded by gently undulating hills which have had their tops rounded by the passage of the ice across them. This level country ends to the west in a rugged area where the plateau has been dissected by deep valleys.

The railway begins the descent towards Trondhjem

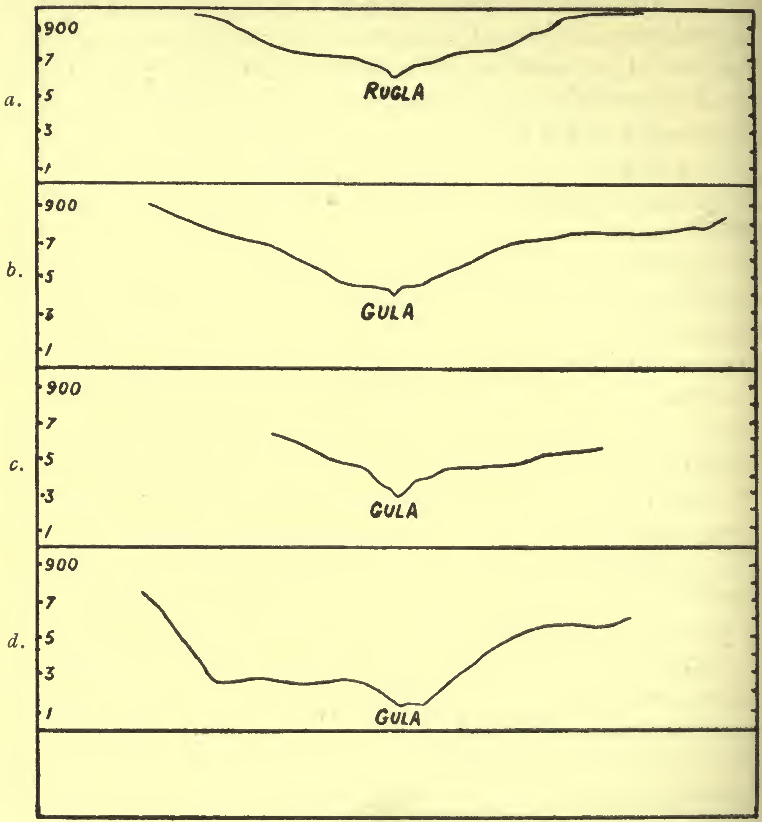

FIG. 74.—SECTIONS OF THE GULA VALLEY, NORWAY.

a. Section across the Rugla Valley, a tributary to the Gula, showing the small river-cut trench on the floor of an old glaciated valley.
b. Section across the Gula Valley; the present river-valley is cut on the floor of a wide glaciated valley.
c. Section still lower down the Gula Valley, with a larger V-shaped valley cut on the floor of the older valley.
d. Section across the lower part where the valley is passing into the condition of a fiord-valley by the abrasion of the spurs.

down the Rugla Valley; this is ice-worn to its floor, on which a river has cut a narrow canyon (Fig. 74 *a*). The Rugla enters the wider Gula Valley, which is similar in transverse section, though it is broader, and on the floor of the valley are numerous glaciated surfaces, which show that the present floor of the valley has not been materially deepened since glacial times. The Gula River leaves its first broad basin and flows by a narrow, sinuous gorge into a second basin. The cross-section still has the form of a widely open V. It is not until the valley approaches sea-level that the walls have been cut back sufficiently for the valley to have the form of a fiord-like trough-valley. The sections (Fig. 74 *a* to *d*), illustrate the various stages in the course of this valley between the small mountain-valley with the gorge on its floor near the edge of the plateau, and the big trough-valley in the lowland.

The same contrast is well shown in many parts of the Scottish highlands; it may be seen, for example, when ascending the Grampians by the railway from Perth to the Spey Valley, before reaching the Pass of Dalnaspidal. The general contour of the country is open, with blunt, rounded, down-like hills and broad, shallow valleys. The whole of this district was swept by an ice-sheet which has had a levelling effect upon the country. The valleys down which the ice escaped from the plateau were mainly influenced by valley-glaciers, and in their lower parts the abrasion along the walls has cut them back into flat faces and given the valleys a U-shaped cross-section. Thus, the Spey Valley on the north and the Tay Valley to the south both show beautiful examples of ice-faceted spurs and long, ice-smoothed, and straightened valleys.

The evidence, therefore, seems to me to show that glaciers have a power of cutting back spurs which is greater than that of water, and that many fiords have been betroughed by the removal of the spurs by glacial abrasion. But spur-truncation implies the previous existence of the spurs, and that the spurs themselves were due to the action of rivers and streams before the occupation of the valley by ice. Spur-truncation is an argument in favour of the widening and strengthening of valleys by glacial action, but not of their deepening. It is an erosive, not a corrosive, process. During many rambles amongst the glaciated valleys of Scotland I have made numerous estimates of the amount of material which is shown to have been removed by spur-truncation. And the conclusion has been gradually impressed on me that the glaciers have not materially deepened the valleys except where the ice has induced pot-hole action or where it flowed in a suddenly contracted channel or over decomposed rock.

9. Glacial Protection

A glacier flowing down a main valley will flatten the walls if there be no active excavation of the lateral valleys. Where the tributary streams are in full activity they keep pace with the main stream in cutting down their channels. The main valley and its tributaries would then agree with Playfair's famous law,[1] and have a continuous "accordant" slope; the walls of the main valley would be notched to their base by the side-valleys. If, however, the side-valleys only notch the walls of the main valley the latter has been deepened more rapidly than the lateral valleys. In glaciated areas, by whatever process, the lateral valleys have often been relatively protected during the glacial occupation.

A cover of snow or a stagnant glacier must in many ways act as a blanket to the rocks beneath, and must protect them from many agencies which cause the decay of rocks. The most widespread, and, taking the world as a whole, the most potent cause in the decay of rocks is the slow action of the atmosphere, which oxidises some of the constituents and converts others into carbonates. The soluble constituents are then removed by water which has percolated downwards, and the rocks are

[1] This law is stated and lucidly explained by Prof. Davis (**1909**, p. 72).

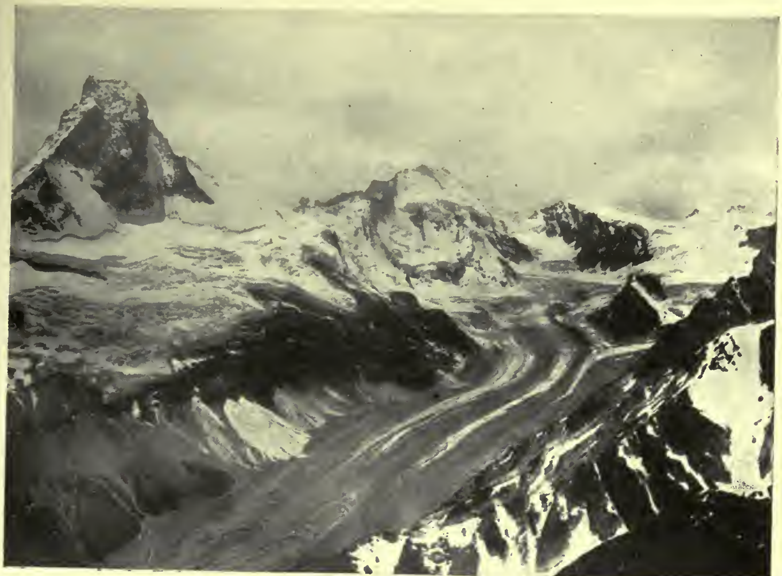

Photo by W Lamond Howie.

FIG. 1.—VIEW ACROSS THE Z'MUTT GLACIER TO THE MATTERHORN, Showing the protection of the platform by the Matterhorn Glacier. (*Vide* p. 433.)

Photo by Rev. A. E. Robertson.

FIG. 2.—BEN LUI, WITH ITS GREAT CORRIE AND TRUNCATED RIDGES. (*Vide* p. 464.)

shattered by innumerable small cracks due to alternate freezing and thawing. From all these processes a covering of snow and ice protects the material underneath.

This protective influence of ice was well pointed out by Alex. Müller in 1874. He says (**1874**, p. 480) that—

"The factors of weathering are: alternation of temperature, with the consequent alternation of expansion and contraction, especially during the temporary ice-formation; oxidation, with alteration of volume and loosening of joints; penetration by water and carbonic acid; the influence of vegetation. All these factors under an ice-cover become very much weakened, if not altogether removed. The mechanical working of flowing glacier-ice should not, on the contrary, be underestimated."

The protective action of ice has been frequently and well stated. Rutimeyer described the regions of eternal snow and ice as regions of rest which are protected from valley-formation (**1869**, p. 35), and Pfaff (**1874**), held that "with glaciation valley-formation is stopped and only goes on outside the ice-sheet."

Whymper (**1871**, p. 154), in a vigorous criticism of the views of Ramsay and Tyndall, declared that glaciers, "either considered by themselves, or in comparison with other powers, should be regarded as eminently conservative in their acts and in their intentions." This view has been emphatically endorsed by many later authorities, including Bonney, Kilian, Frech, and Garwood.

Many Alpine views show the contrast between the protective influence of sluggish ice and the erosive influence of an actively flowing glacier. Thus, in Pl. VIII. Fig. 1, the view across the Z'mutt Glacier to the Matterhorn well illustrates this contrast. The photograph, for which I am indebted to Mr. W. L. Howie, shows the Z'mutt Glacier flowing at the foot of a bare rock-wall; between the top of this cliff and the Matterhorn is a platform covered by the comparatively stagnant ice of the Matterhorn Glacier which has protected the rocks beneath it. It therefore remains on a raised shelf beside the main valley. Prof. Garwood (**1910**) has called attention to, and illustrated by his beautiful photographs many other examples of the same phenomenon.

Glaciers, therefore, have this double effect. They are protective in some cases, and they are powerful agents of abrasion where ice armed with rock-debris presses heavily against projecting bars of rock.

10. Hanging Valleys

Glacial abrasion appears to be greatest upon the margin of the ice, and it thus widens and straightens the main valleys. The effect is, therefore, to leave the mouths of the tributary valleys high upon the hillsides instead of level with the floor of the main valley. Such valleys are known as "hanging valleys," one of the happy terms for which geologists are indebted to Prof. G. K. Gilbert. Their existence was first used as an argument for the glacial excavation of the main valleys by Sir James Hector in 1863.[1] But hanging valleys are due to many other processes than glacial action, for they are caused by any agency which deepens a main valley more rapidly than the tributaries. Thus, when the sea cuts back a cliff more rapidly than streams can deepen their channels, they are left in hanging valleys, such as those which have been described on the coast of Devonshire by Mr. Arber,[2] and are well shown on the western coast of tropical Africa (Fig. 77). They may also be caused when a country is being uplifted more quickly than the streams can lower their beds. Thus, Fig. 75, of the coast near Cape Japounski, on the Asiatic shore of the Bering Sea, shows hanging

[1] See *ante*, p. 356 The argument was independently introduced by H. Gannett, in his description of Lake Chelan, *Nat. Geog. Mag.* (1898), vol. ix., p. 419.

[2] E. A. N. Arber, *The Coast Scenery of North Devon* (1911), p. 144, pl. xlv., etc.

valleys which Dawson attributes to an uplift (**1894**, p. 128).

Rivers produce hanging valleys by the erosion of their banks. River-erosion is especially apt to cause hanging valleys where the tributary valleys are protected by snow or where, owing to the existence of local snow-fields upon the mountains, the precipitation may be locally very irregular. River-formed hanging valleys are numerous in limestone countries where, as in Dalmatia, the rocks are porous and much of the drainage is discharged to the main streams through underground channels. Hanging valleys are also frequently formed by fault-action. Crosby has described an American example near Georgetown, Colorado, and beautiful examples of fault-formed hanging

FIG. 75.—HANGING VALLEY NEAR CAPE JAPOUNSKI, EASTERN SIBERIA (AFTER DAWSON).

valleys occur along the coasts and rift-valleys of Equatorial Africa, and at levels far below that at which there is evidence of the action of ice. These equatorial hanging valleys may be illustrated by two examples from the shore of the Albert Nyanza, less than 100 miles from the Equator and at the level of little over 3,000 ft. above the sea; they are shown on Fig. 76; and by a sketch of the western coast of Africa, in Angola (Fig. 77).

Hanging valleys are numerous in Scotland. Many of them are preglacial valleys which have been left empty by diversion of the drainage during the evolution of the existing river-system. Others are due to the deepening of the main valleys by the combined action of ice and water during the glacial period.

Some of the most accessible of these Scottish hanging valleys occur on the shores of Loch Lomond and Loch Long. The upper part of Loch Long is a subsequent

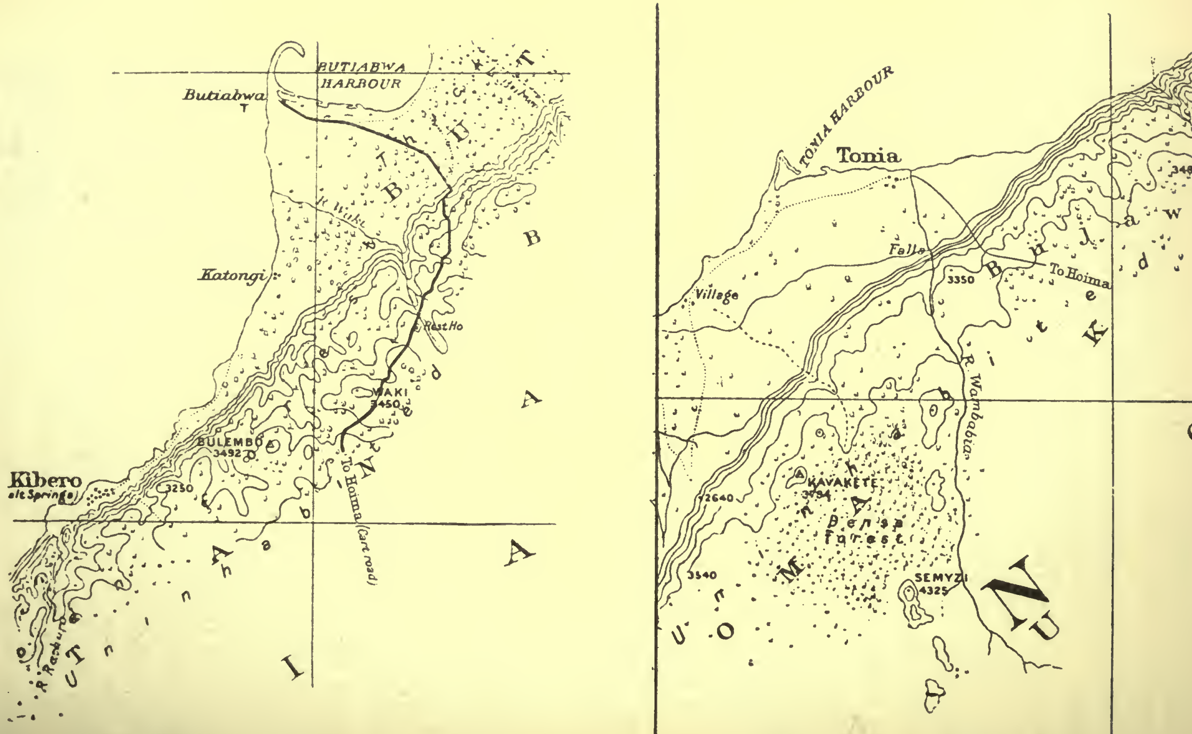

FIG. 76.—HANGING VALLEYS ON THE SOUTH-EASTERN SHORE OF THE ALBERT NYANZA.
From map 1/250,000 Uganda-Congo Commission 1906–8, War Office General Staff, No. 2,471, 1909.

valley, which has cut across an old valley-system that probably dates from Oligocene or perhaps Eocene times. Loch Long was widened, straightened, and perhaps locally deepened by ice; and during this process some of the lateral valleys have been left hanging upon the hillsides. But that these hanging valleys are due rather to glacial protection of their floors and not to glacial corrosion of the main valley is shown by the case of Glencroe, which enters Loch Long near its head. This valley is clearly river-cut, for it is a sinuous, V-shaped gorge with overlapping spurs; and, as it lay at right angles to the main direction of the ice-movement, it was filled with comparatively stagnant ice and its lower part was very little

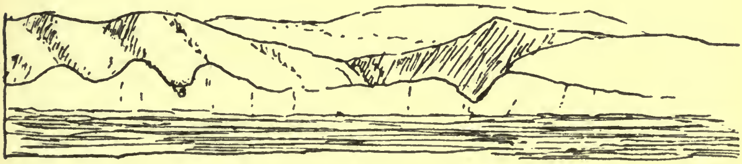

FIG. 77.—HANGING VALLEYS AND TRUNCATED SPURS ON THE COAST OF BENGUELLA, WEST AFRICA.

Lat. 11° S., near Nova Redonda (*African Pilot*, vol. ii., 6th edit. 1910, p. 234).

influenced by glacial abrasion. But its mouth is level with the shore of Loch Long, and it was doubtless deeper, for the channel has been filled by a delta. The evidence of Glencroe seems to me conclusive that the hanging valleys on the side of Loch Long were not left by glacial deepening of the Loch Long valley, for they were in existence as hanging valleys in preglacial times; they are old valleys that have been left undeepened owing to the diversions of their drainage during preglacial times on the formation of the Loch Long valley. These hanging valleys were cut by small rivers which were beheaded in preglacial times.

The beautiful hanging valley of Strath na Uisge, half a mile above the northern end of Loch Lomond, on the western side of Glen Falloch, appears to be a preglacial river-valley, that once continued eastward across the Falloch and on down Glen Gyle to Loch Katrine. It was probably beheaded by a subsequent river working along the Loch Lomond fault and was left hanging in preglacial times.

The deepening of many main valleys was no doubt partially due to corrosion in glacial times, but it was by no means necessarily due to the action of ice. Most geologists adopt the view that, during the glacial period, there was a series of alternate periods of increase and decrease of the ice, and that the ice sometimes almost completely disappeared.[1] During the retreat of the ice vast floods of water must have been set free by its melting, and such river-floods are especially active agents in river-corrosion. Every student of river-action knows that a single strong flood will make greater changes in a river-channel than erosion by the normal stream will effect in many years. Mr. E. C. Andrews (**1908**), has well described the simulation of glacial features by floods in New South Wales ; and such river-floods would have been numerous and worked under especially favourable conditions during the interglacial periods.

II. Summary

In summarising the results of this chapter, the evidence seems to me to point to a position intermediate between that of the extreme advocates of the two schools. On the one hand, glaciers have three means—the removal of decayed rock, direct action on the floor of an arm of the sea by replacement of the sea-water, and depth of pot-hole formation—which enable them to hollow out basins deeper than those that may be made by rivers.

[1] For the weighty arguments against the existence of several distinct glaciations in the British area see Lamplugh (**1906**). Prof. J. Geikie, on the other hand (**1894**, and elsewhere), maintains the existence of numerous glacial periods in Scotland and in other glaciated countries. The evidence for the interglacial periods in Switzerland has been convincingly stated by Penck and Bruckner (**1909**).

Glaciers also cut back spurs and give valleys the trough-shape possessed by fiords. On the other hand, ice has a protective as well as an eroding influence, and the claim that glaciers excavate deep basins in hard rock does not seem to me yet established, except to a small extent under special circumstances. Glaciers may lick out decayed material and thus produce a hollow; but, except where they act on local masses of rotten rock, or where they work by means of pot-holes, they do not appear to excavate deep rock-basins. An ice-sheet has no doubt a marked influence on the scenery and physiography of any country it may cover, for it sweeps away the superficial layer of decayed rock and soil; it alters the river-systems by establishing glacial dams and causing local irregularities in precipitation, and thus gives rivers special powers of attack; but excavation by ice alone seems to have been limited to the widening and moulding of preglacial valleys, and in comparison with the preglacial agencies its effect has been slight.

CHAPTER XXI

ON THE GLACIAL ORIGIN OF FIORDS

Crawl on, old ice-worm, from the solemn hills,
  Press deep thy burrowing snout among the stones;
Mutter and murmur with thy turbid rills,
  And crush the old earth's bones.

A. C. Benson.

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1. The Argument from Distribution.—2. From Trough-valleys.—3. From Thresholds.—4. From Rock-basins.—5. From Hanging Valleys.—6. From Spurless Walls.

The claim for the glacial origin of fiord-valleys is usually based upon four chief arguments. First, their restriction to countries which have been formerly glaciated and to high latitudes; second, their trough-shaped form; third, the usual presence of a deep interior basin separated from the sea by a raised threshold; fourth, the fact that the main valleys have been cut much deeper than their tributaries, which often join them as "hanging valleys."

1. The Argument from Distribution

The argument based upon distribution is the oldest, the most popular, and the weightiest. It was first advanced by Dana in 1849, when he called attention to the restriction of fiords to comparatively high latitudes. He has been represented as therefore regarding this distribution as due to the glacial origin of fiords. But Dana clearly recognised that it was due to the limitation of fiords to two zones of subsidence.

"There are, then," he said (Dana, **1849**, p. 380), "certain fiord latitudes—or *a fiord zone* for the globe—both north and south of the equator. New Zealand and the Auckland and other islands partake much of the same character, and are the only lands in the southern hemisphere, besides the extremity of America, which reach into the southern fiord zone. These facts lead to interesting conclusions respecting extended areas of subsidence encircling our globe."

Dana subsequently pointed out (**1856**, p. 26), that the fiords occur in areas which had been formerly much elevated, and he appeared to recognise that, as these elevated areas were mainly in the higher latitudes, the elevation might have been the cause of the glaciation. The association of fiords and high latitudes might be a coincidence, as the variations in level of the circumpolar belts might be the cause of both glaciation and fiords. The view has gradually become more general that fiords are restricted to glaciated districts. Thus Profs. Supan and Günther, in the earlier editions of their great works, both accepted various arms of the sea in non-glaciated districts as fiords; but both later adopted the view that fiords occur only in areas that have been glaciated.

The weak point in the argument from distribution is that it depends upon a definition of fiord which assumes the point in question. Thus Sir Henry Howorth, Hahn, Lawson, and other authors (see p. 61), have claimed that there are fiords in regions that have never been glaciated. Other authors, such as Dr. O. Nordenskjöld, decline to accept any non-glaciated valleys as fiords, and dismiss them as pseudo-fiords. But the Dalmatian gulfs, for example, are so fiord-like that general observers always regard them as fiords. The Gulf of Cattaro is justly described as a fiord in the passage quoted on p. 202, and as a fiord Nimrod Sound in China may also be regarded.

Though some of the inlets in tropical and temperate regions which have been called fiords cannot be maintained as such, and though others of them are only fiords in the last stages of decay, yet I am forced to the conclusion that there is no definition of fiord which will exclude some inlets in non-glaciated countries. It is true that fiords are most abundant in glaciated areas; but, as Dana suggested in 1849, this fact is quite consistent with their dependence on earth-movements.

The restriction of fiords is not to glaciated coasts, but to coasts bordering areas of recent subsidence in various parts of the earth.

2. From Trough-valleys

The existence of trough-valleys is also inadequate proof of a glacial origin, for long trough-valleys are formed in various ways. They are produced by faulting and by torrential rivers. Glacial action only causes trough-valleys where the structure of the country helps in the development of this geographical form.

3. From Thresholds

A threshold occurs, according to Leipoldt, across the entrance to every fiord; but there are so many fiords without thresholds that his proposed law is invalid (see *ante*, pp. 65, 148). The number of exceptions would be reduced by the definition of Dr. O. Nordenskjöld, according to which the threshold need not be at the mouth of the fiord. He would accept any ridge across a fiord as a threshold.

The presence of a threshold is not proof of the glacial origin of that fiord. For thresholds are often mere banks of sediment. Von Richthofen, in fact, held that they were always sedimentary in origin, and this view is probably correct for most of them, though others are probably due to tilting or subsidence. Nearly every type of gulf, bay, and estuary has similar irregularities on its floor. Thresholds, as shown previously (pp. 65–6), occur at the harbours of San Francisco and Rio Janeiro. Chesapeake Bay is no fiord, but it has a well-marked basin and threshold. The depth within is 114 ft.; just within the mouth the deepest sounding is only 51 ft., and the sea outside is shallow.

Most large rivers, even in tropical countries, have similar irregularities in their channels. Thus the Mississippi, near its mouth, is 120 ft. deep; but the various "Passes" through its delta have maximum depths of only 3, 10, 7½, 8, and 35 ft.[1]

Again, the river Tagus, near Lisbon, four miles from its mouth, has a depth of 150 ft.; but in front of its mouth is a bar, where, according to the Admiralty Chart,[2] the maximum depth is 42 ft.

4. From Rock-basins

There seems no satisfactory rule by which the basins and thresholds of true fiords can be distinguished from the pools and shallows due to mere irregular corrosion and deposition by rivers. Many lake-basins are due to other causes than glacial excavation. Thus, Marr (**1895**) has shown that some of the tarns in the Lake District are not true rock-basins; they are apparently, for they discharge their overflow across a rock-rim; but the original outlet was down a valley which has been filled by sediments. Rutimeyer (**1869**), has shown that the theory of glacial excavation is quite insufficient to explain the Alpine lake-basins. Prof. Bonney (**1873**), has pointed out what seem to be insuperable difficulties in applying that theory to the lakes of the Tyrol. Rock-basins with flat floors and steep sides and cross-sections as trough-shaped as those of fiords occur in the lakes and valleys of volcanic districts.

[1] *Mississippi River, from the Passes to Grand Prairie, Louisiana* (United States Coast and Geod. Surv., 1906).

[2] No. 87, 1910.

Thus, the section through Lake Taupo given by Prof. Marshall (**1905**, p. 169), has the same form as a section across a fiord; but it is almost certain that Lake Taupo is due to simple subsidence in a volcanic area.

Rock-basins, therefore, are of four main kinds—cauldrons due to subsidence, hollows excavated by the removal of irregularly weathered rock, hollows drilled into hard, fresh rocks by pot-hole action, and old valleys closed at their mouths by uplift either by faulting or the tilting of the district.

5. From Hanging Valleys

The strongest claim for the glacial formation of fiords in recent years has been in Prof. W. M. Davis's famous memoir on *Glacial Erosion in France, Switzerland, and Norway,* in which he first joined the ranks of those who demand "wholesale glacial erosion" (Davis, 1900, in **1909**, p. 635). He rested his argument for the glacial origin of the Norwegian fiords mainly on their association with hanging valleys, which he described as the features most "compulsory of a belief in strong glacial erosion" (**1909,** p. 655).[1] He recognised that the fiord-valleys themselves were preceded by narrow, preglacial canyons; but he claimed that these must have been deepened and widened by thousands of feet into the fiord-troughs. He says that even if it were assumed that preglacial rivers had cut canyons to the present depths of the fiords, extensive glacial erosion must have taken place to cut back the originally sinuous walls, with their succession of ravines and buttresses, into the present flat walls of the fiord-troughs. It is true that a glacier flowing down a narrow, sinuous valley would be under the most favourable conditions for erosion. The ice would press on both sides against rock-walls which had been weakened by weathering and by fissures. The edge of the glacier would be con-

[1] F. Carney (**1909,** p. 208), also describes the hanging valley as the most convincing argument for deep valley-erosion by glaciers.

tinually rearmed with coarse rock-fragments which had fallen on it, and the projecting spurs would be reduced by the loss of blocks of rock pressed out by frost. Nevertheless, inspection of a considerable series of Norwegian fiords from Tromsö to Christiania has left on me the impression that the amount of glacial widening has been small in comparison with the amount excavated in preglacial times. The question at issue between the glacial and tectonic theories is as to the relative amount of the preglacial and glacial excavation. Norway was probably rising in level throughout Pliocene and late Miocene times; and the rivers were then working under the conditions most favourable to rapid corrosion. The assumption that the rivers had cut their main valleys down to their base-level in preglacial times is probably correct. The spurs from the walls of such canyons are usually short, and erosion by the rivers would cut them back; and the flattening of the spurs would give the valleys the form of troughs such as may be seen now in process of formation by river-action in the North Island of New Zealand.

6. From Spurless Walls

If the fiord-valleys have been deepened by thousands of feet by glacial erosion, as Prof. Davis believes, then the preglacial canyons must have been very shallow as well as narrow. But, considering the length of time during which the rivers had been operating under most favourable conditions for the excavation of valleys, it seems most probable that a series of wide canyons with short-spurred walls had been already formed at the beginning of glacial times; also that many high-level valleys had been left as hanging valleys owing to the diversion of their waters into the main valleys which had been excavated along the great tectonic rifts.

Long, spurless walls are well known in many regions which have not been subject to glaciated action, as in Fig. 78, of one wall of the Nile Valley over 100 miles south of Cairo. Many of the maps of southern and central Italy on the scale of 1 to 100,000, show long, wall-like ridges. The map of the environs of Florence (Sheet F. 106), shows, to the north-north-west of the city, on Monte Morello (3,018 ft.), contours as serrate as the outlines of Vauban's forts; but the adjacent face of Monte della Calvana, which rises to almost the same height (3,005 ft.), has long, straight contours along the Bisenzio Valley. On the western side of that river, Monte le Coste (1,736 ft.) has also long, flat, spurless slopes. The same feature can be seen farther south in Italy; for example, in the valley of the Potenza River to the west of San Severino (Sheet F. 124).

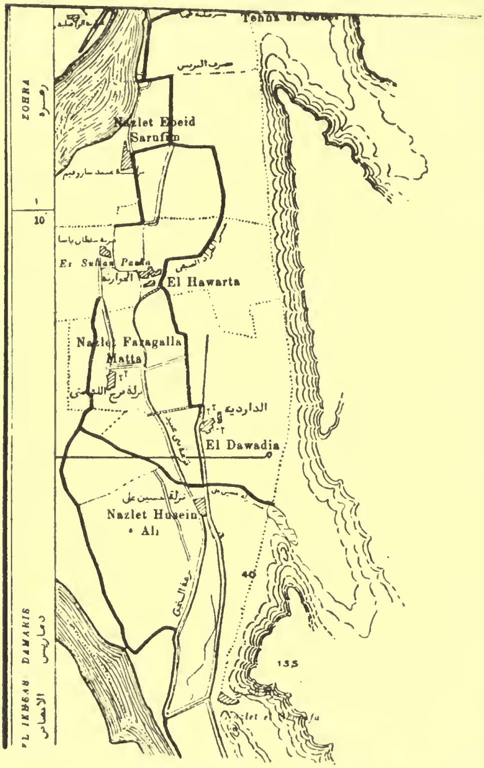

FIG. 78.—SPURLESS WALL OF THE NILE VALLEY, 120 MILES SOUTH OF CAIRO.
Scale 1 : about 70,000. Survey Dept. Egypt, 1908, Sheet X. 1, S.W. Minia.

The Italian map on the scale of 1 to 100,000 of the neighbourhood of Avezzano shows, on Monte Velino, a series of hanging valleys at the height of 3,300 ft.; they are separated by flattened, faceted spurs (Sheet F. 145, lat. 42° 9′ N.).

Straight ridges with faceted spurs are shown on many of the maps of the United States to the south of the glaciated districts. Thus, they appear conspicuously on the bank of the Ohio River in West Virginia in the map of the Clarington Quadrangle; also in the Hummelston sheet (lat. 40° 25′ N.) in Pennsylvania; on the Susquehanna River in the Harrisburg sheet, and still farther south in Texas they are shown on the Mariscal Mountain (3,940 ft.) in the maps of the Chisos Mountain Quadrangle in Brewster County.

The combination of hanging valleys and truncated spurs is often found where it cannot be due to glacial action. Good instances can be seen on the southern side of the Tagus opposite Lisbon; in fact, I cannot remember to have seen any considerable mountain-chain or mountain-area in any non-glaciated district which does not show truncated spurs, spurless walls, and hanging valleys.

CHAPTER XXII

EVIDENCE AGAINST THE GLACIAL ORIGIN OF FIORDS

From what has already been noted of glacier action, the reader cannot but be aware that its universal effect is to round and soften the contours of the mountain subjected to it; so that a glacier may be considered a vast instrument of friction, a white sandpaper, applied slowly but irresistibly to all the roughnesses of the hill which it covers. And this effect is, of course, greatest when the ice flows fastest, and contains more imbedded stones; that is to say, greater towards the lower part of a mountain than near its summit.

RUSKIN.

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1. Some Glaciated Areas Fiordless.—2. The Shape and Arrangement of Fiords often Inconsistent with their Glacial Erosion.—3. Their Preglacial Age.

1. FIORDLESS GLACIATED AREAS

THE argument from distribution is the strongest in support of the theory of the glacial origin of fiords. It is, however, attended by so many difficulties that it must be dismissed as inadequate. Even the general outlines of fiord-distribution are inconsistent with the theory (see Map, Fig. 82, p. 467). In Scotland the same rocks occur on both the eastern and western coasts; yet the fiords are limited to the western coast, and the long, narrow freshwater lochs to the western half of the country. These facts cannot be explained by the difference in altitude, for the largest of the highest areas in Scotland is on the eastern side of the country in the eastern Grampians. Yet there are no large fiord-like lochs in that district, although it was one of the most severely glaciated areas in Scotland. The Spey Valley, for example, shows some of the finest instances to be seen in Scotland of the cutting off of spurs and the straightening and widening of valleys, but the Spey Valley has no deep loch-basins.

It may be suggested that rock-basins were carved out in this district and were filled by the deposition of sediment in post-glacial times. There are, no doubt, many buried channels with floors below sea-level in the eastern part of the British Isles. Such are the well-known buried channels of the Tay and the Forth and of the river Stour near Sudbury between Suffolk and Essex. But these deep channels appear to have been all preglacial in origin, and they were filled during glacial times. There is no evidence that they were deepened by the ice. Thus, the deep depression in the Stour Valley was partially filled by an older sheet of boulder-clay, which was not removed by the agent that deposited the upper boulder-clay. The deep, drift-filled channels of the eastern side of the British Isles correspond to others on the western side of the country, such as the preglacial valley of the Kelvin to the west of Glasgow. They afford no evidence of the existence of glacier-basins cut out by ice, and they have been filled mainly by glacial deposits.

The striking contrast between the eastern and the western coasts of Scotland shows that an ice-sheet alone is an unsatisfying explanation of the origin of the fiords. The same lesson is shown by the eastern coast of England. It was intensely glaciated, and that in districts composed of soft rocks, which might have been expected to be easily affected by glacial corrosion ; but the only fiord-like lakes are in the western highlands of England and Wales, and there are no fiord-like basins or valleys in eastern England.

The evidence from Scandinavia is similar. The western coasts are indented by fiords, while the eastern coasts are not. Sweden was intensely glaciated, but the ice-sheet which covered it, planed down the irregularities of the country instead of digging out deep basins. The Swedish eastern coast is indented only by fiards, and not by fiords. It may be suggested that the absence of deep basins is due to the low level of the adjacent country, and to the presence of the Baltic Sea, which during the glacial period stood at a higher level than it does now. It is, however, maintained by those who hold the glacial origin of fiords that deep basins may be eroded below sea-level. Thus, in order to apply the glacial theory to Alaska and Greenland it is explained that a glacier flowing down a valley into the sea displaces the sea-water, and thus the ice continues the corrosion of its floor below sea-level. Hence, we might expect the formation in Sweden of fiord-basins much deeper than the comparatively shallow fiards. Similarly, North Germany was flooded by ice, which was abundantly armed with rock-material; the North German plain consists of comparatively soft materials, which might have been easily corroded into deep basins. The föhrden of Schleswig-Holstein show that if any such channels had been formed in glacial times they might have escaped being filled up or destroyed. North Germany is one of the many countries which have been powerfully glaciated without the production of fiords.

2. Shape and Arrangement Inconsistent with Glacial Erosion

Turning from the general distribution of fiords to the detailed study of special fiord-areas, several features may be recognised which do not agree with the glacial erosion of the fiords. Thus, their shapes are quite inconsistent with their excavation by glaciers. J. W. Tayler in **1870** (p. 158), pointed to a fiord south of Arksut, in western Greenland, as having a shape quite inconsistent with a glacial origin. Kjerulf (**1881,** pp. 4–9), drew the same conclusion from the fiord-like basin occupied by Lake

Ekern in Norway. Most fiord countries supply abundant instances of the fiords and the ice-movements having different directions.

Scotland contains many instructive examples. The general movement of the ice during the glaciation of Scotland is shown in a map by Sir Archibald Geikie (**1901**, pl. iv.), which is generally accepted as correct in its main features. In many places the ice has moved across the country quite regardless of the direction of the lake-basins and fiords; and the same fact has been shown for most of the fiord-areas. It may be illustrated by reference to figures which have been previously given of the Shetlands, Orkneys, and Mount Desert in Maine.

The reticular arrangement of the fiords is quite unexplained by their glacial origin, and so also are the long channels parallel to the coast. Most glacialists have admitted the difficulty of explaining them by glacial erosion.[1] Ice flowing from the highlands toward the sea would not have cut its deepest and longest channels at right angles to its course. The seaward bifurcation of many fiords also indicates that they were not developed by the glacial enlargement of ordinary river-valleys.

3. The Preglacial Age of the Fiord-valley

The most conclusive argument against the glacial origin of the fiords is the preglacial age of their valleys; and it appears to be admitted for practically all fiord-areas that the valleys are preglacial, though it is claimed that they were enlarged into fiords by glacial action. The question is, therefore, whether the glaciers produced sufficiently radical changes to convert ordinary valleys into fiord-valleys. Fiord-valleys are shown, both by their form and arrangement, not to have arisen from ordinary river-cut valleys. Their plan clearly shows that they have been formed along great lines of dis-

[1] For example, O. Nordenskjöld (**1908**, p. 272).

ruption, and many features in them indicate that the effects of glacial erosion have been comparatively slight.

Professor Davis (**1909**, p. 655) has referred especially to the Hardanger Fiord as having been so much enlarged by glaciation that the formation of the fiord should be attributed to glacial agencies; he claims that it has been both widened and deepened by thousands of feet by glaciation. The greatest depth measured from the surface of the plateau to the floor of the fiord known in the Hardanger Fiord or any of its branches is 6,500 ft. in the Sör Fiord, and the width across the valley there is about 5,000 ft. Accordingly, if the preglacial valley had been thousands of feet narrower and shallower it would have been very small and shallow; but Reusch has shown that along the sides of the Sör Fiord, as well as in other places in the Hardanger Fiord, there are preglacial ledges (Fig. 18, p. 87), and the fiord must therefore have been mainly excavated before its occupation by ice. In all the main Norwegian fiords that I have seen there are numerous relics of the preglacial topography. The same is clear in the Scotch valleys. They have been straightened and their walls smoothed by spur-truncation. There are, however, many irregularities on the floors of these valleys which indicate that the ice had no great powers of removing masses of hard, unweathered rock.

CHAPTER XXIII

THE TECTONIC ORIGIN OF FIORDS

Immediately the mountains huge appear
Emergent, and their broad, bare backs upheave
Into the clouds, their tops ascend the sky,
So high as heaved the tumid hills, so low
Down sunk a hollow bottom, broad and deep,
Capacious bed of waters.

. . . . .

Part rise in crystal wall, or ridge direct.

MILTON.

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1. Fiords not River-valleys.—2. Essential Difference between the Tectonic and Glacial Theories.—3. Tectonic Valleys.—4. Disruption Clefts and their Relation to Fiords.—5. The Tectonic Agent, the Main Cause of Fiords.

1. FIORDS NOT RIVER-VALLEYS

THE rise of fiords from denudation by ordinary rivers, though it has often been suggested, is inadequate. This process is sufficient to explain firths or estuaries which are scattered at sufficient intervals along a coast to allow for the wide catchment-areas necessary for great rivers. More crowded estuaries, which belong to the class of rias, may be formed along a coast composed of alternate bands of hard and soft rocks; for the soft beds will be worn into valleys and the subsidence of the country will form a number of rias separated by narrow rock-ledges. Many great fiords are, however, too close together for their formation as river-channels to be at all probable, while many fiord-networks are quite unlike the arrangement of river-valleys.

2. Essential Difference between the Tectonic and Glacial Theories

The tectonic theory was first suggested from the resemblance of the plan of many fiord groups to a network of cracks; but, as the cracks were not seen, many geologists, with Helland (**1872**, pp. 545–7), dismissed the resemblance as misleading. Sir Andrew Ramsay rejected the tectonic theory, as he assumed that it required the valleys to be formed as gaping fissures of their present width; and he pointed out that the Alpine lake-basins, which are very similar in nature to fiords, occur in areas which in recent geological times have been compressed instead of stretched. (Ramsay, **1862**, pp. 190, 191.)

The tectonic and glacial theories have several points in common. The fiords are most numerous in the higher latitudes and are found amongst mountains; they therefore usually occur in districts which have been glaciated, and most fiord-valleys have been occupied by glaciers. It is also certain that glaciers have some eroding power, and must therefore have influenced the form of the valleys down which they flowed. Both theories, moreover, recognise that, in every fiord district of which we have much knowledge, the fiords were initiated as preglacial valleys.

The term "tectonic" means pertaining to construction or to building up, and it is correctly applied to that branch of geology which deals with the formation of land-masses by earth-movements. It may appear less appropriate to the formation of negative land-forms—valleys and basins—than to the positive land-forms—mountains, plains, and plateaus; but, as valleys due to disruption are connected with the uplift of the lands, they may be regarded as tectonic in origin, just as basins formed by subsidence are regarded as tectonic, they being the counterpart of the blocks which are uplifted. The tectonic theory does not assume that the fiord-valleys were formed as open fissures of the full width of the present valleys. The fissures may have been of various widths, dependent upon their various causes.

The fundamental difference between the tectonic and glacial theories is the question which of the two agencies contributed to fiords their essential characteristics. According to some authors the influence of glaciers has been insignificant. According to others the pre-glacial valleys were so unlike the fiords that, as maintained by Brown and Davis, they could not be called fiords until they had been glaciated, and thus converted from winding canyons into wide, straight fiords. A third school, represented by Prof. Günther and Dr. O. Nordenskjöld, combine both theories, for they regard the fiords as excavated mainly by glaciers, which can, however, only make fiords along lines weakened by previous disruption. Dr. Nordenskjöld considers glaciers as the main agent of excavation ; so he is to be regarded as a member of the glacial school.

3. Tectonic Valleys

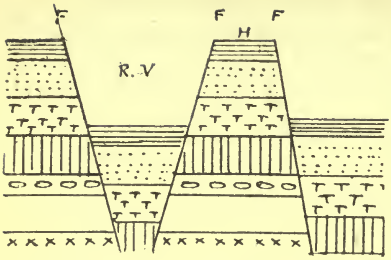
The tectonic theory explains fiords as a series of valleys, of which the plan was determined by fractures due to the stretching of an area of hard rock during an uplift caused by pressure from below ; the fractures have been enlarged by various denuding agents, amongst which glaciers played their part.

Tectonic valleys are of several kinds :

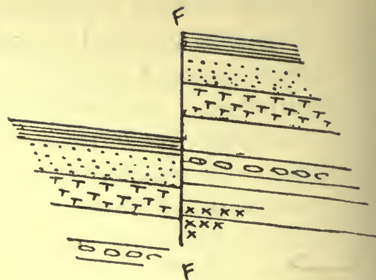
(1) Rift-valleys due to subsidence of bands of land between parallel faults (Fig. 79 *a*).

(2) Fault-valleys formed directly as open fissures by single faults ; they may be caused by the sliding of a block of rock down an inclined fault-plane (Fig. 79 *c*) or by the faulting of tilted strata (Fig. 79 *b*).

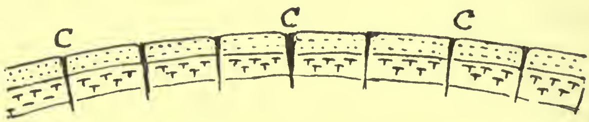
(3) Valleys formed along fault-planes owing to the



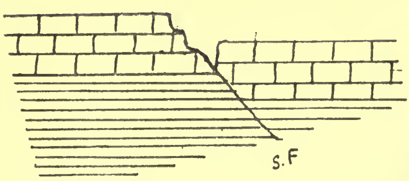
a. By parallel Faults. F = Fault; H = Horst;
R.V. = Rift-valley.



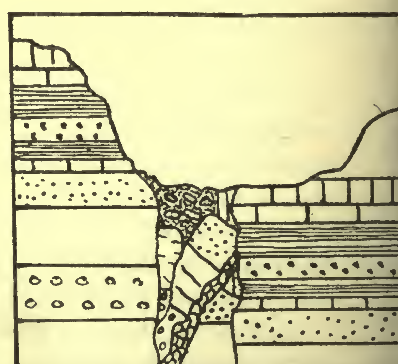
b. By simple Fault in titled rocks.



d. By parallel clefts due to wide uplift; the gaping clefts (*c*) are widened by weathering.



c. By slip Fault (S.F.) in jointed rocks.



e By multiple Faults and removal of the shattered rocks.

FIG. 79.—THE STRUCTURES OF TECTONIC VALLEYS

removal by denudation of a belt of rocks which has been crushed by earth-movements (Fig. 79 *e*).[1]

(4) Valleys formed along disruption-clefts, such as master-joints or diaclases, formed by the fracture of hard rocks by rupture during an uplift or by the contraction of the rocks while cooling or shrinking (Fig. 79 *d*). A system of diaclases often extends over a wide area, and is continuous in disconnected lands. Thus, Haughton (**1865**) described the remarkably close agreement between the directions of the joints in southern Ireland and Cornwall. The diaclases are often independent of the geological structure of the country, though they naturally bend to take advantage of some plane of weakness or to pass around some specially hard block of material, just as a split in wood avoids a knot. The regularity of the diaclases shows that they were made long after the formation of the rocks and even after the great folds that determined the grain of the country.

4. Disruption-clefts and their Relation to Fiords

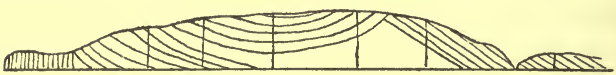
Diaclases are probably the most important of the four kinds of fractures in connection with the formation of fiords. Diaclases occur either as parallel or intersecting ruptures. The stretching of rocks when raised into a ridge by an upfold produces parallel ruptures or widens pre-existing joints (Fig. 80). The main diaclases are usually crossed by transverse joints, and they together form a network of fissures. Fissure networks also result from the upraising of an area into a dome by uplift at the centre. The whole rupture-system, then, consists of a series of major concentric fractures traversed by a radial series; and parts of the system taken in detail

[1] The influence of such crushed belts in the Scottish valleys has been described by Peach and Horne (in Murray and Pullar, **1910**, vol. i. p. 459, etc.), who call them "shatter-belts."

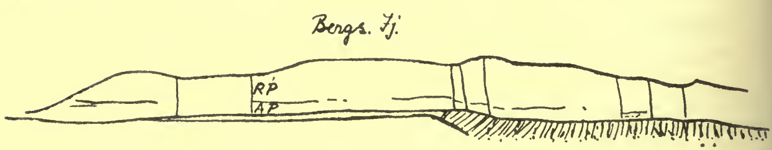
consist of fractures breaking the ground into rectangular or triangular blocks.

Disruption, due to the stretching of a wide sheet of rock by uplift, therefore explains the general arrangement of fiords along the coast of an upraised land in a curved concentric series, which is crossed by a transverse or radial series. It also explains why all the geographical elements in a fiord district have so frequently a parallel arrangement, and why the land is so often divided into angular blocks separated by reticular straits or valleys.

The limitation of fiords to areas composed of hard rocks



a. In Gneisses, Umanak Fiord, western coast of Greenland (after Steenstrup).



b. In the "Porfyrfront," Bergsfjeld, near Christiania (after Kjerulf).

FIG. 80.—VERTICAL CLEFTS CAUSED BY WIDE UPFOLDS.

is also thus explained. It has often been remarked that fiords only occur in regions of very ancient rocks; but this restriction depends on the hardness and not on the age of the rocks. Fiords, for example, intersect the Cretaceous and Kainozoic rocks in the neighbourhood of Disco in West Greenland; but the existence of fiords there is due to the presence of sheets of hard basalt. Fiords are not formed in areas composed of younger sedimentary rocks because, when they are uplifted, they yield by stretching or are torn by innumerable small joints regularly distributed through the whole rock. Hence the whole rock-sheet is weakened, without the formation of the long, deep clefts which give rise to fiords.

The diaclases or faults along fiords are not often seen, for they are usually buried on the floor of the valley or are covered by banks of talus along its sides. They have been seen sufficiently often, however, to show their general association with fiords. The dependence of fiord topography on joints was established at Julianehaab in south-western Greenland in a well-known memoir by Kornerup (**1881**, see Fig. 49). The association of fiords with various types of ruptures is, in fact, apparent throughout the fiord districts of the world. It has been shown by Kjerulf (**1878** and **1880**, pp. 329–34), and Sederholm (**1911**, pp. 42–4 and map), for the valley-networks of Norway and Finland. That fiords often lie along trough-faults has been proved, for example, by Kjerulf and Brögger for the Christiania Fiord, and by O. Nordenskjöld for the Hurry Inlet in eastern Greenland. The evidence is so clear in Scotland and Ireland that, according to Kinahan (**1875**, p. 209), every valley and lake-basin that he visited in the Highlands of Scotland was connected with a break, and in south-western Cork all the transverse valleys, and probably also all the longitudinal ones, were determined by breaks or faults (**1875**, p. 181).

The influence of numerous small faults along joint-planes (or "Spaltenverwerfungen" as he calls them), has been shown by Brögger.

The occurrence of the fiord-systems in long belts along fractured coasts is well illustrated by those of British Columbia and south-eastern Alaska, and of Patagonia.

Diaclases influence ordinary land-valleys as well as fiords. Daubrée has shown that the arrangement of the valleys in parts of northern France and Belgium is due to erosion along joints (**1875**, pp. 357–68, pls. iii.–v.), and this fact has been proved in many other countries. Thus many maps of the unglaciated hills of Australia show that the valleys form an incomplete network due to their erosion along the bands of weaker rocks and along the joints at right angles to the strike of the rocks. This arrangement is well indicated, for example, in the maps showing the distribution of alluvial deposits in the valleys around Ballarat. Similar cases have been described in America, as by Brigham (**1898**), who aptly refers to the arrangement as "trellised drainage" (Fig. 81). Hobbs has described the "joint controlled drainage" of Wisconsin and New York, where

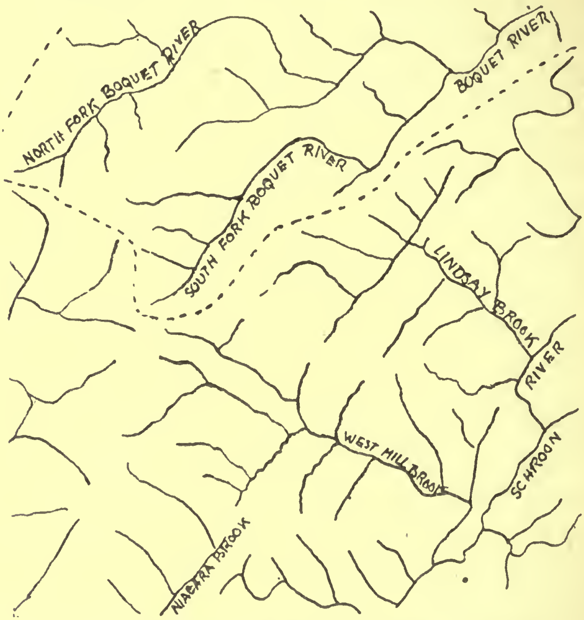


FIG. 81.—TRELLISED DRAINAGE (AFTER BRIGHAM).

the chief hydrographic lines, of which that of Seneca is sixty miles in length, follow the joint-planes (**1905**, No. 2, p. 373). This feature is so well known that Prof. Günther (**1899**, p. 866), refers to valleys as developed on "Spaltennetze," or rupture-networks, and Prof. Herbertson (**1910**, p. 26) describes the river-valleys in tablelands as making "a more or less rectangular network, most of the bends and channels forming right angles."

All valleys, indeed, have been attributed to erosion along ruptures. Naumann, in 1850, classified mountain-valleys [1] into those due to rupturing (*Spaltung*), elevation, subsidence and erosion ; and he stated [2] that " most of the longitudinal valleys of mountains are to be considered as valleys of elevation, and most cross-valleys as rupture-valleys." Desor (**1865**, p. 71), went further and attributed all cross-valleys to ruptures ; and Murchison (**1870**, p. 328) went still further, for he declared that the true origin of " all abrupt fissures in hard rocks into which bays of the sea enter, or in which rivers flow, was never produced by such sea or river, but must be referred to original breaks in the crust, of which the waters have taken advantage and have found the most natural issue." This view is no doubt exaggerated, like the contradictory verdict by Le Conte,[3] that " the transverse or radiating valleys are always formed by erosion " ; but many valley-systems have certainly been formed along planes of disruption in rocks ; and fiords are due to especially large ruptures caused by the slow upheaval of wide areas and probably enlarged by repeated oscillations. These deep ruptures were developed on a regular plan, and therefore gave rise to valleys which are straight and have angular branching ; and, as fiords only occur in hard rocks, their angles are not so soon rounded as those of valleys in softer deposits. Owing to the length of the diaclases, the depth also is considerable, and valleys are soon worn out along them to the base-level of the streams. Where two ruptures intersect, the rocks at the angles are weakened by decay from two faces, and thus is produced a circular or oval area of rotten material, which ice may remove and leave a rock-basin.

[1] Naumann, *Lehrbuch der Geog.* (1850) vol. i. p. 405.
[2] *Ibid.*, p. 406.
[3] *Elements of Geology*, 1878, p. 44.

5. The Tectonic Agent the Main Cause of Fiords

The connection between fiords and ruptures due to the upheaval of the fiord districts was first clearly recognised by Peschel in 1866. He then claimed that "the fiords did not result from erosion, but from heaving from below, as well as through contraction of the rocks in consequence of crystallisation."[1] The ruptures he referred mainly to rending of the rocks by a wide, arch-like fold (Fig. 79 *d*). He, however, regarded those ruptures as narrow and as enlarged by ice-action; the fiords he described as the "empty dwellings of former ice-streams" (Peschel, **1878,** p. 19). He, therefore, accepted their restriction to high latitudes (p. 13). He, nevertheless, regarded the fiords as due primarily to ruptures, as erosion could not have made valleys on such courses; he regarded their divergent instead of convergent branching seaward as due to the shattering (*Zertrümmerung*) and disruption of the coasts by upheaval.

Murchison adopted the same conclusion and urged, in his Presidential Address to the Royal Geographical Society in 1870, that fiords and canyons are due to the earth's crust having been broken up from beneath. Cracks were thus made that opened into fissures, which the rivers entered and fashioned. (Murchison, **1870,** pp. 327, 328.)

Gurlt (**1874,** p. 150), affirming that the action of glaciers is to plane and not to erode, necessarily concluded that the formation of lake-basins and fiords must undoubtedly be ascribed to some other agency. Fiords and mountain-lakes, he says, "are the valleys of preglacial dislocation-cracks (*Spalten*), which may well have been widened, and their upper ends lengthened, by the influence of flowing glacier-ice; but they could never have been thus originated."

[1] Peschel (**1870**), p. 161; this part was reprinted from an issue in 1866.

In all the fiord-regions the fiord-making movements appear to have begun in the late Miocene and continued in the Pliocene. Hence the whole of the Pliocene period was available for denudation to enlarge the ruptures; and the symmetry of the original network has been often marred by the excavation of valleys along planes or lines of weakness due to the original structure of the rocks.

The tectonic theory, therefore, explains not only the plan of the fiords, but their essential features, including their great length in proportion to their width, their depth and the steepness of their walls. The fiords are deep as the atmospheric agents work downward along the vertical fissures more than laterally into the blocks of hard rock; and owing to this weakening of the bed of the canyon corrosion is more marked than erosion. The earth-movements also drowned the lower valleys beneath the sea, and, by tilting the country, converted many of the old valleys into deep basins.

It may be suggested that the difference between the various schools is mainly a question of terms and of degree, and that, as glaciers admittedly flowed down most fiord-valleys, the ice should be regarded as the cause of the fiords, since it acted after the earth-movements. On the same ground river-valleys should not be attributed to river-erosion; for the most conspicuous features of mature river-cut valleys are due to the various geological agencies which have been at work after the excavation by the river had ceased. Rain-wash has smoothed the irregularities on the banks; turf upholds the steep slopes; earth-worms have formed a mantle of soil and buried the loose rocks; vegetation usually forms the most pleasing adornments of the scenery. Although the dominant features of the landscape are due to wind, rain, vegetation, and various animals, a river-valley is regarded as having been made by the river to which it owes its origin, and not by the subsidiary agents which have given the final touches to the scenery. Similarly with fiords. If tectonic agencies have given the valleys their frames and glaciers have only contributed a varnish, fiord-valleys should be included in the class of tectonic valleys.

The problem, then, is, what was the condition of the fiord-valleys at the beginning of the glacial period? And as far as concerns the hard rock-masses which form the foundation of most fiord-areas, glaciers have had but a comparatively slight effect. Thus in Scotland the main relief of the country is apparently not essentially different from that at the beginning of the glaciation. The most important geographical change has been in the river-systems, for the sweeping out of blocks of decayed rock formed many lake-basins, and the filling up of lowland valleys by drift caused innumerable diversions of rivers. But the amount of hard rock which has been removed seems to me comparatively small. Repeated measurements to determine the probable difference of the present and preglacial contours show that a comparatively slight amount of glacial abrasion would account for the present glaciated forms. The shape of Ben Lui and the position of the great corrie on its north-eastern face appear at first to indicate extensive glacial erosion. The faceted spurs beside the corrie (shown on Pl. VIII. Fig. 2) have been shortened by glacial abrasion. This change is an instance of the wearing back of an exposed rock-rib projecting into the path of a powerful glacier; and, though the slopes of Ben Lui have no doubt been changed in character, the main topography of the mountain appears to be essentially the same as in preglacial times.

Valleys excavated in hard, steeply inclined rocks by a powerful river which is joined by comparatively small tributaries are often straight and trough-shaped, with the floor wide and flat and with the spurs on the sides steep and short. This type of valley is common in the highlands of north-eastern Victoria; and both there and in the last tropical non-glaciated country which I visited—the plateau of Angola—topographic forms developed by ordinary atmospheric and river denudation are so similar to those of glaciated areas, that glacial agencies have been unnecessarily invoked in both cases.

Amongst the authorities on each fiord district of the world the view has been gradually spreading[1] that all the main features of the existing topography were preglacial. The evidence, on the whole, seems strongly in favour of the conclusion that glaciers added very little to the size of the fiord-valleys that they found prepared for them; and, as the valleys owe to tectonic agencies their essential and distinctive features, which the agents of denudation gradually destroy as they convert fiords into fiards and rias, the fiord-valleys may be justly described as of tectonic origin.

[1] See *ante*, pp. 88, 171–2, 244, 263, 275, 288, 318, 345, 364, etc.

CHAPTER XXIV

THE DISTRIBUTION OF FIORDS IN RELATION TO THE HEAVING EARTH

The labouring earth
Discloses a tremendous birth.
YOUNG.

1. Fiords generally on Western Coasts.—2. The Distribution of Fiords in Latitude in Relation to Circumpolar Uplifts, and the Sequence from Drowned Rift-valleys to Cleft-formed Fiords.—3. Fiords in Low Latitudes.—4. The Meridional Fractures of the Tropics.—5. The Difference between the Fiord-fractures and those of the Tropics in Relation to Variations in Polar Flattening.—6. The Deformation of the Earth in Consequence of its Contraction in Relation to Mountain-folding.—7. The Circumpolar Oscillation.—8. Absence of Fiords from the Arctic Shores of Asia and Western America.

1. FIORDS GENERALLY ON WESTERN COASTS

ONE of the most striking features in the distribution of fiords is their general restriction to the western sides of the lands. This is true for all the fiords of Europe, including Scandinavia, Scotland, Dalmatia, and the Ægean Sea, and also for the rias of Ireland, Spain, and the Mediterranean islands. The rule also holds for the fiords of South America, Australia, New Zealand, and Antarctica. The only important exceptions are in North America—where fiords occur on the eastern coasts of Greenland, Baffin Land, Labrador, the maritime provinces of eastern Canada, and Maine—and in Eastern Asia where there are fiords and rias on the coasts of China and the Bering Sea.

The predominance of fiords on western coasts is not

Drowned sunk-lands.
-o-o-o- Line of 3,000 ft. deep.
- - - - Chief fiard coasts.
x x x Rias.
oooooo Glaciated coasts without fiords.
Depth over 20,000 ft.
Fiord coasts.

FIG. 82.—SKETCH-MAP OF DISTRIBUTION OF FIORDS.

fully explained by the western sides of the continents being more mountainous than the eastern; for that is only another result of the same geographical cause. The occurrence of the chief fiords and mountain-systems on the western sides of the continents is probably a consequence of the rotation of the earth from east to west. Owing to the unequal strength of the different parts of the earth's crust, the rotation must cause a tendency for the surface to buckle along north and south lines; and during periods of widespread disturbances of the crust the raised areas would tend to lag toward the east.

The atmosphere has a general drift from west to east as it lags behind the rotating earth; and, if any block of the earth's crust has its attachment to its foundation loosened, it must also tend to move slowly eastward. Its advance would be obstructed by the resistance of the land before it, and it would thus be thrown into folds along lines running north and south. These folds would usually be highest on the western sides of the continents,[1] and the areas still farther to the west would be left comparatively unsupported, and would therefore probably subside before the region again came to rest. Cracks beside or radiating from the sinking areas would fracture the western coasts and thus give rise to fiords.

All the exceptions to the rule that fiords are characteristic of western coasts are situated where the land to the east has subsided. Thus Greenland and Iceland, being plateaus left by the foundering of the land both to east and west, have fiords on both coasts; and eastern China and Labrador, being plateaus to the west of foundered regions, have fiords or rias on their eastern coast.

[1] The chief exceptions to the rule that the highest land is to the west are in the unfolded plateaus of Australia and Africa, and France and Spain, where the recent folds trend east and west.

2. The Distribution of Fiords in Latitude in Relation to Circumpolar Uplifts, and the Sequence from Drowned Rift-valleys to Cleft-formed Fiords

The occurrence of most of the fiord districts in high northern latitudes and in moderate southern latitudes is the second striking feature in their distribution. This also is to be explained by reference to earth-movements.

There is convincing evidence of recent great variations in level of the Arctic and subarctic regions. This circumpolar oscillation was probably one result of the earth-movements which uplifted the Alps and formed the basins of the North Atlantic and Arctic Oceans.

The sinking of the floors of these oceans doubtless fractured the adjacent lands,[1] and formed fiords where the coasts are composed of hard rocks.

Along the edge of each fiord district the fractures produced rift-valleys and sunk-lands. Farther from the foundered area the land was traversed by a network of cracks and long fissures with occasional branches and angular bends. The typical fiords are situated along these cracks. Where the cracks were formed across lowlands of hard rocks the fiords are replaced by fiards and rias, while in areas composed of soft rock they pass into ordinary estuaries and föhrden. Thus, on the European side of the Atlantic, Spitsbergen is traversed by fiords formed as rift-valleys, and fiords of the same type appear on the northern coasts of Iceland (see Fig. 30) and Norway, while the great West Fiord between the Lofotens and the mainland was probably formed as a rift-valley. Farther south the

[1] Since this chapter was written Baron de Geer has published (September 1912) a valuable paper and map attributing the formation of the fiords of north-western Europe and eastern Greenland to the fracturing of the margins of the great basins formed by the subsidence of the North Atlantic and Arctic Oceans.

drowned rift-valleys along the border of the Arctic Ocean are replaced by cleft-formed fiords which begin to the north as tributaries on the sides of the rift-valleys as on the southern shore of the Varanger Fiord (see Fig. 25); the cleft-formed fiords increase in size southward, as in the reticular fiord-network near Trondhjem and in the Sogne and Hardanger Fiords; on the southern side of the fractured Scandinavian earth-block, fiords of the rift-valley type are represented by the Christiania Fiord; and on the margin of the fiord district, where the oscillation was slighter and ceased earlier and denudation was more powerful, occur the föhrden of Schleswig-Holstein and the Baltic fiards.

In the British Isles there is a similar sequence from south to north; the straits between the islands of the Orkneys and Shetlands include fiords formed as rift-valleys, and such also is the Minch, which separates the Hebrides from Scotland and corresponds in position to the West Fiord of Norway. Farther south are the reticular cleft-formed fiords of the Scottish lochs; and to the south of the existing fiord district relics of fiords are found in Cornwall and Brittany, and well-developed rias on the coast of south-western Ireland and north-western Spain.

In North America there is the same general succession; for there is a gradual passage from the drowned rift-valleys of northern Greenland and the Arctic Archipelago into the typical fiords of southern Greenland and Baffin Land, and thence to the fiards of Canada and Maine; and along the western coast the drowned rift-valleys of Cook Inlet and Shelikof Strait are succeeded by the cleft-formed fiords of south-eastern Alaska and British Columbia, and the drowned rift-valleys reappear in Puget Sound and the fiard-like arms of the sea near Vancouver.

In Patagonia the sequence is similar but reversed, for the chief sunk-lands and rift-valleys occur to the south on both sides of Drake Strait; they are followed by cleft-formed fiords and fiord-networks, and this fiord-system ends northward with the fiards of Chiloe and the drowned rift-valleys and sunk-lands which separate that island from the mainland.

In New Zealand, though the fiord series is shorter, the sequence is similar to that in Patagonia.

The most striking difference between the arrangement of the fiords in the Northern and Southern Hemispheres is that in the latter they are farther from the pole—a natural result of the tetrahedral arrangement of land and water and the consequent antipodal position of continent and ocean.[1] The Arctic Ocean is antipodal to the Antarctic continent, where the only fiords occur facing Drake Strait and opposite South America. Antarctica appears elsewhere free from fiords, but in the Southern Hemisphere all the lands between the parallels of 42° or 44° and 62° are indented by fiords; they occur in South Georgia, South Shetlands, Graham Land, Kerguelen, New Zealand, Campbell Island, and Patagonia. The fiords occur mainly in two belts. The northern belt surrounds the Arctic Ocean, and the southern belt surrounds the Antarctic continent.

3. Fiords in Low Latitudes

The other fiord-systems of the world are found in the neighbourhood of areas of great coastal fractures, which were probably due to the readjustment of the earth's crust after the great disturbances which upraised the Miocene mountain-systems. Thus the eastern coasts of the sunklands of the Adriatic and Ægean Seas are indented by inlets which have the essential characteristics of fiords. The Red Sea is a drowned rift-valley, and its shores were probably indented by fiords, in

[1] A statement of this theory is given in the author's *The Making of the Earth* (1912), pp. 128–60, in the Home University Library.

Sinai and elsewhere; but, owing to the arid climate and the lack of perennial streams, the old valleys have been filled by drifts. The eastern coast of China, Korea, and the south-western shores of the Japanese archipelago are also indented by fiords, which are probably due to the foundering of the China and Japan Seas, for their indented coasts are recognised as great fracture-lines. The same event probably caused the disruption of a formerly continuous land into the Philippine Archipelago. Contemporary movements gave the Strait of Malacca and the Malay Peninsula their indented coasts, and the oscillations connected with the formation of the Timor Sea—shown, for example, by the raised coral reefs and associated foraminiferal limestones of Christmas Island[1] —were probably the cause of the fiards of north-western Australia.

4. The Meridional Fractures of the Tropics

While the circumpolar belts were being fractured by the fiord-making oscillations, the tropical regions of the world were undergoing earth-movements of a different kind. They did not share either the great oscillation or reticular fracturing of the fiord districts. They were affected by movements along lines most of which trend approximately from north to south. The tropical coasts do not show the successive raised beaches, which are so conspicuous on the shores of Scandinavia, Scotland, northern North America, or southern New Zealand.

I once searched in vain along the coast of British East Africa, at intervals from Mombasa to Lamu, for evidence of any considerable uplift. Some recent coral limestones were said to occur about 300 ft. above sea-level on the hills near Magarini; but this report was based on some blocks of limestone that had been carried up by man. Raised coral reefs on Mombasa Island

[1] C. W. Andrews, *A Monograph of Christmas Island* (1900), pp. 269–98.

indicate an uplift there; but the absence of widespread raised beaches from East Africa shows that the coastal uplifts have been limited and local.

The coast of tropical West Africa in Angola from north of Lobito Bay to Benguella, which I recently inspected, is approximately straight, for the old valleys have been filled by sediment. There are occasional projections of alluvial land on the lee-side of the chief river-mouths; but there are no raised beaches higher than those flung up by storms. There is no evidence either of recent regional elevation or of subsidence. The land has no doubt been reduced by the foundering of strips parallel to the coast, and is intersected by a series of parallel faults. Owing to the absence of recent rocks in the area there is no proof of the precise age of these faults. The latest deposits they cross are Upper Cretaceous in age; but the clearness of the fault-scarps shows that they were formed long after that period. Probably they are relatively modern, and are the West African equivalents of the faults which formed the Great Rift-valley in eastern Africa.

In Australia the evidence is similar. Some reported raised beaches beside Port Philip are kitchen-middens formed of shells carried up from the shore by aborigines. Along the southern coast of Australia there is evidence of the marine submergence of wide areas in recent geological periods. Along the eastern coast of Australia numerous drowned valleys, such as Sydney Harbour, afford clear evidence of submergence, while the rivers show the influence of changes due to the deep subsidence of the former eastward extension of the continent. There is, however, no evidence of widespread uplift, and nothing on the Australian coast comparable to the raised beaches of southern New Zealand.

The greatest oscillations in level of tropical regions within recent geological times were apparently in the West Indies; but they were probably due to the isostatic uplift of the Caribbean Islands during the subsidence of the Caribbean Sea. In the Pacific Ocean raised coral reefs in some areas and atolls in others indicate that some areas have been rising while others have been sinking. But, as a rule, the recent movements in tropical regions have been comparatively simple, and the main fractures were along meridional lines; these lines are most conspicuous south of the Equator, for the chief exceptions, the northern coast of South America and the coast of Guinea in Africa, are both north of it.

5. The Difference between the Fiord-fractures and those of the Tropics in Relation to Polar Flattening

The difference between the equatorial fractures and the disruptions of the fiord districts would, according to Pecsi (**1911**), naturally result from a slight change in the shape of the earth due to oscillation of the Polar regions. He holds that a diminution of the flatness of the earth would produce foldings perpendicular to the Equator and large rift-valleys (*fossés*) perpendicular to the meridians. It is therefore natural that most of the fiords run east and west, while the equatorial fractures,[1] and the great channels which lie beside the fiord districts have a general trend of north and south. As the crust of our earth varies greatly in strength in different parts, both of Pecsi's series of earth-movements would necessarily depart from their diagrammatic course in accordance with the strength of the rocks they traverse.

Pecsi's work shows that the distribution of fiords is mathematically consistent with the view that their origin was due to a deformation of the earth. Further support

[1] The movements on lines perpendicular to the Equator which Pecsi describes as foldings would include great monoclinal folds, or series of step-faults, or even of single faults, which would have the same effect as a simple fold.

for the theory comes from the study of earthquakes. Dr. Milne has shown, from seismic data, that the earth is more rigid along bands extending east and west than along directions from north to south. Hence the earth could change in shape more easily by the heaving of the polar than of the equatorial areas.

6. The Deformation of the Earth in Consequence of its Contraction in Relation to Mountain-folding

These movements of the crust necessarily follow from the deformation of the earth in course of its slow contraction, a process which is accepted by most geologists. The shrinkage of the earth has been denied, but the geological evidence on this subject appears capable of no other explanation. The oldest rocks are all violently tilted and folded as if they had been pressed laterally into a smaller space. The younger rocks have been less disturbed. They are often nearly horizontal over large areas, and intense crumpling has been restricted to special bands. It appears that in recent geological times the lateral compression has mainly affected some long, narrow bands, which are widely distributed over the earth.

The crumpling of the crust shows that it has been forced into a smaller surface. Hence the earth has been reduced in size. The movements due to this shrinkage have not taken place uniformly throughout geological time. Long periods with only gentle movements of the earth's crust have alternated with epochs of violent disturbance and disruption, as in the Devonian, Lower Permian, and the Miocene.

The limitation of the mountain-forming disturbances to narrow bands would be a natural consequence of the gradual increase in thickness and strength of the crust. The contraction of the earth at first caused the crumpling of the whole crust; but subsequently certain bands were folded into mountain-chains, while the intervening areas underwent slow vertical movements. The widespread movements, as Prof. Suess has shown, were mainly subsidences, which were probably due to the withdrawal of support owing to the shrinkage of the internal mass of the earth. The chief subsidences formed the four ocean-basins. The slow, widespread movements due to the collapse of the crust gradually deform the earth, and the violent epochs of disturbance mark the recovery towards the spheroidal form; and after the main disturbances various areas appear to have continued in slow oscillation, while the earth's crust was regaining equilibrium.

These movements of deformation most readily affected the polar regions, for they could yield more easily to these panting movements of uplift and depression. (See Fig. 4.)

The last of the periods of world-wide crustal disturbance reached its greatest intensity in the Miocene; and to it we owe the existing mountain-systems of the world. The uplift of the different mountain-chains in one mountain-system were not all synchronous; the elevation of the Pyrenees, for example, began earlier than that of the Alps. The movements ranged from the Oligocene to the Pliocene; but they may be all regarded as members of one connected series. The chief mountain-system of the Old World—including the Pyrenees, Alps, Apennines, Carpathians, and Balkan Mountains in Europe, the Atlas in Africa, the Caucasus, Himalaya, and the main mountain-chains of Persia, Burmah, Thibet, and of the north-eastern parts of China and of Siberia—were all upheaved by one great series of crustal disturbances, which culminated in the upper Kainozoic.

The two other chief mountain-systems of the world are the western mountains of North and South America; they were formed at the same time, but the elevation of the different component chains was not simultaneous. Thus the Andes may be younger in Patagonia than they are farther north.

Upper Kainozoic mountains also occur in New Zealand. The last great episode of mountain formation was, therefore, world-wide in its influence.

The upheaval of the mountains was accompanied by the subsidence of vast areas outside the continents and of smaller basins within them; these great subsidences appear to have been most extensive in the Pliocene period when other large areas were undergoing slow elevation. These widespread movements were secondary results of the mountain-building disturbances.

The mountains of the Alpine System were due to folds of which the axes generally trend east and west, and which were caused by the land being thrust to the north. Some of the later earth-folding waves travelled on from the Alpine line into northern Europe; and they raised a great arch over the Weald of south-eastern England, and some wide, low uplifts farther to the north.

These movements upraised much of north-western Europe, while subsidence to the west was enlarging the basin of the North Atlantic. The stretching of the heaved areas opened vertical clefts across them, while their margins were torn by parallel faults which caused rift-valleys.

During the Pliocene uplift Greenland must have been attached to Europe, for many of its land-plants are Scandinavian and its flora as a whole is circumpolar and not American. Hence, during the life-time of the present flora of northern Europe, Greenland was connected to the Old World. It was subsequently detached by the enlargement of the Norwegian Sea into a channel that united the Atlantic and Arctic Oceans. Spitsbergen and Franz Josef Land were still joined to the mainland of Europe, which then extended about as far northward as Greenland does now. This north-western corner of Europe was then broken up by the subsidence of the land which is now the floor of the Barents Sea. Spitsbergen was thus detached from Europe. The date of this separation is determined as Upper Pliocene or Pleistocene; for it was sufficiently long ago for the foxes which live on Spitsbergen to have developed into a new variety though not into a new species.[1]

The eastern and western trend of the Alpine movements is concordant with the course of most of the northern fiords, from the Arctic Archipelago on the west to Nova Zembla and the New Siberian Islands on the east. The direction of the fiords was probably determined by disruptions caused by upfolds parallel to those of the Alps. There is abundant evidence that the Arctic lands have been uplifted in recent geological times. It was clearly stated by Sir Henry Howorth in **1873**, and it led Prof. Suess to his view of a periodic surging of the ocean waters to and from the polar seas.

7. The Circumpolar Oscillation

Sir Henry Howorth's conclusion that there has been a great circumpolar oscillation of the land appears the better explanation of the facts, and it explains also the distribution of the fiords. They are absent from Arctic localities where the crust has undergone the least oscillation. Thus the coast of eastern Greenland is free of fiords from about 66° to 77° N. probably because this coast was opposite the Icelandic ridge (see Fig. 45), and underwent less variations in level than the coasts on either side.

The heaving of the crust in the Arctic regions also explains the contrast between the fiords of northern and southern Greenland. All the southern part of the country is now sinking, so that many of the fiords have been converted into fiards, and the southern fiords are clefts made by the previous uplift and drowned by the

[1] G. E. H. Barrett-Hamilton and J. L. Bonhote, "Two Subspecies of Arctic Fox," *Ann. Mag. Nat. Hist.*, (1898), Ser. 7, vol. i. p. 287. The Spitsbergen variety also lives in Iceland and Greenland.

subsidence. Further north the coasts on both sides of Greenland are fringed by islands, which are the fragments of a fractured belt of coast-land. Still further north the fiords become fewer but larger, and on the border of the deep Arctic basin rift-valleys replace the widened cleft-valleys of southern Greenland.

The circumpolar lands have, in fact, been recently tilted. Northern Scandinavia has been rising, while the southern part of the country has been stationary. Southern Greenland has been sinking, while northern Greenland has been stationary or rising. In northern Alaska, St. Michael Island and other localities beside the Bering Sea have undergone uplift in historic times, while farther south the chief recent movement has been a subsidence; and the tilting of the country has been proved by geological evidence in Alaska, and by the slope of old beaver-dams in British Columbia.

The formation of fiords, with their deep basins, requires widespread oscillation and tilting. The simple foundering of part of the crust would not form a full fiord-system. Thus most of the deepest basins on the ocean floors occur in the middle zone of the earth, though they range as far north as the Aleutian Islands; but such "deeps" may occur close to the land, as off Peru and northern Chile (*cf.* Fig. 82), without the formation of fiords on the adjacent shores. Sinai has been fractured by the subsidence of the gulfs on either side, and its valleys would form typical fiords if they were submerged beneath the sea. On the other hand, the greatest and the longest fiords of Norway are opposite the shallow southern part of the Norwegian Sea.

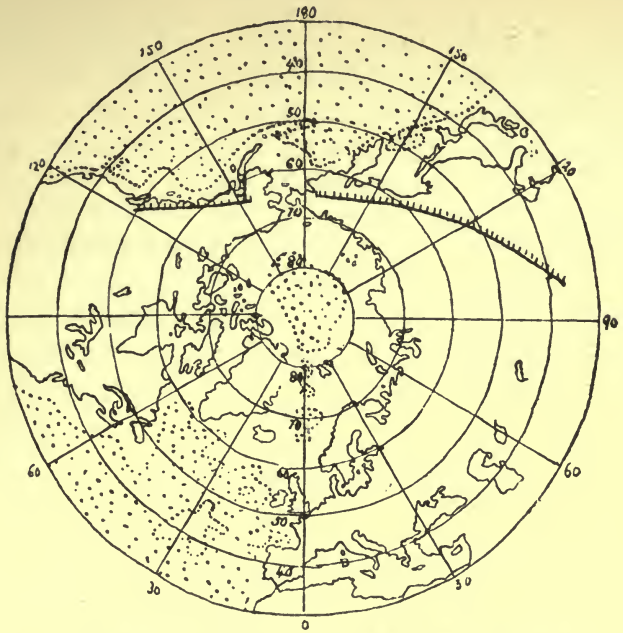
The most typical fiord-valleys occur where wide areas have been slowly upheaved into a flat dome or arch. The slow uplift has rent the land along parallel or intersecting cracks. The fiord districts of the world are all plateaus, which have been shattered by a Pliocene or possibly sometimes a later uplift. Whatever may have been the previous geological history of the fiord districts, they have all been planed down into peneplanes, which have been uplifted into plateaus; and during this uplift they were cracked by straight, zigzag, or intersecting fissures. The margins of the fiord districts have been greatly faulted owing to the loss of lateral support during the formation of the adjacent seas, and were thus broken by rift-valleys and sunk-lands.

8. Absence of Fiords from the Arctic Shores of Asia and Western America

The alternate upheaval and depression of two circumpolar belts explain the distribution of the main fiord-systems of the world, but it may appear inconsistent with the lack of fiords from the coasts of the Arctic Ocean in northern Asia and western America. Their absence is probably due to the earth-movements at the north of the Pacific having been different from those around the northern end of the Atlantic.

The Pacific basin is bounded to the north by a chain of plateaus, which have been uplifted along one apparently continuous series of fractures. The coastal margin of the plateaus of British Columbia and Alaska is continued westward in eastern Asia as the scarps of the plateau beside the Sea of Okhotsk and of the Khinghan Mountains of China (Fig. 83); and the adjacent coasts of Asia in Japan, Korea, and southern China are indented by fiords, though most of them have been worn down into fiards and rias.

This great series of fractures upraised a wide belt of land which shortly before had been folded into mountain-chains, and from the uplifted Pacific edge the land sloped down across the plains of Siberia and western America to the Arctic coast. These coasts shared to some extent in the polar uplift; for the rias of Siberia would appear to indicate recent subsidences, though the



The Boundary Scarp of the North Pacific basin from British Columbia to the Khinghan Mountains of China.
Sea below 10,000 ft. deep.

FIG. 83.—SKETCH-MAP OF NORTHERN ENDS OF PACIFIC AND ATLANTIC OCEANS.

northern coast of America, west of the Arctic archipelago, presents none of the appearances of a sinking land.

The shores of the North Atlantic and the adjacent parts of the Arctic Ocean are high lands which have been uplifted by a widespread movement, and not, like the Pacific, by a linear fracture along a recently folded belt; they have, therefore, been indented by fiords, while northern Asia and western America slope gently downward into the Arctic Ocean through a fiordless coast.

The fundamental difference between the borders of the Atlantic and Pacific Oceans finds another illustration in the prevalence of fiords along the northern end of the Atlantic trough, and their absence from those parts of the Arctic Ocean which lie north of the Pacific.

CHAPTER XXV

FIORD SCENERY—ITS CHARACTER AND INFLUENCE

A sea-born service through the mountains felt,
Till into one loved vision all things melt;
Or like those hymns that soothe with graver sound
The gulfy coast of Norway iron-bound.

WORDSWORTH.

Tous les corps ont leurs contours,
Mais d'où vient la ligne qui touche ?

SULLY-PRUDHOMME.

THE study of fiords is of value to the geographer and geologist, as fiords mark out regions of special heaving of the earth's crust, and thus throw light on its structure and deformation. They appeal to a wider public by the great attractiveness of their scenery and the charm of their repose.

The fiord regions have long stood apart from the main stream of human activity; and, alike in Europe, North and South America, and New Zealand, the fiord districts are still sparsely populated and comparatively poor. The chief product of their soil is timber, but, though their vast pine-forests contribute most useful material to the world at large, they yield a crop that is not very remunerative in proportion to the area occupied. Some fiord districts have valuable mineral deposits; but they have proved less profitable than the deposits in the adjacent mining fields, outside the fiord areas. The most important commercial asset of the fiord districts is their water-power; for they all have a heavy rainfall or snowfall, and their hanging valleys offer most convenient sites for water-storage and the production of cheap power. With the rising cost of coal and increasing facilities in the transmission and use of electricity, the fiord districts may ultimately prove among the world's most prolific sources of light and power.

The other chief asset of the fiords is their scenery, which promises to place them among the most recreative of the world's playgrounds.

"The Alaska coast," Dr. Henry Gannet predicts, "is to become the show-place of the earth, and pilgrims, not only from the United States, but from far beyond the seas, will throng in endless procession to see it. Its grandeur is more valuable than the gold or the fish or the timber, for it will never be exhausted. This value, measured by direct returns in money received from tourists, will be enormous; measured by health and pleasure it will be incalculable." [1]

The attraction of fiords is at first sight difficult to explain, for fiords occur under geographical conditions that do not produce scenery of the first rank, since a dissected plateau presents the least beautiful of mountain forms. Anthony Trollope indeed, in his description of the country around Lake Wakatipu in New Zealand, after mentioning some of the characteristic features of this land-form, comments on its exceptionally picturesque appearance. The mountain-ridges, he says—

"Are sharp and broken, making the hill-tops look like a vast saw with irregular gaps in it. Perhaps no shape of mountain-top is more picturesque than this. The summits are nearly as high as those of Switzerland, that of Mount Earnshaw at the head of the lake being 9,165 ft. above sea-level. The mountains themselves, however, do not look to be so big as the Alps. There is no one peak which strikes one as does the Matterhorn, no one head like the head of Mont Blanc; no one mountain which

[1] H. Gannett (**1902**, p. 277).

seems to be quite so much of a mountain as the Yungfrau. But the effect of the sun shining on the line of peaks was equal to anything I had seen elsewhere." [1]

This description shows Anthony Trollope's keen geographical insight. But in that very passage, while extolling the scenery, he notes, with unconscious regret, the absence of dominant peaks, and observes that the mountains do not give the full impression of their size.

A plateau in which dissection has only gone far enough to carve deep, narrow valleys, and where large areas of level surface are still left, lacks the width of the plain and the grandeur of the mountain.

The scenery of a dissected plateau is finest on its borders, where it embraces both the mountainous upland and the plains at its foot. In such a position, a view may on one side stretch over undulating moors covered by bog and heather, broken only by deep valleys with patches of purple pine-wood or a few tufts of feathery birch-trees on their slopes, and with fiord-like lakes gleaming along their floors; while, on the other side, the fertile plain spreads out in green meadow and golden corn-land; and the interest of the contrast between upland and lowland is heightened by the indication of man's presence given in distant tower or in frayed banks of smoke. Hence the favourite views in the Scottish Highlands are from such mountains as Ben Lomond and Ben Ledi, where the only remains of the old plateau are on the scattered hill-tops, and wide valleys lead the eye to the Midland Valley of Scotland, and on past smoking town, dark wood, and chequered farm-lands to the sheen of the distant estuary. Farther north, though the bulk of the population and the most frequented tourist resorts cling to the sunny eastern coast, the most thrilling views lie where the many peaks, from Ben Nevis to the hills of Assynt, look across a wide expanse of loch-broken coastland to the western sea and the islands of the outer Hebrides.

[1] A. Trollope (1876, p. 550).

The typical inland view in the Central Highlands is dull and depressing. Some of the valleys are diversified by birch-woods, but except when the hills are coloured by the flowering of the heather, they are often a waste of monotonous moorland, with wide depressions covered by sheets of grey-green moss, alternating with brown patches of barren peat ; too often the only rocks exposed on the smooth hillsides are banks of frost-shattered debris, while the green mounds of gravel at the foot of the hills show, by the water which oozes from them, that they are as sodden as a wet sponge. The only sign of human occupation in this untilled land may be the straight line of a deer-fence, or a row of black shooting-butts, though the white tree-stumps in the peat indicate that forests once covered the land, and the grey stone footings still visible in the heather remain as melancholy relics of former homesteads. The hills are bare mounds, large enough to be tedious, but too uniform to give any feeling of height, while the heavy sky-line has none of the beauty of an uplifted line of mountain-peaks. There is much truth in Ruskin's remark that some mountains show "the perfection of beauty," and others "the extreme of ugliness." [1]

A dissected plateau in a cold, wet climate has a comparatively poor type of scenery ; it is poorest when the country has been glaciated, for then the rocks have lost their boldness and the surface has the rolling contour of downlands without their pleasanter features, and its curves are lumpy and uninteresting. Certain curves in a landscape unquestionably give much greater pleasure to the beholder than others. The kind of curve described by a piece of rope when one end is uplifted while the other end lies slack upon the ground is curiously agreeable to the eye. It is the curve taken by a pile of loose material, under the influence of various geographical agencies. We see it where the sides of an old valley

[1] Ruskin, *Modern Painters*, vol. iv. p. 358.

fall to the river-plain or in the slope of a mature volcanic cone; the outline of Fusiyama, in Japan, owes its charm to this same graceful curve—a curve, moreover, constantly used by Eastern nations to give a form of beauty to their temples. Ruskin called this curve "the line of rest," and Hogarth described it as "the line of beauty." Spenser, with poetic insight, suggests the explanation of its charm:

> That Beauty is not, as fond men misdeem,
> An outward show of things, that only seem.

The stability and security which usually accompany this curve are probably the source, though it may be the unconscious source, of the pleasure it gives us.

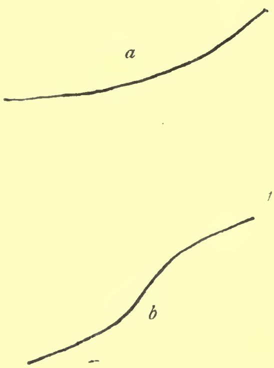


Fig. 84.—(*a*) The Normal Denudation Curve; (*b*) that of a Glaciated Slope.

Now, in the glaciated area, the action of the ice has been to cut away the toes of the earlier slopes; the bulging sides of the valleys present a convex appearance (Fig. 84), and the graceful maturity of the concave slopes, wrought by the age-long action of wind and rain, has disappeared.

The passage of an ice-sheet across a country has the further effect of wearing down its mountain-peaks and narrow crests into blunt bosses and rounded ridges. But the glory of the mountain is in its boldness; the soaring peaks call to the adventurous spirit of man, and the excitement of danger from crumbling crag or falling avalanche awakens the joyous exhilaration which the primitive man may feel when he goes out to do battle with his kind, but which civilised man can only know when he accepts the challenge of Nature herself.

This supreme delight of mountain scenery is lacking in the rounded surfaces and wall-like cliffs of the glaciated mountain districts, and thus the fiord-valleys share the gloom of some Alpine valleys without the stimulus of the Alpine peaks.

The scenery of glaciated fiords has impressed many observers with a sense of monotony; the valleys are long and straight, and many miles of them can be seen at a glance, and for hours together the tourist on his steamer passes between bare rock-walls and wishes to push them back. Beyond the head of the fiord may be a vista of mountains with snow-field or glacier; but often the fiord is continued only by a dull valley with a flat, swampy floor at the foot of the bare hill-sides, which gradually close as the valley bends in the distance. As most of the side-valleys open high on the fiord-walls, they are hidden from the passengers on a steamer. The loss of the views up them is not adequately compensated by the water-falls which plunge into the fiord from these hanging valleys; for, owing to the net-work of valleys in a fiord district, the streams are usually small. Except after heavy rain or during the melting of snow in spring, the waterfalls have but a small volume, and no great force and power—the main elements in their beauty. The dark, waveless waters of the fiords add to the sense of dull stagnation, as they have neither the rich colour of the Alpine lake nor the majesty of the heaving, boundless sea.

Usually, moreover, the fiords are treeless or are clothed by sheets of pine and fir forest, which do little to relieve the monotony of the scenery; and occasional tufts of birch that would elsewhere pass unnoticed may give a locality a reputation for beauty. The monotony, as it affects the traveller along the fiord, is well described by Sir Martin Conway in his sympathetic account of Patagonian scenery.

"It must be admitted that the scenery of Smyth

Channel is rather monotonous; always fine, no doubt, but always fine in the same way. The views are composed of the same elements—a calm water-highway, wooded islands and shores, waterfalls and cliffs above, and large, ice-rounded and bare summits reaching up into a roof of heavy clouds, the whole enveloped in sombre and solemn gloom. It is all impressive enough when you come freshly to it, but as the hours of each day draw slowly along it becomes a little wearisome, so that an effort must be made to fix the attention and not lose the charm of change, because the changes that do take place are within a narrow compass." [1]

Yet the simplicity and similarity of the land-forms along the fiords, though they may lessen the beauty of the scenery as a whole, are sometimes a source of fresh beauty of their own. Some happy play of light may transform the view into one of entrancing loveliness, when the rounded islands, scattered through a network of straits, repeat their simple forms amid the ever-varying effects of distance and reflection. The fortunate traveller may enjoy such a scene from the hill above Bergen, or from the old Venetian fort at Sebenico over the limestone islands and the labyrinthine channels of the Adriatic coast. To see the fiords at their best, watch them from some island summit, when the summer sun is low in the west, and its rays pass up the fiords, and the glowing colours of twilight tint the sheets of rippled water, the valley walls, the faces of the rock-gables, and the distant snow-fields on the mainland. The gorgeous colouring can be enjoyed to the full, as its changes come slowly and not with the tantalising swiftness of a short tropical sunset. Such views, however, have to be seized at the right time. Within an hour all the colour and charm may have gone; and there is then nothing to look at save brown, hummocky hills, dull bands of grey water, and distant snow-fields that end in a hard line across a leaden sky. But such

[1] M. Conway (1902, pp. 141–3).

glorious colour-effects are exceptional in the fiords. I have travelled half-down the Norwegian coast without seeing one gleam of coloured sky. Owing to their wet climates, fiord countries are usually shrouded in heavy clouds, though when these are lighted by sunshine and the clouds and mists are twisted into weird forms by the draughty winds along the fiord avenues, they add a rare beauty to the landscape.

The abiding charm, however, of the fiord lies in its solitude and its repose. The very spirit of rest seems to brood over the recesses of a great fiord: the lake-like smoothness of the water, the overpowering massiveness of the dark walls, the insignificance of man and his works, the relaxing humidity of the air, and the heaviness of the clouded sky, all compose a soothing harmony of restfulness and peace. It is not surprising, under modern circumstances, that the fiords are growing in popularity as a holiday ground, giving rest and recreation to the tired dwellers in more crowded lands. Their ease of access is a further advantage to the traveller seeking health and repose ; a cruise along their shores gives change of scene without fatigue and the sensation of travel without its hardships. There are no worries of catching trains and sampling hotels, and the sleepy air of the sea can be breathed on a surface smooth as a lake.

The comfort and tranquillity of boat travelling is an element, often an unrecognised element, in the attractiveness of places where such mode of transit can be employed. The Rhine largely gained its reputation among eighteenth-century travellers, weary with the contentions and discomfort of the road, by the ease and security of its waterway, which put them in the best temper for the calm enjoyment of its scenery. The visitor to Venice in the seventeenth century, accustomed to the dirt and disorder of his own unpaved and unpoliced streets, must have revelled in the smoothly gliding gondola, and credited to the beauty of the city the enjoyment he derived from its comfort. This advantage of boat-travelling is enjoyed to the full by the modern visitor to the fiords, and is an added attraction to their quietness and their peaceful scenery.

But the influence of this scenery has had a very different effect upon the permanent dwellers among the fiords. The prevalent gloom is broken for awhile during the prolonged daylight of midsummer, when the fiords are most frequented by visitors; but during the rest of the year fiord districts are unusually cloudy and the typical fiord scenery tends to develop the spirit that Ruskin has so graphically depicted as "the Mountain Gloom." The supremacy of the sombre elements in fiord-scenery is shown in its influence on national character and temperament.

The intellectual differences evolved by life in narrow fiord-valleys, with their dominant monotony and gloom, and the sunshine of shallow dales or open plains, are illustrated by the contrast between the Norwegian and the Swede: they are both members of the same race, being the only existing nations of unmixed Teutonic breed; they live in adjacent lands in the same latitudes and under similar climates; yet the Norse, in harmony with the rougher, harder life on the fiord, has become essentially a man of action. His courage and love of freedom carried him across the rough seas of the North Atlantic centuries before the Mediterranean seamen, with their larger boats and milder seas, had found their way to the New World. The same capacity has given the modern Norsemen their remarkable success in polar exploration, and that strong individualism which is still the dominant note in Norwegian literature.

The Swedes, on the other hand, are characterised by a charming courtesy and by artistic culture, and their work by a fertility of invention which has produced from Sweden so many distinguished leaders of modern thought.

The same contrast is shown among the British Celts.

Instructive comparison between the peoples of the Highlands and Lowlands of Scotland is difficult, because of racial differences; but the western Highlander and the Irishman are both Celts, and they live under climates which have much in common. The main differences in their geographical environment are that the Highlanders dwell isolated in their deep fiord-valleys and the Irishman lives on sunnier and more friendly plains. The spirit of the Scottish Celt, as expressed in the poems attributed to Ossian, shows the influence of his sombre environment in a love of the wierd and the melancholy, and a sternness and fixedness of purpose that still survive in the Highland glen; whereas his Irish cousin has developed an impulsive good-humour and an easy-going disposition more akin to his natural surroundings.

The Montenegrin, from his valleys beside the fiord of Cattaro, presents a contrast to the Italian which is similar to that between the two Scandinavian nations; for, though the Montenegrin has always held his rugged fastnesses safe from the Turk, he still wears the black cap adopted in mournful memory of his defeat at Kossovo nearly five centuries ago; whereas the people of Italy have suffered successive conquests without any permanent reduction in their national gaiety.

If a census could be taken it would probably be found that the fiords have produced, in proportion to their population, more men of action, but fewer artists and inventors, than the plains; we owe, however, to the spirit born within their quiet recesses the religious imagination, which, transplanted to a more fertile soil, has had such an ennobling influence on the thought and life of western Europe, and thus on the whole development of the modern world.

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LIST OF GEOLOGICAL HORIZONS AND SOME GEOLOGICAL TERMS

In the following table the oldest rocks are at the end of the table.

Kainozoic	Pleistocene.	These 3 divisions = Neocene.
	Pliocene.	
	Miocene.	
	Oligocene.	
	Eocene.	
Mesozoic	Cretaceous.	
	Jurassic.	
	Triassic (New Red Sandstone).	
Palæozoic	Permian.	
	Carboniferous.	
	Devonian (Old Red Sandstone).	
	Silurian.	
	Ordovician.	
	Cambrian.	
Archæozoic or Eozoic.		

Base-level.—The level below which a river cannot wear away its bed.

Block-mountains.—Mountains composed of blocks of rock which have been tilted or raised in masses by faults.

Conglomerate.—A rock composed of rounded pebbles.

Fault.—A fracture in the earth's crust along which the rocks on one side have been displaced.

Foliation.—The arrangement of minerals in a crystalline rock in their parallel layers. The layers are thin in schists and thicker in gneiss.

Friction-breccia.—A breccia, *i.e.* a rock composed of angular pebbles, which has been formed by friction between rocks during earth-movements.

Horst.—A block of high land left upraised by the subsidence of the surrounding areas.

Joints.—Cracks in rocks due to twisting, contraction, or pressure.

Lignite.—A variety of coal.

Liman Coast.—An alluvial coast usually with many lagoons (from *Limus*, Lat. mud).

Monoclinal.—A fold in the earth's crust having only one side.

Moraines.—Deposits of earth and stones left by glaciers.

Orography.—The branch of geology which deals with mountains and mountain-structure.

Phonolite.—A lava rich in alkalies.

Plutonic.—Igneous rocks which have been formed deep below the earth's surface.

Porphyrite.—A partially decomposed andesite, a lava so named from its abundance in the Andes.

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