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Patterns of deposition at the continental margin*

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GENERAL STATEMENT

The term " continental shelf and slope ", " continental terrace ", or " continental platform ", as it has been used for decades in the geological literature, connotes to most geologists the submerged margin of the land masses. But with our rapidly increasing knowledge of submarine geology the fact is becoming apparent that being under water is about the only attribute that many of these areas have in common. It is high time for a reappraisal of what these features really are, and to examine their origin, and to consider critically whether the term should be applied indiscriminately to the submerged margin of any large land mass, no matter how dissimilar the topography and the structure may appear to be.

A continental terrace, as the term will be used here, is a three-dimensional sedimentary structure. The shelf is the shallow, gently sloping upper surface, and the slope is the steep seaward face. It is our purpose here to trace the development of such a sedimentary structure from its earliest beginnings, and to try to show that, where continental margins do not exhibit this simple structure, the answer probably lies in unravelling the varied events of their geologic history rather than in trying to find an oceanographic interpretation. For it is on this point that much of the confusion in the present day literature has arisen as modern marine surveying reveals a bewildering variety of forms. We are fortunate in having preserved two large terraces which have remained basically unaltered ever since their earliest beginnings. For these two terraces, although ancient, are primitive in their structure; they are archetypes, to borrow a term from biology, of many other more complex forms that have evolved in other parts of the globe, whose origin has now been obscured by subsequent events. I refer, of course, to the platforms bordering the eastern and Gulf coasts of the United States. And we are doubly fortunate in that these submerged margins together with their emerged coastal plains have been the sites of intensive geological investigation.

Around the world today the submerged continental margins are of varying widths. The extreme cases are the shelf off Siberia facing the Arctic Basin, three to four hundred miles in width, in contrast to the west coast of South America where the shelf is practically non-existent. At the present time all the continents are largely emergent and the shallow, interior seas which have repeatedly flooded them in the past have largely drained away. Consequently, the continental terraces are now the chief sites where marine sediments are accumulating. There is one major exception to this:

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namely the deep basins and shallow inter-island platforms of the East Indies. This, however, is a completely different structural picture, and we will return to this case later.

The investigation of these submerged borderlands, their sediments, topography and structure, is one of the main fields of endeavour in submarine geology today. It should be clearly borne in mind that the present continental slope, however formed, is only a topographic feature and does not represent any sort of boundary between hypothetical continental and oceanic blocks of the crust. In fact, recent seismic work off Nova Scotia and Georges Bank (Officer and Ewing, 1954) would seem to suggest that there is no difference in the density of the basement complex which underlies this continental terrace, at least to the limits of this particular survey (Fig. 1). The terrace itself is made up of three major divisions of rocks with three distinct velocities. The aprons of detritus which have been deposited on and around continental margins and in marginal geosynclines result in a very complex depositional picture. Progressive orogenies have in many cases further complicated an already intricate stratigraphy. Luckily modern advances in marine geophysics offer some hope that the tangle can some day be unravelled.

THE ATLANTIC AND GULF TERRACES

The Atlantic and Gulf terraces have had a parallel evolution, and, when considering their development, the coastal plain and continental platform should be taken as a unit. In the case of the Atlantic the oldest beds are Lower Cretaceous, and in the Gulf, Jurassic. In simplest terms both are comprised of wedges of inter-fingering continental and marine sediments which thicken in a seaward direction, and in both instances deposition is still going on in the same fashion (Fig. 2). In the Gulf Coastal Plain the formations may be considered a series of truncated wedges lying one on the other, and normal faulting that is contemporaneous with deposition is common (Storm, 1945). This fact should be remembered when the peculiar topography of the Gulf slope is discussed, because the major faults have been traced to the limit of drilling, and furthermore the displacement increases downwards, amounting to hundreds of feet in the older beds, in contrast to but a few near the surface. No such extensive faulting occurs in the Atlantic Plain, although gentle archings and downwarps occur due to basement topography, as is also the case with the Gulf. Both of these terraces have been built unconformably on old erosion surfaces. Updip, where the basement is known, in the western section, the sediments of the Gulf Plain rest on the deformed Palaeozoic rocks of the Ouachita system, and in its eastern portions the Cretaceous laps over the southwestward plunging Appalachians (King, 1951); downdip the formations have thickened so much that the drill has not reached these rocks or any others which may form the basement in a seaward direction. The surface on which the Atlantic Plain rests is well known throughout due to lesser accumulation. The formations feather out updip against the crystallines of the Fall Line, and a crystalline igneous basement has been reached many times in drilling for oil or water over its whole extent (Spangler and Peterson, 1950; Spangler, 1950). It has every appearance of being a peneplaned surface which at present has a gentle seaward dip increasing towards the coastline.

The stratigraphic column at the present shoreline in the Gulf is many times thicker than it is on the Atlantic side; the seas advanced much farther inland and the plains

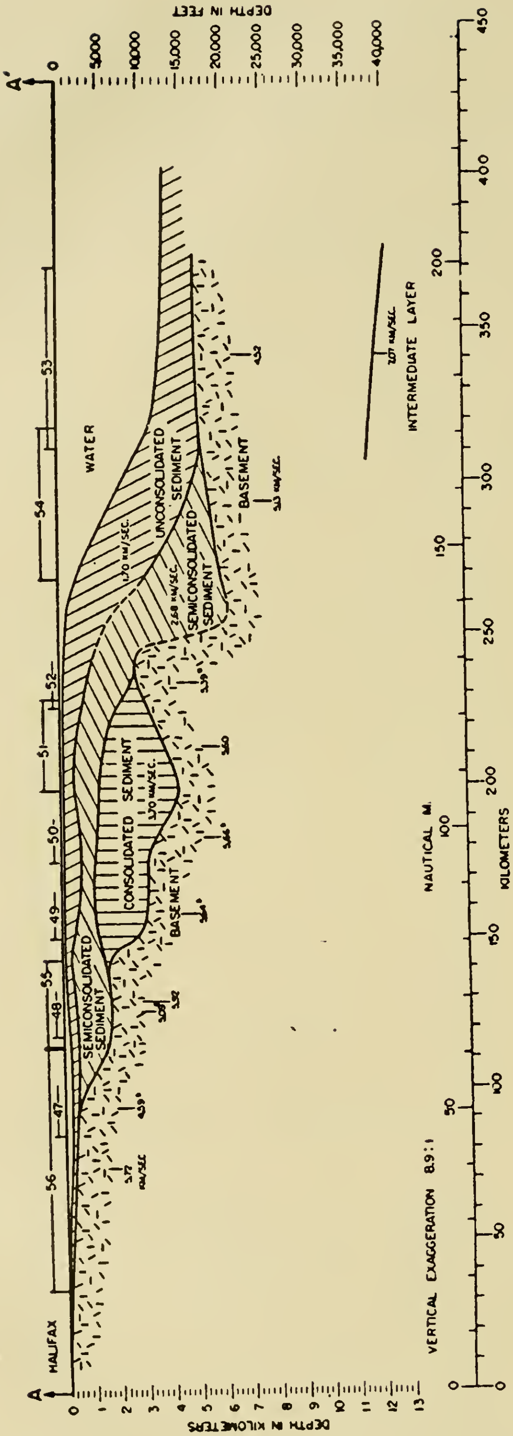

Fig. 1. Section across the continental terrace off Halifax, Nova Scotia. (From OFFICER and EWING.)

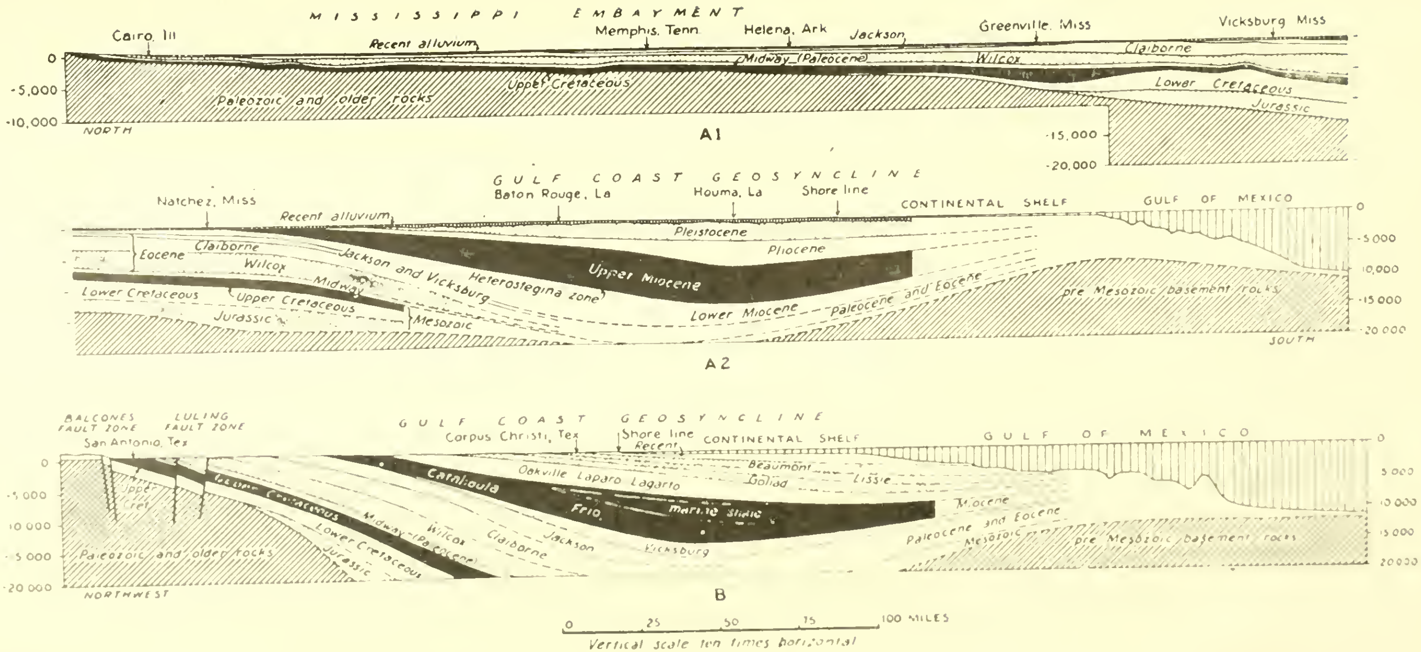

Fig. 2. (A1 and A2) Generalized section along the axis of Mississippi Embayment from Cairo, Illinois to the continental slope. (B) Generalized section across Gulf Coastal Plain and continental terrace from San Antonio to Corpus Christi, Texas and across the continental terrace. (From KING.)

are, therefore, considerably broader. But the same depositional pattern of overlapping lenses is common to each. As STEPHENSON (1926) observed many years ago in commenting on the stratigraphy of both areas, " The different kinds of materials do not form separate, uniform sheets extending throughout the entire length of the Atlantic and Gulf Plain, for the sediments laid down at any given time differed from place to place and the conditions of sedimentation constantly shifted from time to time. Briefly stated, this means that no two columnar sections, unless closely adjacent to each other, are identical in lithologic succession ". In other words, major and minor transgressions and regressions followed each other with startling rapidity. Deposition has been punctuated by many hiatuses, but the net result has been a growth in thickness and in width, until at present these terraces, coastal plain and continental platforms have attained tremendous proportions, particularly in the Gulf. Since Lower Cretaceous time, then, when both terraces began to assume their present shape, conditions governing transportation and deposition have remained virtually unchanged. The parallel development of these sedimentary wedges affords an excellent illustration of what will happen when a major sea is forced to deal for long periods of time with large supplies of sediment of varying texture over a fluctuating strandline. The same structure will be built along any continental margin; the details will, of course, be modified, depending on the proportions of the variables, but the overall pattern should be recognized. It is not often that the oceanographic and geologic environment has remained so constant for such a long period to permit such a full development.

By way of illustration let us glance briefly at the contemporary oceanographic and sedimentary picture. The Atlantic shelf is, at present, an area of non-deposition, and in places is even undergoing erosion. From New Jersey southwards reworked material from outcropping Coastal Plain formations furnished much of the bottom material, as is evident from the fossils and from the lithology (STETSON, 1936). Consequently, the shelf is predominantly sandy. True, the northern rivers carry little sediment, but although those of the middle and south Atlantic states which do have a large suspended load debouch into bays and sounds, all of the sediment is not trapped in them. What fine material is being delivered to the sea is by-passed to the slope. Cores taken in the silts and clays of varying textures on the slope from Cape Hatteras to New England and in the nearby Atlantic basin show that deposition has been of the order of 50–70 cm since the last cold period, which presumably can be correlated with the last advance of the Wisconsin ice (STETSON, 1949). South of Hatteras the slope and Blake Plateau have generally hard bottoms (*Ibid*, 1949). Temperature and salinity data indicate that the Gulf Stream impinges strongly against this portion of the slope (ISELIN, 1936) and sweeps over the surface of the Blake Plateau, preventing any deposition in these two areas.

Turning now to the Gulf shelf, we find what is evidently an area of deposition. Silts of varying textures predominate except for a narrow, sandy strip close to the beach. This is the more usual condition around the world today; it is the large, sandy expanses that are unusual, and the only shelf that is in any way comparable to the one off the eastern United States is found off Argentina. In the case of the Gulf it is probable that more material is being supplied to the sea than it can transport, and the result is that the continental terrace is at present growing at the expense of the Gulf, a process that has been predominant since the beginning of the Tertiary.

The slope is covered with a fine, uniform clay which has a median diameter of about 1 micron, and this texture continues across the bottom of the Sigsbee Deep (STETSON, 1953). This has not always been the case, and, in fact, in the very recent past such uniformity was not present as the cores indicate. For instance, a brown clay now covers the central part of the eastern Gulf, while unconformably below it, at a depth of only a few inches, lies Globigerina ooze.

Our ignorance of bottom currents is profound, and any estimate of bottom velocities must in most cases be based on the grain size of the sediment. It can be taken for granted, for instance, that clean, well sorted sands indicate bottom currents of half a knot or better, conversely, silts and clays can only be deposited under lesser velocities. Waves and tides are the most obvious producers of bottom currents although the competence of the former with increasing depth has recently been questioned (DIETZ and MENARD, 1951). But there can be no question as to the competence of both over the shallower bottoms, and bottom currents from these two sources certainly have higher velocities in the Atlantic than in the Gulf. The winds of Atlantic storms, except for hurricanes, have, by and large, higher velocities and a longer fetch, and are therefore capable of building waves with longer periods. These in turn are capable of moving sedimentary particles at greater depths, and in far greater quantities along the strand, by beach drifting and strong longshore currents. The tidal range on the open Gulf coast is small compared with the Atlantic (roughly 1·5 feet at Galveston, as with 4–5 feet at Delaware Breakwater), and there must be a consequent reduction in the velocities of the tidal currents. I am well aware that this is tantamount to saying that we really don't know how sedimentary particles move over the deeper bottoms; but move they do, as their texture shows. For all intents and purposes, once they are out of sight their transport can only be inferred. There are few quantitative data, and in this direction the oceanographer has so far largely drawn a blank.

PRIMARY TERRACE CONSTRUCTION

Every advance and retreat of the sea leaves its impression on the stratigraphic record, and the numerous unconformities and facies changes exhibited by the overlapping lenses of the Coastal Plain formations are concrete evidence of the numerous oscillations of the strandline. A change of existing sea level, would, in fact, alter the sedimentary distribution which has been described above. For instance, a deepening of the Atlantic shelf would once more make this platform an area of deposition, as it has been many times before.

Under the simplest conditions, during rising sea level, onlap means that the younger deposits overlap the older in a shoreward direction. The nearshore sediments are sandy or gravelly, while the offshore deposits resulting from the same sea-level, and therefore of the same age, will be muddy. In vertical cross-section this eventually results in an overlapping of shales on sandstones. It is a time of continuous accumulation of sediment in a deepening sea, and the continental shelf grows in thickness as well as in width, as successive layers are added to its surface as well as to its forward slope. Conversely, during falling sea-level, offlap means that the younger deposits overlap the older in a seaward direction. As the sea retreats, some of the coarser deposits of the shoal water zone are transported seaward and overlap the older and finer muds which had previously been laid down in deeper water. The surface of the shelf is undergoing erosion, with a reduction in thickness, or perhaps the entire removal of strata deposited near shore during the previous onlap, but it continues to grow in width because deposition is uninterrupted in the deeper water over the seaward slope. Equilibrium, or still stand, will likewise produce a forward growth of the slope; little or nothing is added to the thickness, although there is no loss.

Through all the oscillations of the strand, as well as during periods when sea-level remained constant, the face of the slope always progresses steadily seaward into deeper water. Since Cretaceous time the basement has been sinking with occasional reversals, and the sum total of these oscillatory movements has been downwards. The result has been a terrace constructed of a huge series of overlapping lenses of sediments of diverse lithology. Consequently, although both terraces have grown intermittently in thickness with many depositional breaks, they have grown continuously in width. For example, total thickness of the sedimentary formations along the axis of the geosyncline at the coast near the Texas-Louisiana line has been estimated at more than 40,000 feet (LOWMAN, 1949), but the maximum width of the whole terrace is measured by the 700 odd miles lying between Cairo, Illinois (the high water mark of the Upper Cretaceous seas) and the present continental slope. On the Atlantic side the sedimentary wedge at the shoreline is slightly less than 10,000 feet thick, as logged in an oil well drilled at Cape Hatteras. Offshore, seismic profiles run by the Lamont Geological Observatory indicate a maximum thickness of the order of 16,000 feet in a basin southeast of Delaware Bay, with a rise in the basement seaward near the present continental slope (EWING *et al.*, 1950). Its greatest width is about 175 miles lying on a traverse through Cape May from the Fall Line to the break-in slope. The thickness of the sedimentary prism offshore in the Gulf is, at present, unknown.

TURBIDITY CURRENTS AND SLOPE TOPOGRAPHY

The underwater topography of the Atlantic slope shows a dendritic drainage pattern (VEATCH and SMITH, 1939), characteristic of many land surfaces, of main stream valleys with tributaries, although the streams may have been submarine flows of muddy water known as turbidity currents, and not rivers flowing under the air. Numerous canyons gash the continental slope from Georges Bank to the Chesapeake, and some of them, such as the Hudson, are of considerable size. Perhaps a brief explanation of these submarine streams of muddy water is in order, as they are thought by many geologists to be the erosive agents responsible for the spectacular and enigmatic submarine canyons, which we are now discovering to be world wide. The density of any water mass is increased by a suspended load of sediment. Consequently muddy water will flow under clear water of the same temperature and salinity. Many of the silts and clays of the continental slope have a very high water content, frequently running over 150% of dry weight, and are consequently very unstable and will liquify easily by jarring such as could be produced by a submarine earthquake. Theoretically, the resultant flow may start out as a liquid slump and quickly change into a dense flow of turbid water, thought by some to attain considerable velocity, and hence great erosive power, as it slides down the steep continental slope. Flows of this type have never been observed in the ocean, but gentle turbidity currents are known to flow along the bottom of the whole length of man-made Lake Mead, where the muddy Colorado River plunges beneath the clear waters of that Lake. They have also been observed in some glacial lakes such as Geneva.

What factual data exist at present are all on the depositional side. In areas of low gradients we have the deep sea plains, crossed by the mid-ocean channels with their leveed banks (Menard, 1955; Dietz, 1955; Heezen *et al.*, 1955), and the same type of channels are found in various Swiss lakes (Daly, 1936). Graded bedding, long a somewhat obscure depositional process, can be best explained by turbidity flows.

So much attention has been focused on the supposed potential energy of the turbidity current by their proponents that the factors that will dissipate this energy such as friction of turbulent flow along boundaries, entraining of clear water, and settling of particles have all but been lost sight of. One source of confusion is the difference between a true turbidity current and a submarine slump or slide. Doubtless a slide starting on a steep slope would eventually grade into a turbidity current, but there must be a great difference in energy at the start as well as in the mechanics of their motion and their erosive power. Witness the conflict of opinion over the velocities and even the type of the Grand Banks " flow " which parted the Western Union cables following the earthquake of 1928 (Kullenberg, 1954). Possibly this may seem academic, but when the term " turbidity current " is mentioned many people visualize a suspension current such as flows along the bottom of Lake Mead or in the Swiss lakes. These patently have no erosive power; and it is not a question of having a super Colorado River and producing a turbid suspension of greater volume. Possibly a mud or sediment slide or flow would be a better term to apply to the initial slump of unstable sediment failing under gravitational stress, restricting turbidity current to the transporting and depositing agent. When looked at objectively, the dynamic role assigned to density currents by their advocates may be seen to have more than a tinge of wishful thinking induced by an attempt to escape from the horns of a dilemma. Obviously an enormous amount of vigorous erosion must have taken place to cut the submarine canyons and to make matters worse, during the late glacial period, which is only yesterday. Conventional rivers would require more relative displacement of land and sea than most geologists will admit is probable or possible. To circumvent this, the turbidity current has been hailed almost overnight as the answer to all vexing problems of submarine erosion.

The topography of the continental slope in the northwestern Gulf of Mexico is very complicated as Gealy (1955) has pointed out, and, according to her analysis, has probably been produced by a variety of causes. Sub-aerial erosion, the failure of unstable sediments which are under shearing stress, salt domes and crustal faulting have all played a part. An extensive scarp bounds the Sigsee Deep and continues around the continental slope off the west Florida platform, where it is found to be over 7000 feet high (Jordan, 1951 and Fig. 3). Pronounced normal faulting could be the only cause for cliffs such as these. Higher up on the slope the troughs and ridges and hummocky topography is thought to be the surface expression of lesser shearing at depth plus erosion by sediment flows and slumps. The material is largely furnished by the thick Pleistocene deposits lying on the upper parts of the slope.

MOBILE CONTINENTAL MARGINS

As an historical background to the existing terraces, consider the " long succession of geosynclines of differing kinds and trends " with their attendant island arcs, such as has been postulated by many authors (Kay, 1951) lying along the Atlantic and Gulf margins during Palaeozoic time. In a situation such as this the supply of detritus comes from within the orthogeosynclines themselves, from fluctuating upwarps of their floors, from volcanoes and igneous intrusions, and from the islands themselves. The volcanic rocks within the sedimentary series seem to be restricted to what are termed the eugeosynclines, while the miogeosynclines contain only sediments. This is in direct contrast to the views of those who consider the hypothetical continent of Appalachia lying somewhere near the present 100 fathom line the sole source. The Dutch East Indies have been cited as a modern large-scale parallel to the paleogeography along the eastern seaboard and along the Gulf during the Palaeozoic.

Temporarily at least, orogenic activity and vulcanism has ceased along the eastern and Gulf coasts of the United States; and the parallel geosynclinal belts, the Appalachian, the Ouachita and the Witchita systems, have long been quiescent. The net result since Cretaceous time has been the construction of two " paraliageosynclines " according to KAY's terminology. These are linear troughs of undeformed sediments lying along the outer margins of the geosynclinal belts, and their seaward limits form the present continental slope. Obviously their strata, which in the case of the Atlantic and Gulf are thickening seaward at the present shoreline, must thin as the outer margins are reached, but there are few data on this point.

Continental terraces like these obviously need an extensive hinterland to supply the sediments if they are to reach any sizable proportions, and furthermore the drainage must be into the ocean. These conditions are not always met, which may be the explanation for our inability to find comparable structures built during the Palaeozoic. KUENEN (1950) has speculated on what could have happened to them, reasoning that, because of the much greater interval of time that was available for their building, such structures would not be easy to hide. It well may be, however, that under mobile geosynclinal conditions they never existed.

Specifically, in the case which we are considering here, the two terraces are now building on what are probably the bevelled surfaces of the rocks forming the outer parts of the Palaeozoic eugeosynclines peneplaned after orogenic and plutonic activity had ceased. They serve as models of the simple forms which will be constructed by the processes of marine transportation and deposition when these operations are not interfered with by activity in the mobile belts.

The sediments, topography and structure of but very few submerged continental areas are well enough known to warrant critical comment. Aside from the two under discussion, we have only the areas off California, Norway, the West Indies, and Indonesia, for which adequate bathymetric charts exist. Some oceanic areas have been charted in considerable detail, but they have no bearing on this problem. The East Indies have already been mentioned as a modern illustration of deposition in eugeosynclines and miogeosynclines. The West Indies present a somewhat analogous case, but very little is known about the sediments.

Off California the sedimentary platforms have been extensively faulted and tectonically broken up into numerous basins and ridges. Occasional granitic outcrops have been found in the walls of a few of the minor, nearshore submarine canyons, but extensive rock dredging shows that they are only small intrusions and that the continental terrace, like that in the Atlantic, is composed of Cretaceous and Tertiary sediments. Nothing is known about the basement. The continental slope along the entire margin is in many cases controlled by long fault scarps of considerable displacement (SHEPARD and EMERY, 1941). The same is true of the walls of the deep

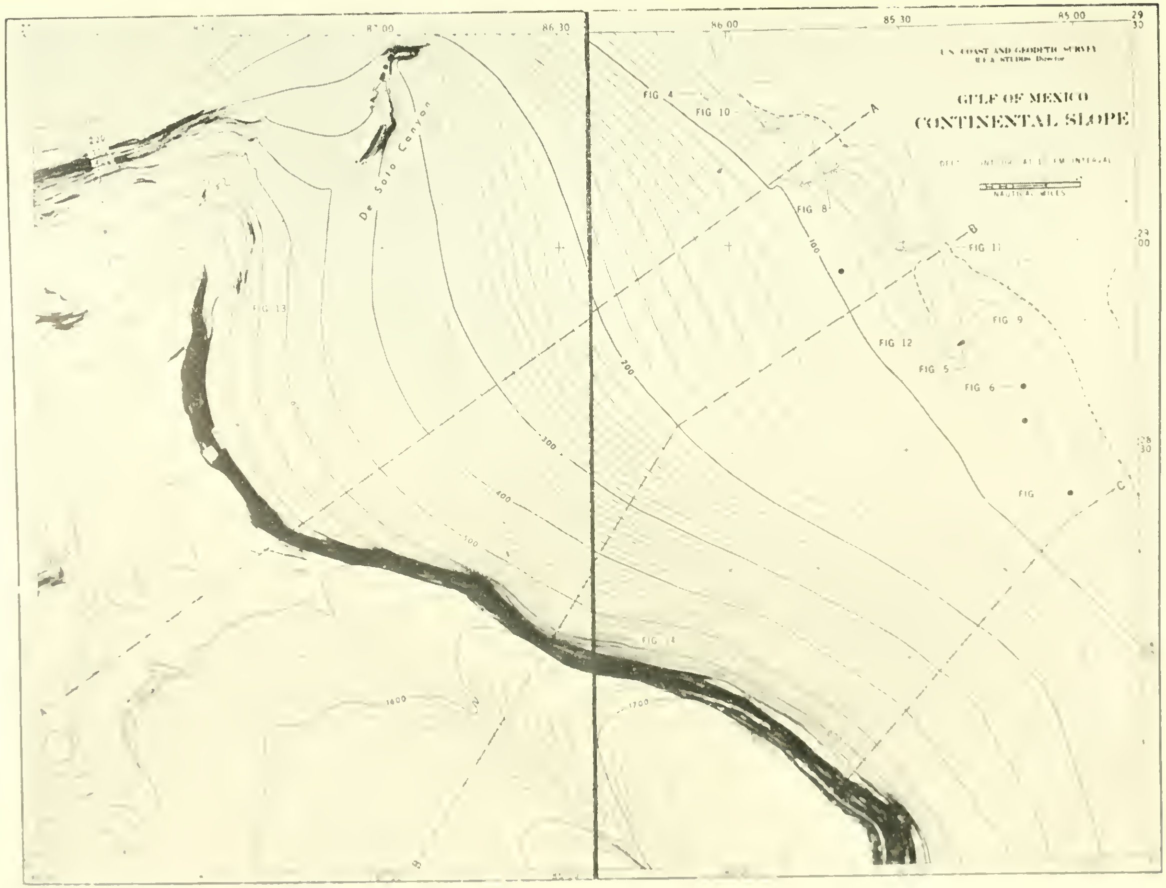

Fig. 3. A portion of the fault scarp forming the continental slope off the west Florida platform. (From JORDAN)

basins which are so characteristic of the southern section. The continental slope off the west Florida platform (Fig. 3) represents the most striking submarine fault scarp known at present, in places attaining a height of over 7000 feet. This can be traced around the Keys into Florida Strait, but its height has diminished to about 600 feet (JORDAN, 1954).

HOLTEDAHL (1950) concluded that the Norwegian shelf consists of consolidated rock which probably belongs to the same complex which makes up the hinterland, that is, granites and metamorphics, and that the whole is partially covered with a veneer of glacial debris of all types. The slope is controlled by what are apparently a series of step faults. Obviously, any comparisons as regards a depositional origin of the slope can no longer be made in this case, and there is nothing now to suggest a sedimentary origin for this entire borderland. Possibly it represents the eroded roots of a former eugeosyncline upon which no " paraliageosyncline " has been built, for lack of an adequate area from which the sediments might have been supplied.

A case that appears to be somewhat analogous is found off the end of the Breton Peninsula. Extensive areas of rocky bottom extending out towards the continental slope are shown on the chart of bottom lithology appearing in the Atlas de France for 1935, with DANGEARD as the authority. It would be reasonable to suppose that the igneous complex making up this peninsula plunges beneath the sea, although there is no notation of rock types, and there are no charts which give any clear picture of bottom topography.

There is enough diversity in the examples cited above to make the geologist pause before assigning any blanket mode of formation to the continental shelf and slope. It is not our purpose here to review the older mechanical theories such as the abrasion platform and the marine delta. Today they have few adherents (DIETZ, 1952). It is becoming apparent that each continental margin must be studied on its own merits; its history, structure and lithology must be known, and we must also know something about the oceanographic conditions which control sedimentation beyond the coastline. Without adequate marine topographic surveys we are still only guessing, and these must be supplemented by bottom coring and dredging. The case presented here for offlap and onlap is an attempt to reduce the sedimentary picture to its simplest, most primitive terms, in situations where oceanographic conditions have remained constant for long periods of time. From this point on it will be obvious to anyone that an endless succession of variables can be introduced to alter the pattern of the prototype.

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