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GEOLOGIE EN MIJNBOUW

RHYTHMIC PATTERNS ON DUTCH NORTH SEA BEACHES[1]

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SUMMARY

This paper deals with the different kinds of ripple marks, which are found on the North Sea beaches of the Dutch coast. They are treated according to the classification given in an earlier communication (VAN STRAATEN, 1953). Their distribution, directions and possible modes of formation are discussed, and two typical sections across the beach of Ameland are presented (fig. 1, A-B). Finally, a new type of ripple mark, formed by the wind, is described under the name "(wind-)antiripplets".

INTRODUCTION

In the foregoing issue of this journal the author published some data concerning ripple marks and other rhythmic patterns, which are found on the bottom of the Dutch Wadden Sea and of the Basin of Arcachon (France). A revised classification of the phenomena was suggested, based upon the shapes of the ripples and their orientation to the unidirectional or oscillatory currents, by which they are produced. Some new kinds of ripple mark were described and some new names given, which will be used also in the present communication.

The North Sea beaches of the Netherlands are almost everywhere composed of loose sand. Only rarely small outcrops may be present of subrecent peat or clay (e.g. on the island of Walcheren and between Hook of Holland and Scheveningen).

The distribution of ripple marks on these sands beaches depends in the first place on the differences between the "foreshore" and "backshore" (JOHNSON, 1938, p. 162). The foreshore, exposed at low tide, and covered twice a day by sea water, is characterized by the usually wet condition of the bottom and the presence of lows and balls and all kinds of subaqueously formed ripple marks. The backshore is covered by water only during exceptionally high tides and strong gales. On this upper part of the beach the sand is normally quite dry and mostly only wind ripple marks and small sand dunes are seen.

In fig. 1 two sections are given through the North Sea beach at Nes (Ameland). It is believed that these sections are fairly representative for the average conditions along the whole Dutch coast (at least in periods of normal weather circumstances). The sections were measured after the bottom had been uncovered by the receding tide. Practically all ripple marks, indicated on the sections, are therefore formed during the ebb stage, the greater part even only just before the final retreat of the water. It is not possible to use the indicated directions of the ripples and the corresponding directions of sediment transport for a reconstruction of the general sand movement on the beach (the case of the transverse megaripples excepted). During the earlier ebb stages and during the flood these movements may have been of a quite different nature.

LOWS AND BALLS

The positions and properties of the subaqueously produced ripple marks are entirely dependent on the major relief features. Along the Dutch coast these consist mainly in flat topped ridges (balls, or fulls) and shallow troughs (lows), of which some 2 to 4 systems may be observed in the intertidal zone. Below the low tide line still other ridges and troughs are usually present. The number of lows and balls on beaches is dependent on the bottom slope. On steep beaches they may be altogether absent, while gently sloping beaches seem to be particularly favourable for their development.

This relief is primarily caused by the influence of the waves, coming from the sea, upon the bottom. The lows and balls of the intertidal zone, moreover, appear to be connected more or less directly with the action of breakers. The details of the formation mean-

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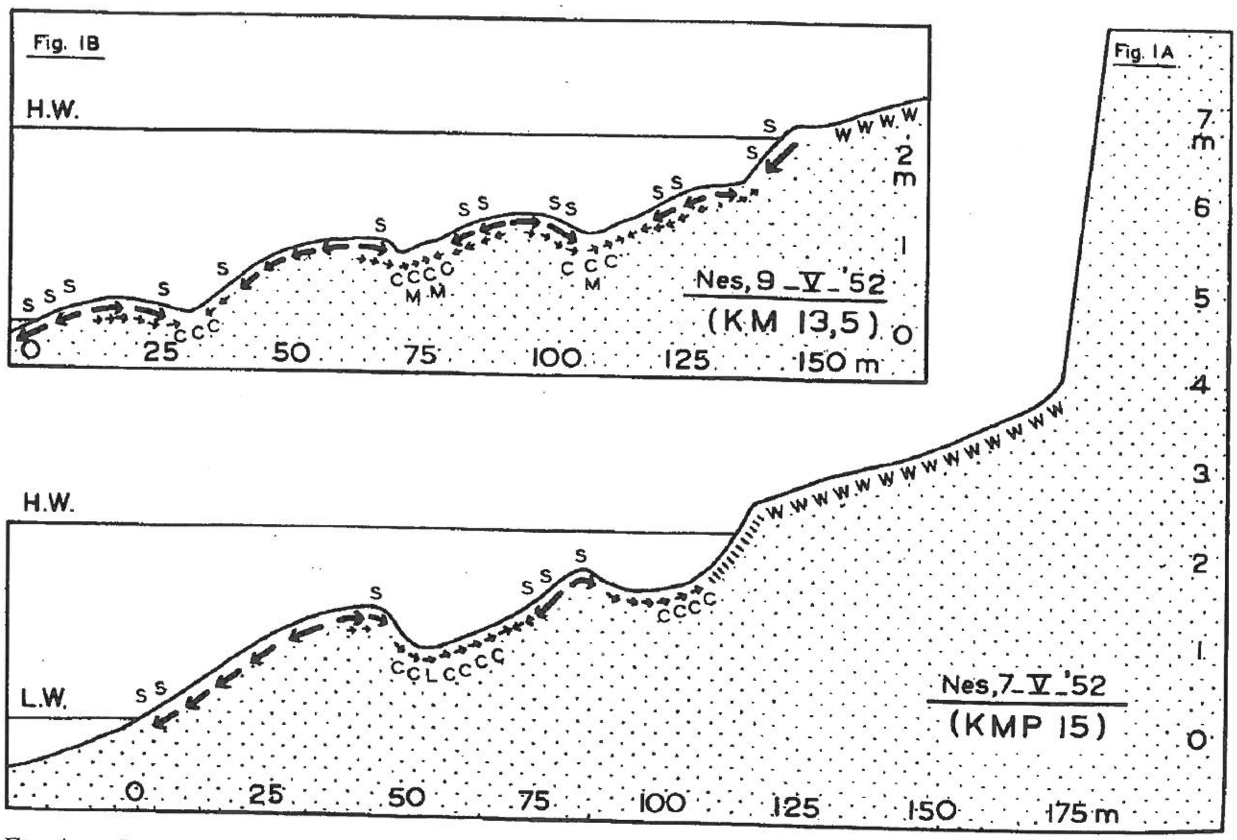


Fig. 1 — Sections at right angles to the beach at Nes (Ameland). *Heavy arrows:* Rhomboid ripple mark; the directions of the arrows correspond with those of the currents by which the ripples were produced. *Small arrows:* Transverse ripples formed by waves, swash and backwash with movement normal to the beach: asymmetric wave ripples and current ripples; the directions of the arrows correspond with those of the steeper sides of the ripples. *SSS:* Sand waves. *CCC:* Ordinary current ripples formed by flow of water *parallel* to the beach. *M:* Transverse magaripples. *L:* Linguoid ripples. |||||: Wind-anti-ripplets. *www:* Wind ripples.

while present a very complicated problem. Experiments have been carried out in wave tanks, wherein systems of ridges and troughs were produced on the "shores" and "off-shores" (TIMMERMANS, 1935; EVANS, 1940; BAGNOLD, 1947). EVANS and BAGNOLD both observed the formation of an excavation trough at the place of the plunging of the breakers, accompanied by an accumulation of the eroded sediment immediately "seaward" of the troughs. In the experiment of TIMMERMANS another accumulation was formed on the land-ward side. It is very difficult, however, to apply these results to the natural conditions. The waves in nature, with their much greater dimensions may well have some fundamentally different properties. Then, a great variation exists in nature between the sizes of waves during stormy and during quiet weather circumstances. Moreover, the separate waves of the same series are seldom of constant dimensions. Another factor is the vertical oscillation of the water level due to the tides. Finally, the waves and the surf produce, on natural beaches, secondary current phenomena, which can hardly be imitated in the laboratory, but which seem to be of great importance for the formation of the bottom relief. The present writer does not feel competent to enter into the details of these questions.

The lows and balls generally increase both in width and height from the high tide level downwards. This is well shown in the sections of fig. 1, A and B.[3]

The seaward slopes of the balls are usually less steep than the landward slopes, with the exception, however, of the uppermost ridge(s) where the reserved condition seems to be more common. Although the general pattern of lows and balls may be quite stable (TIMMERMANS, 1935) a slight landward displacement of the balls is sometimes observed. This appears to

[3] Below the low tide level in fig. B the seaward slope of the bottom continued for 55 m until a depth was reached of 90 cm. Seaward of this point a large ball was present, very asymmetrical in cross section, with its steep side to the land. The top of the ball was 25 cm below the water, 75 m from the low tide line.

be the case especially during periods of calm weather, whereas during gales and high tides a seaward movement may be substituted, together with a flattening out of the whole relief.

The balls do not form continuous ridges along the whole length of the beach, but are interrupted by more or less shallow cross channels, which will be referred to in this paper as "outlets" ("muien" in Dutch). Often

Halfway between the outlets the lows may show a minimum in depth: a kind of watershed. The water, pushed over the ball by the waves, flows away from this watershed in two opposed directions. The watershed is not always exactly halfway between the outlets. It may be shifted to one side, often so far, that all the water in the lows flows in the same direction (fig. 2). TIMMERMANS supposed that this condition is caused by the longshore tidal

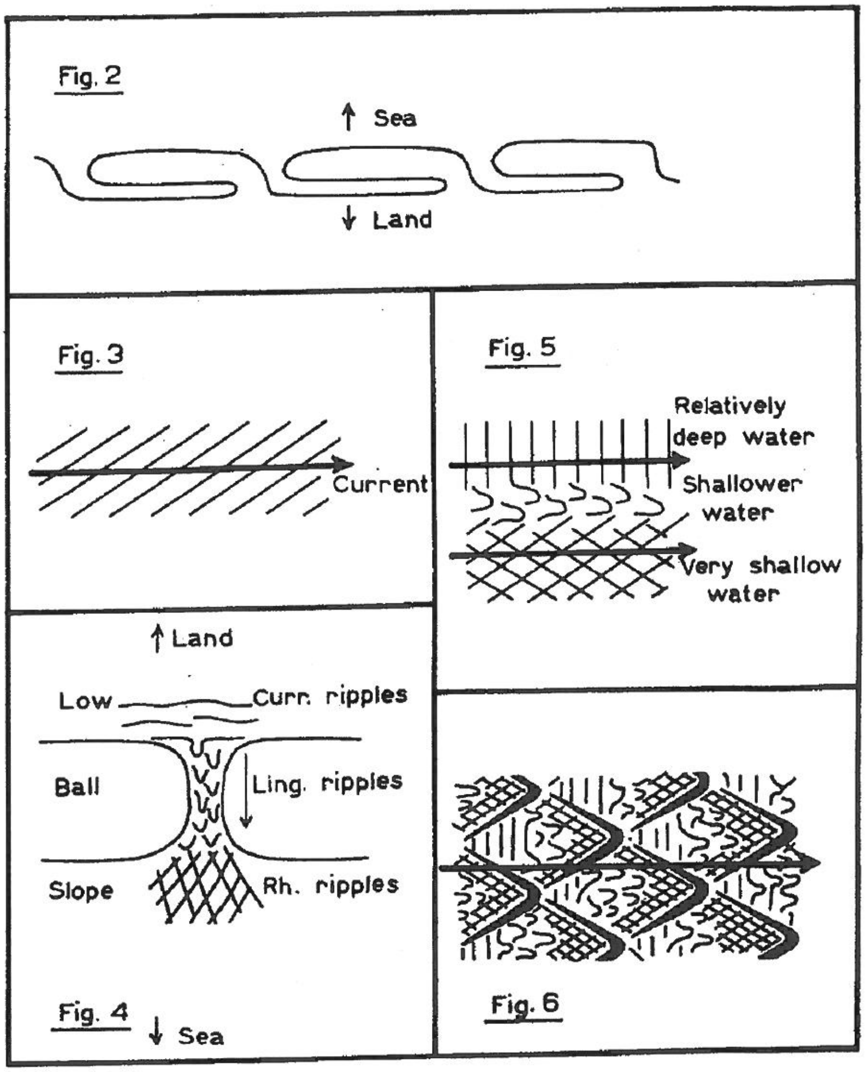


Fig. 2—6. (For explanation see text).

these outlets occur at regular distances from each other. They are eroded by the water that has been accumulated in the lows by the waves breaking over the balls. Strong seaward currents may develop in the outlets, which sometimes extend far into the sea. They belong to the so called "rip currents" (SHEPARD et al., 1941).

currents during the stages of high water. Another factor seems to be of at least equal importance, viz. the direction of the wind during the preceding tides. Along an East-West running beach (like that of Ameland), a westerly wind tends to push the swash water in an easterly direction and a shifting of the watersheds to the West will be the result.

RHOMBOID RIPPLE MARKS

In the sections shown in fig. 1, A-B it is seen that, on the balls, rhomboid ripples are the most abundant of all kinds of markings. This may be perhaps a little surprizing, since these ripples have originally been considered as rather peculiar and rare. The cause is apparently their inconspicuous character. Unless very strongly developed, they will easily escape the attention of most visitors who are not especially on the look-out for these phenomena.

The ripples possess a very flat, rhomb shaped "stoss side" and two steep lee sides. The longer axis of the rhomb corresponds to the current direction. This direction may be marked also by systems of straight groovings. The ripples travel downstream by deposition of material on the lee sides, in the same manner as ordinary current ripples. Sometimes a concentration of comparatively heavy or coarse material is found on the lee sides (ore grains, fine shell detritus). The two lee sides are not always of equal development. Often one set is much less distinct than the other, or even wholly lacking (fig. 3; pl. I, A).

It has been thought that the rhomboidal ripples are typical for the action of backwash on beaches. JOHNSON even named them "backwash ripples". TIMMERMANS noticed that the same ripples occur also on the landward slopes of balls. By the present author they were observed in still other situations, and also outside the environment of beaches along the open sea, e.g. on the bottom of small tidal gullies in the Wadden Sea, in wadi's of the NW Sahara, etc.

The exact manner of formation of rhomboid ripple mark is not yet fully understood. This is not to be wondered at, since it is very difficult to do any measurements of the physical conditions. The water is of very slight depth, which is furthermore not constant but decreases rapidly. The current velocities are high, not constant either and also probably very different between the bottom and the water surface. Finally the ripples develop usually so suddenly that the observer is caught unprepared ever and again.

WOODFORD (1935) supposes that the ripples are the result of rhombic interference patterns of standing waves, developed at current velocities which exceed the critical value $v = \sqrt{gh}$ (h standing for the depth, g for the gravity acceleration). The critical velocity, according to this formula, would be 45 cm/sec for a depth of 2 cm, 38 cm/sec for a depth of 1,5 cm etc. Such conditions are often realized on the beaches. The ripple marks would then be the combined result of (standing) waves and unidirectional flow. WOODFORD does not go into the question of the rhythmic character of the patterns. Very likely one must consider both the effect of waves upon the bottom and the reciprocal influence of the bottom relief on the condition of the water surface. It seems probable at least that, once the rhomboid ripples have been formed, the position of the standing waves is dependent on the ripple relief. The waves would then be located on the lee sides of the ripples, to be displaced slowly downstream together with the migration of the ripples.

The top angle of the rhombs must be the same as that between the two systems of standing waves in the water. This latter diminishes with increasing current velocity.

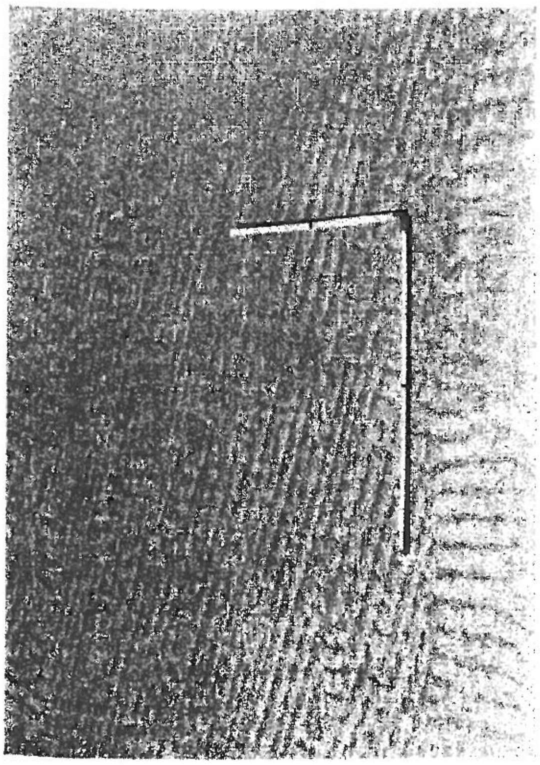
PLATE I

A — Rhomboid ripple marks and transverse current ripples on the top part of a ball. The wave length of the transverse ripples is about 4 cm. The rhomboid ripples show unequal development of the two lee side systems. Current direction towards the left (landward). North Sea beach Hollum, Ameland, 19-V-'52.

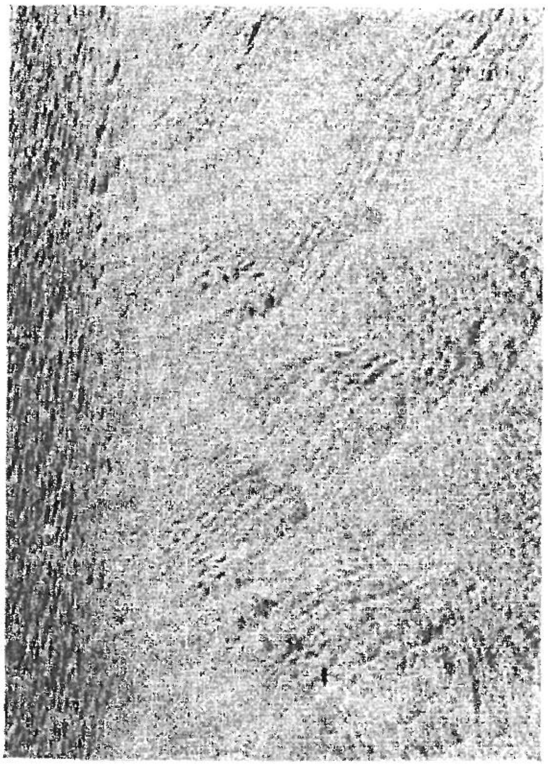
B — Initial stages of rhomboid megaripples on the (gently sloping) landward side of a ball. There is a secondary formation of transverse current ripples and linguoid ripple marks. The ripples are produced by the swash, moving away from the observer. In the background a low is seen, with asymmetric wave ripples. North Sea beach Ameland, near Pinkegat, 10-V-'52.

C — Wind-anti-ripplets with wave lengths of 1,5—2 cm, migrating against the wind, which blows from the right. Newly supplied sand grains have been deposited on the steep stoss sides of the ripplets. The photograph was taken immediately after a strong gust of the wind and the new grains were still dry. The deposition of sand was concentrated in streaks parallel to the wind. North Sea beach, Schiermonnikoog, 6-VII-'52.

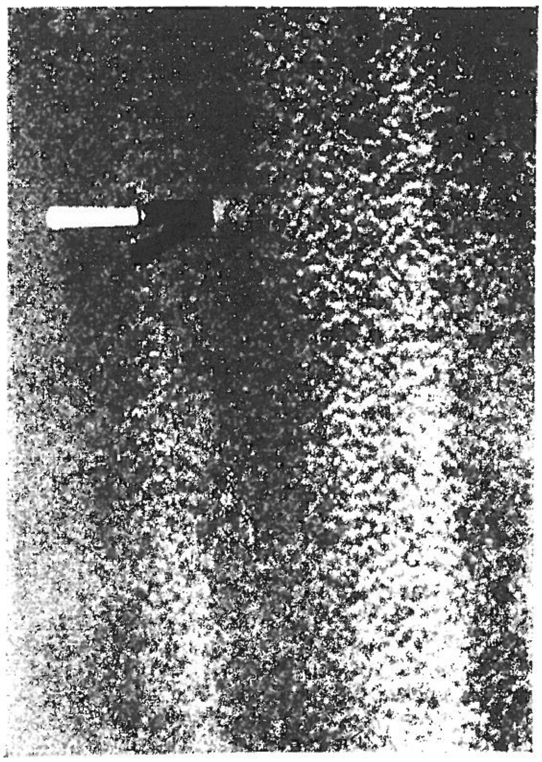
D— Wind-anti-ripplets with wave lenghts of about 1 cm, formed by wind blowing from the left (E). North Sea beach, Hollum, Ameland, 19-V-'52.



A



B



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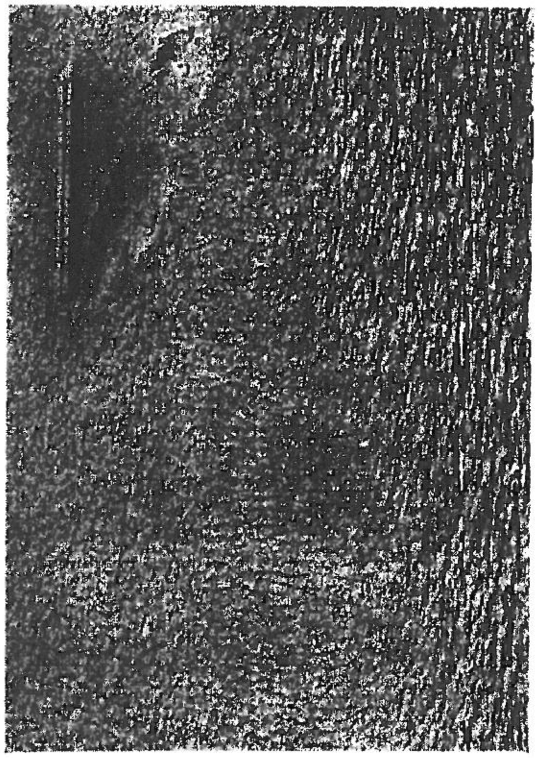

D

WOODFORD and DEMAREST (1947) [4] both found a decrease in top angle downslope, i.e. in the direction in which the backwash is accelerated by gravity. Comparatively steep slopes favour of course high backwash velocities. The beach on which DEMAREST studied his rhomboid ripples had slopes from 6° to 12°. It cannot be concluded reversely, however, as was done by WOODFORD, that rhomboid ripple marks indicate relatively steep slopes, since it

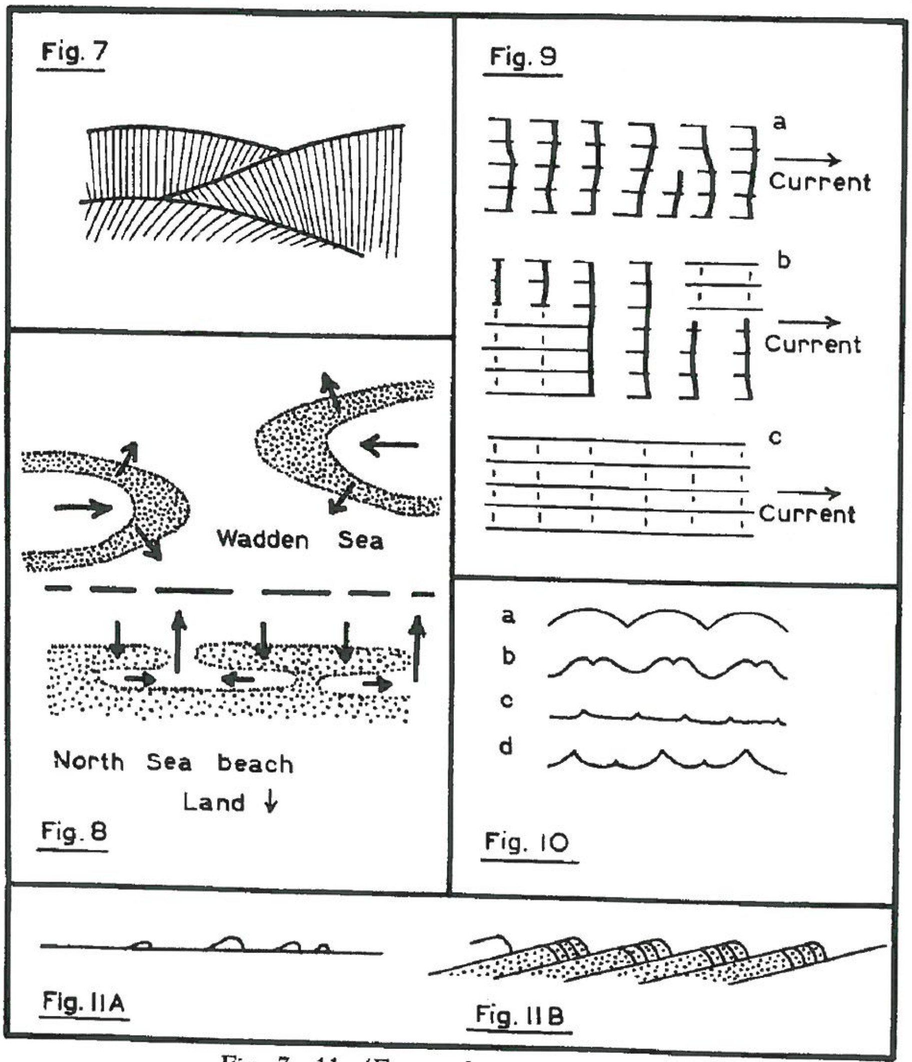

Fig. 7—11. (For explanation see text).

is not at all necessary that the high current velocities are acquired on the place of ripple formation itself. As a matter of fact, the same ripples are abundantly formed on horizontal surfaces (top parts of balls, see fig. 1; bottom of gullies and wadi's). The only necessary conditions for the development of rhomboid ripple marks appear to be: shallow water, rapid flow and a smooth bottom.

Additional insight in the mode of their formation might be gained by the relations to other types of ripple mark near by or at the same places. Instructive cases, observed several times, were those of the ripple distribution in miniature outlets (fig. 4). In the relatively deep water in the low ordinary current ripples had been formed. In the outlet the water was of smaller depth. Here linguoid

[4] DEMAREST claims that the movements of the saturation water in the beach sand have also something to do with the origin of rhomboid ripples. The water of the tip of the swash seeped, in his cases, into the bottom, to be released again, during the backwash, some distance further down the slope. In this way the thin sheet of water was formed, which flowed in the wake of the "true" backwash and in which the rhomboid ripple marks developed. It is not probable, however, that this is the only way in which the necessary thin sheet of water can develop, as was supposed by this author. In his examples the beaches had steep slopes and were composed of very coarse sand, both conditions favouring a comparatively rapid flow of water through the sediment. In the Dutch instances the slopes of the seaward sides of the balls are generally much less steep (in fig. 1, B the maximum angle being only 3°, at 40 m from the Low Tide Line). The sand on the other hand is considerably finer, e.g. 90 % of the grains smaller than 300 to 400 μ.

ripples were present. Where the water had left the narrow zone of the outlet and had spread out in a still shallower layer over the smooth seaward slope of the ball, the linguoid ripples again made place gradually for rhomboid ripples. Similar combinations of these three kinds of ripple mark were found on the (gently sloping) bank of a small low at Terheide aan Zee (fig. 5) and as a superimposed relief on rhomboid megaripples on the beaches of Ameland and Terschelling (fig. 6). A direct relation between the kind of ripple mark and the water depth is apparent and it seems moreover that the transitions are quite continuous, without e.g. a "smooth interstage".

In fig. 1 it is seen that on the smooth surface of the balls the rhomboid ripple marks are often found at the same places as ordinary current ripples. An example of such a combination pattern is shown in pl. I, A. The directions of asymmetry (and of migration) are then the same for both kinds. Linguoid ripples are never observed on these smooth bottoms. Probably this is the consequence of the sheet flow of the water over the balls: the flow lines all lie in parallel, vertical planes. Both rhomboid ripples and transverse current ripples may be formed under such conditions, but for linguoid ripples it is essential that the flow lines can become curved in horizontal (lateral) directions.

Fig. 1 shows furthermore that the orientations [5] of the rhomboid ripple marks do not always correspond with those of the slopes of the balls. The line, dividing landward and seaward pointing [5] ripples lies frequently some distance down the seaward slope. Between this line and the top of the ball the rhomboid ripples point upslope. These ripples are produced by the swash and the fact that they are preserved may be due to two circumstances. Either the backwash, starting at the top of the ball has not immediately sufficient strength to transform them into seaward pointing ripples, or there was no backwash at all in these places, the tip of the swash soaking into the bottom.

RHOMBOID MEGARIPPLES

In former publications it was argued that transverse megaripples ("giant ripples") normally develop from ordinary current ripples by adequately prolonged duration of one and the same process. The experiments by MULLER (1941) show that current ripples have a tendency to increase both in wave length and height. The larger a ripple, the more material has to be transported and the slower its downstream movement will be. A small ripple will therefore advance over a larger one, until their crests coïncide. Then its material is added to the lee side of the larger ripple, thus increasing the dimensions of this latter at the cost of its own existence. It was stated above that, apart from the diagonal position of their lee sides, the rhomboid ripples migrate downstream in just the same way as the ordinary current ripples. It seems likely, therefore, that also the process of megaripple formation is the same for both kinds.

Initial stages of such megaripples are shown in pl. I, B. On beaches they seem to be restricted to the landward slopes of the balls. They are often associated with delta-like extensions of sand over the bottom of the adjoining low. An important sediment transportation is thus indicated, which is well in agreement with the explanation for the megaripples just given.

After the megaripples (or rather, their initial stages) have attained a certain size, the water depths on the proximal parts of the stoss sides will be sufficient for the development of other ripple marks. Often these are ordinary current ripples, but linguoid ripples may also form, as well as combinations of these two (cf. fig. 6). The outer edges of the megaripples, meanwhile, remain covered by (small scale) rhomboid ripple marks.

LONGITUDINAL RIPPLE MARKS

Where very shallow water flows over smooth bottoms, longitudinal accumulations of sediment are sometimes produced. In the Wadden Sea this material usually consists of mud, e.g. in the shape of fecal pellets from molluscs or other organisms. The ridges may be fairly regularly interspaced. This distances between them range, in the different systems, from a few mm up to about 2 cm.

On the North Sea beaches longitudinal forms of a somewhat other character are found. They are of very minute size, with heights not exceeding 1 mm, and show little regularity in interspacing. Often they are noticed only when rendered conspicuous by the concentration of ore grains or fine shell detritus (cf. HAENTZSCHEL, 1939). Instead of ripple marks the terms lineation or striation seem more appropriate. They are frequently found on the smooth surfaces of the balls, where

5 Whenever in this communication mention is made of the "direction" or "orientation" of ripples the direction is meant in which they migrate, or last migrated.

their formation is due either to the backwash or the swash. In the latter case the striations end abruptly on the well known "swash marks" (fig. 7). They have not been indicated in fig. 1.

REGRESSIVE SANDWAVES

It was seen above that in very shallow water, flowing with high velocities, a diagonal pattern of standing waves may originate, causing the appearance of rhomboid ripple mark. In rapidly flowing water of somewhat greater depths the formation of rhomboid ripples has never been observed. Here standing waves frequently develop with their crests at right angles to the current direction. A closer inspection of these waves reveals the fact that they are usually not restricted to a fixed position, but move slowly upstream, at the same time generally augmenting in height. This may go so far that the waves become too steep and break. Then they travel quickly downstream with a diminished height, after which a new stage of slow upstream movement sets in. The phenomenon may be repeated rhythmically during a long time.

The appearance of these waves on the water surface is linked with the formation of "undulations" in the bottom which are called "sand waves". They are well known since the experiments of GILBERT (1914). These showed that in very slow currents no ripples were formed at all. At a first critical velocity ordinary transverse current ripples developed. After increase of the velocity up to a following critical point their formation ended again and the bottom became comparatively flat. Then, by still further increase of the current velocity a third critical value was reached, and "sand waves" were formed. The disappearance of the ordinary current ripples and the subsequent establishment of a smooth bottom surface requires of course a certain lapse of time. In nature, current velocities are often increased very suddenly and it is probable that in such cases the smooth interstage is passed over and that sandwaves develop directly out of the current ripples.

The upstream movement of the waves in the water is linked with a corresponding migration of the sand waves due to the deposition of (generally coarse) material on the stoss sides. The sandwaves are then called "regressive sandwaves". It is not known to the author what happens with the sandwaves in the brief spells of downstream travelling of the waves on the water surface. Probably the effect is quite subordinate to the displacements during the regressive stages.

The sand waves have, in profile, both rounded troughs and crests. Symmetrical as well as slightly asymmetrical cross sections are found. The wave lenghts range, in correspondance with those of the water waves, from a few cm to about one meter. Their height is mostly small, e.g. 1/50 of the wave length, but may be much more. Sometimes the crests of the sandwaves grow even considerably above the level of the water in the troughs.

Regressive sandwaves are abundantly formed in the outlets of the lows on the North Sea beaches. In these places, however, they have to be observed during the formation itself. As BUCHER states (1919, p. 177): "Sandwaves, in this sense, can not exist with velocities smaller than those creating them. With a decrease of velocity they either disappear or are transformed."

Yet elsewhere on the beaches forms are abundantly seen which present all characteristics of nearly untransformed sand waves. Here the water disappears so quickly from the place of formation that no opportunity for transformation is left. These ripples are found on the seaward and landward slopes of the balls (see fig. 1). Their wave length is usually a few decimeters; their height is small (0,5—1,5 cm); the crests and troughs are well rounded. They are produced by the rapidly flowing water of the backwash and also by the swash as it descends on the landward sides of the balls. Their formation is connected with the appearance of transverse standing waves (cf. the photographs given by TIMMERMANS (1935, pp. 374—375) who first described these ripples). These waves are of a somewhat different nature than those in the water of gullies and outlets. There is scarcely question of wave troughs: only separate crests are seen which rise from an otherwise plane surface. The time of formation is usually very short and in consequence it has not yet been established with certainty in what direction the waves and ripples migrate.

SYMMETRIC WAVE RIPPLES, ASYMMETRIC WAVE RIPPLES AND ORDINARY CURRENT RIPPLES

Where normal waves act on a horizontal bottom, symmetric wave ripple marks will be produced. When the waves reach the shore and the water becomes shallower, they become asymmetrical, the shoreward movement of the water particles being stronger than the

TABLE I — BEACH NES, AMELAND

Date (1952)	8-V	8-V	8-V	8-V	9-V	7-V
Distance from L.W. line ...	38 m	69 m	96 m	49 m	100 m	50 m
Wave length	40 mm	70 mm	100 mm	110 mm	100 mm	110 mm
Height	1,5 mm	4 mm	8 mm	11 mm	12 mm	22 mm
Asymmetry [1]	—	—	—	0.82	—	0.69
h/λ	0.04	0.06	0.08	0.10	0.12	0.20
Situation	Top of ball	Slope of ball	Low	Low	Low	Low
Direction	Landw.	Seaw.	Landw.	Landw.	Landw.	Landw.
Associated ripples	Rhomb.r.	Rhomb.r.	—	—	—	—

[1] Length of stoss side divided by wave length.

backward movement. Then asymmetric wave ripples will be the result, which have their steeper sides pointing up the slope (AYRTON, 1910; EVANS, 1941, 1949). On the beaches the waves give rise to swash and backwash: more or less shallow sheets of water, flowing up and down the slope. The movement herein is that of normal unidirectional currents and ordinary current ripples may be produced (EVANS, 1940; KUENEN, 1950). Thus, between purely symmetrical wave ripples on the one hand, and true current ripples on the other, a continuous series of transition stages exists.

Fig. 1 shows that ripples of this series are abundant on the beaches, both in the lows and on the balls. On the latter they occur often together with rhomboid ripple marks. Both kinds then have the same orientation [6] and their heights and wave lenghts are approximately equal (cf. pl. I, A). Here they are formed by the swash or backwash movements: they are true current ripples with a high degree of asymmetry.

In the lows the oscillation character is more pronounced: more symmetrical cross sections are found and they are moreover of greater dimensions. The ripple directions [6] in the lows are generally landward. At the foot of the seaward slopes of the balls, on the contrary, the ripples have mostly a seaward direction. The two may be separated from each other by a transition zone with symmetrical ripples (e.g. in fig. 1, A at 72 m from the low water line; in fig. 1, B at 78 m).

The ripples on the balls and those in the lows often differ in yet another respect, namely their relative height. Ordinary current ripples, such as are produced in currents of normal velocity and depth, have a height which is generally about one tenth on the wave length. On the balls much smaller values are often found, while in the lows the contrary may be seen: table I.

Apart from a formation by the action of waves, swash and backwash, with movements at right angles to the beach, the same types of ripples may originate in other ways. The waves, coming from the sea are often affected by the bottom relief in such a way that secondary wave motions are produced which deviate considerably from the original direction normal to the shore. Furthermore, wind may raise new waves in the water of the lows itself. Thus other wave ripples are formed, both symmetrical and asymmetrical, with wave-lengths from about one decimeter down to one centimeter. The smaller ripples are usually superimposed on other ones of greater size.

Ordinary current ripples, which have their crests transverse to the direction of the lows, are also of great abundance (fig. 1). They are produced by the currents in the lows, parallel to the beach, and their steeper sides are mostly directed towards the outlets.

TRANSVERSE MEGARIPPLES

Often the currents through the lows are strong and of long duration. In such cases transverse megaripples tend to develop, always with their steeper sides away from the watersheds, in the direction of the outlets. It was described previously (VAN STRAATEN, 1950) how the transverse megaripples in the ebb and flood channels ("scharen") of the Wadden Sea and similar environments elsewhere always point towards the closed ends of these channels (fig. 8). In these "scharen", however, the dominant current direction is towards these closed ends and the water flows off over the shoals. In the case of the lows and balls, the currents are fed by water pushed over the shoals, and the water flows down the lows towards the outlets (fig. 8).

The considerable transport of sand through

[6] Cf. note 5, p. 37.

the lows, indicated by the presence of the transverse megaripples is made possible by a strong supply from the sea, over the balls. By the rip currents, mentioned above, the material is carried out again into the sea. Thus a more or less closed circuit is established and it is not astonishing when, notwithstanding the dominantly landward transport of sand by the waves, very stable positions of lows and balls are reported (TIMMERMANS, 1935).

LINGUOID RIPPLE MARKS

Linguoid ripples are usually formed in very shallow water, flowing with moderate velocities. They may originate directly on a smooth bottom, but also by transformation of already existing surface patterns. Where ordinary transverse current ripples have been formed and the water depth is subsequently reduced, so far that the crests of the ripples are about to be uncovered, linguoid ripples may develop, provided of course that the flow of water continues. The water may then still be passing over the crests, but the flow is concentrated through gaps and lower places, which become widened by erosion. Immediately downstream of these troughs with concentrated flow, cutting across the current ripple crests, the flow lines diverge; sediment is dropped and miniature delta's are built up. After a certain interval the original current ripple relief may have been transformed in this way into a new type of regular pattern: that of the linguoid ripples. The small delta's are arranged along two directions, diagonal to the general current direction. The flow lines diverge over each delta, to be concentrated again towards the next troughs. The flow lines as seen from above are not straight, but sinuously curved. In the troughs, moreover, the water particles may describe helicoidal movements around axes lying in the current direction. The delta's migrate downstream by the deposition of material at the lee sides (and, of course, the simultaneous erosion in the troughs and proximal parts of the delta-stoss sides).

Transformation of current ripples into linguoid ripples is frequently seen when lows have run dry for the greater part, during the falling tide. The patterns however are seldom very regular, since each delta tends to develop individually.

Linguoid ripples may also be formed by increase of water depth, namely by transformation of rhomboid ripple marks. As pointed out above these latter usually show systems of groovings parallel to the current direction. When the water level is only slightly raised, these groovings may deepen considerably, especially those along the longer bisectrix of the rhombs. Then an important concentration of flow lines in these groovings will be the result, especially on the proximal parts, while they diverge again towards the distal parts of the rhombs. The flow lines acquire sinuous shapes and the ripples change gradually into linguoid forms. The diagonal systems of standing waves which (in all probability) cause the rhomboid pattern of ripple marks, give place to more or less diagonal systems of lee side vortices, which have no longer anything to do with high current velocities but are only dependent on the development of the small ripple delta's. Examples of linguoid ripples, formed in this manner, are also abundantly met with. Their patterns may show greater regularity than those developed out of current ripples.

It might be thought that if rhomboid ripple mark changes so easily into linguoid ripples, the reserved phenomenon will also be of general occurrence. This is not the case, however. Where either linguoid or other ripples of relatively pronounced relief have been formed, rhomboid ripples cannot develop. A smooth condition of the bottom is necessary for the formation of these latter.

LONGITUDINAL WAVE-CURRENT-RIPPLES

Transverse current ripples are the normal product of unidirectionally flowing water. When waves are propagated through this water in the direction of the current, the ripples may undergo a change in asymmetry and height, but the general pattern is unaltered and the crests remain at right angles to the stream. The same applies to cases in which waves travel in exactly the opposite, upstream direction. Where the waves move in directions oblique or transverse to the current, however, a new type of ripple mark can be formed; the longitudinal wave-current-ripples (VAN STRAATEN, 1951). These ripples have conspicuously long and straight crests, which are parallel to the current, whatever the direction of the waves may be. The material of the crests is accumulated by the oscillation due to the wave action. The distances between the crests depend on the properties of the waves and on the water depth. The cross sections are either symmetrical or asymmetrical, in connection with the character of the waves. The symmetrical ripples are stationary.

These ripples are often found in the same area as transverse current ripples. The crests of both kinds then are always exactly normal to each other. The following combinations have been observed:

1. Most ripple marks in the area were of the ordinary current ripple type. The longitudinal ripples occupied those places which were relatively sheltered for the current, but not for the waves (e.g. downstream of mussel beds in the Wadden Sea environment).
2. The transverse current ripples were limited to the deeper places, the longitudinal ones to comparatively elevated parts. Probably the ripple distribution was caused by the fact that from the water surface downwards there is a more rapid decrease in oscillation amplitude than in current velocity.
3. The hydrodynamical conditions were favourable for the formation of transverse current ripples. In those places however where their development was made impossible because of the too muddy composition of the bottom material, longitudinal ripple marks were found instead.

In the Wadden Sea the longitudinal wave-current-ripples are extremely common. On the North Sea beaches they are much less frequently encountered. An instance was observed on the beach at Nes (9-V-'52, see fig. 1, 70 m from the low water line). Here the crests were parallel to the direction of the low in which they were formed. The wave length was 6 cm, the cross sections symmetrical, or slightly asymmetrical, with the steeper sides in the landward direction.

COMPLEX PATTERNS

The transverse current ripples and the longitudinal wave-current-ripples, treated above, are often found at one and the same place. A complex pattern is then present, in which the two types of ripple marks may be of equal development, or in which one type dominates over the other, see fig. 9.

On North Sea beaches such combinations are observed from time to time. They are probably less common than on the bottom of the Wadden Sea.

Other complex patterns are formed when two crossing systems of waves pass through a body of (standing) water. These patterns are known as interference wave ripple marks. They are rather common in the lows on the North Sea beaches, especially where steep banks favour the reflection of waves.

Complex patterns are produced also asynchroneously, by superposition of new systems of ripple marks upon pre-existing ones. Because of their more accidental character they will not be treated here.

METARIPPLES

The term metaripples was suggested by BUCHER (1919, p. 181) to denote those "Large ripples" which are not formed directly, but which represent the transformation product of "sandwaves", the transformation resulting from the decrease of an originally high current velocity. These ripples correspond to the "giant ripples" or "transverse megaripples" described by the present author. In the latter's opinion at least the majority of these transverse megaripples has n o t originated by this type of transformation. However, there seems to be no reason to drop the term metaripples itself. On the contrary, it may be applied successfully to a great diversity of surface forms, produced by subsequent modification of earlier ripple marks.

Strictly speaking, most ripple marks which are found exposed on the beach after the water has withdrawn, could be considered as metaripples, since their uncovering usually goes together with small changes in shape: a slight sagging of the crests, small scale erosion phenomena etc. When no essentially new, regular relief forms are produced, however, they will not be treated separately.

True metaripples in the above sense are the forms, described by EVANS (1943, 1949) as the consequence of a diminishing in wave size. Some typical cross sections of such transformed wave ripples are given in fig. 10. Type *a* has been observed a few times on the beach. The kinds *b*, *c*, and *d* are not uncommon on the tidal flats in the Wadden Sea. It was not especially investigated whether they occur also on the North Sea beaches. Probably they will be found occasionally, although they may not be very abundant.

Double-crested ripples of a somewhat different shape from that of fig. 10 b were seen in a low on the beach at Nes. Here they had developed from asymmetric, swash-formed ripples (with their steeper sides towards the land) by transformation due to waves which were produced directly by the wind in the water of the low itself and which travelled in the opposed, seaward sense.

BEACH CUSPS

Beach cusps are mostly seen on comparatively steep beaches, with a coarse (gravelly) composition of the bottom sediment (GUILCHER, 1949). Along the Dutch coast with its gently sloping, sandy beaches, they are not very common, and, if present, only of small elevation. A few photographs of such Dutch examples were given by TIMMERMANS (1935). The present writer cannot add any new information regarding these phenomena.

WIND RIPPLES AND SAND DUNES

Wind ripples are mainly restricted to the backshore, where the sea comes only rarely, during very high tides and strong (landward) gales. Under normal circumstances the surface is here quite dry, a necessary condition for the formation of these ripples.

According to BAGNOLD (1941) their wave length increases with the wind velocity, their height and shape depending on the grading of the sand. These rules hold at least for equilibrium conditions, in which, at a given place, the supply of sand equals the removal "downstream". No new observations were made concerning these ripples.

Besides wind ripples also small sand dunes are usually present on the backshore. Both longitudinal and transverse dunes are encountered. The longitudinal forms are mostly very flat. The transverse dunes which may have typical barchan-shapes are higher, usually a few decimeters. The maximum height observed by the author was just over one meter (measured on the wide backshore N of Hollum, Ameland).

The wind ripples on the crests of these dunes show generally a greater wave length than those along the base, probably in correspondance with higher wind velocities. The formation of the dunes has nothing to do with a development out of small ripples, in the way of subaqueously formed transverse megaripples. When the wind ripples have attained their equilibrium wave length in relation to the wind velocity, they do not increase in size any further.

ANTI-RIPPLETS

A kind of ripple mark which, as far as the author is aware has not yet been described before, is rather commonly seen on the North Sea beaches. The crests of these ripples are at right angles to the wind. The cross sections are very asymmetrical, with the steeper sides facing the wind. The wave length may range from a few mm to about 2 cm; the height probably never surpasses 2 mm. Because of these small dimensions and the upstream orientation of their steep sides, the name (wind-) anti-ripplets seems appropriate.

Ripplets of this kind were seen to originate where a sand-laden wind passed over smooth, moist sand surfaces. The crests migrated against the wind. This appeared to be the consequence of the deposition of new sand grains, supplied by the wind to the stoss sides. Once deposited, these new grains became very soon moistened by capillary attraction of the water from below. In this way they adhered to the surface and were not removed again during subsequent stages. Since the wind blew irregularly, with occasional strong gusts, also the migration of the ripplets had an irregular, jumpy character. The photograph pl. I, C was taken immediately after such a gust of the wind. The freshly deposited grains, concentrated in streaks parallel to the wind, had not yet been moistened and show up in a light colour. The development and migration thus seemed to be mainly the result of deposition (fig. 11, B). Erosion phenomena were, at most, of a quite subordinate effect. In this respect the ripplets differ fundamentally from, for example, transverse current ripples, where deposition (on the lee sides) is always more or less in equilibrium with erosion (on the stoss sides).

Since the formation of the ripplets is dependent on the moistness of the surface, they are not found on the high parts of the beach, above the high tide level. The surface here is usually too dry and the sand grains cannot adhere to it. Only ordinary wind ripples can develop. On the lower parts of the beach, on the other hand, well below the high tide level, the surface is often too wet. Initial stages of ripplets, in the shape of small, isolated ridges, may be formed, but immediately afterwards these ridges will sag together, owing to the soaked condition of the underlying surface. The most favourable places for the formation of the ripplets are usually found just below the high tide line (cf. fig. 1, A).

Since on these places, to say the least, deposition largely dominates over erosion, the surface must be slowly rising. As a matter of fact this was easily demonstrated. Matches, which were stuck into the ripplets, with their upper ends just touching the surface, were soon buried by new sand. It is clear that the upward growth of the surface requires also a slight upward movement of the ground water. Otherwise the freshly supplied grains would not remain stuck. It is not impossible that the water in the bottom has also a regulating effect upon the height of the ripplets. The rising water will sooner attain the top of a low crest than that of a high one. At the tops of the high crests the possibilities for the new sand grains to adhere are therefore relatively reduced and they will not grow so quickly as the lower ripplets.

Between the initial stages of the ripplets and the full grown forms rather large differences exist. The initial ripplets are little more than small, isolated rolls of sand, formed at comparatively irregular interspaces (fig. 11, A). The full grown stages on the other hand show regular distances between the crests and a pronounced difference between a steep stoss side and a very flat upper side. The crests are mereover of greater length. Ripplets of a still more regular character were seen on the beach of Hollum (Ameland) (pl. I, D). They occurred in sand which had become incrusted with salt, due to the evaporation of ground water. Unfortunately no migration of crests or other changes could be noticed. Probably the formation process had already ended at the time of observation. It does not seem unlikely, however, that these ripplets were at least partly the result of a process in which erosion dominated over deposition, that is, of the reserved conditions as were responsible for the cases treated above. It might be, also, that they were originally produced during a stage of dominating deposition; that the incrustation with salt subsequently prevented the movements of the bottom water, so that no more sand grains could remain stuck to the surface and that the existing relief was further modified by erosion.

Many more data have to be collected concerning these phenomena before it can be attempted to offer a reasonable explanation for their origin and rhythmical properties. [7]

[7] Ripplets of similar shapes occur in snow. After the snow fall of 31 Dec. 1952 they were seen in many places in the area between the Hague and Leyden (2 and 3 January). Their steeper sides pointed against the wind; their wave lengths varied from 3 to 7 cm, their heights from 1 to 2 mm. Unfortunately the author was unable to ascertain whether the ripplets had been formed during the snow fall itself or by later wind erosion. The following meteorological data from Valkenburg (Z.H.) (kindly communicated by the K.N.M.I. at De Bilt) may be of some interest: *31 Dec. '52, 9h00—21h00:* Rather continuous, light to moderate snow fall; wind velocities 7½—11 m/sec; atmospheric temperatures —1° C; Dew point temperatures —1 to —2° C; *31 Dec. 1952, 21h00 — 2 Jan. 1953, 9h00:* No appreciable precipitation; wind velocities 2—7½ m/sec; athmospheric temperatures —1 to +2° C; Dew point temperatures —2 to 0° C.

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