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ART. XV.—*On Ripples and Related Sedimentary Surface Forms and their Paleogeographic Interpretation*; by
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PART II. FOSSIL RIPPLES AND THEIR PALEOGEOGRAPHIC INTERPRETATION.

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In the following pages, a number of deductions concerning the paleogeographical interpretation of ripples are presented which seem to follow from the data presented in the first part of this paper. (See the March number, pp. 149-210, including Bibliography.)

INTRODUCTION.

The question, why one or the other type of ripples is not found in a certain sediment, recurs frequently in the following discussions. The answer is always: Either it was not formed or not preserved. While the conditions necessary for their formation are different for the various types of ripples, those favoring their preservation are the same for all. They must all, soon after their formation, be sufficiently covered with sediment settling on them from above¹ (see pp. 156 and 185).

1. In the sea, in rivers and in air, most of this sediment is supplied by a local stirring of the bottom through storms and currents, throwing some sediment into suspension which, when carried by upper currents, settles into quieter layers below. In a sediment too coarse to be carried any distance in suspension, when stirred, this process becomes ineffective.

2. The sediment thus thrown into suspension in the air, may settle in the water of the sea, lakes or of rivers.

3. The load carried by rivers and streams into seas and lakes, reaches the bottom in an unceasing rain of particles.

4. Also, in both water and air, the volcanic sands and dust, ejected during an eruption, locally play a rôle.

Thus, if covered soon enough, even the most transient features may be preserved, like the tracks of flitting crustaceans, the marks left by the trailing arms of a jelly-fish, oscillation-ripples formed during still-water between the tides, or current-ripples produced by an exceptional wind-drift on sediments not ordinarily reached by currents. The shorter the time during which the formation of any of these surface marks is possible, and the rarer the recurrence of conditions favorable for it, the smaller is the probability that they will be preserved.

I. OSCILLATION-RIPPLES.

1. *Description.*

Fossil oscillation-ripples cover the same range of sizes and forms as those found in present waters.² The sharp

¹Page references in the text refer to Part I in the March number. In cases where references to authors are given, see the Bibliography on pp. 209, 210.

²Giant ripples, such as suggested by Gilbert (Ripple-marks and cross bedding, Bull. Geol. Soc. Amer., vol. 10, p. 135-139, 1899), can not be formed directly by wave action. Gilbert's interpretation was refuted on other grounds by Fairchild, (Beach Structure in the Medina Sandstone, Amer. Geologist, vol. 28, pp. 9-13, 1901).

crests in contrast to the broad, rounded troughs, often with a minor ridge in their center, which, of course, never appears on the crests, render these ripples especially valuable for the distinction between the upper and lower surfaces of strata in structural work.—(Cf. p. 184.)

2. Interpretation.

The following points bear on the paleogeographical interpretation of oscillation ripples:

1. The presence of oscillation-ripples in a sediment implies complete *absence of horizontal currents* at the time of their formation.

a. Water bodies, in which sediments showing no other but symmetrical ripples were laid down, must have been practically free from currents of any kind. The two types of currents which alone would produce on a larger scale ripples in standing bodies of water, are tides and wind-drifts. The effect of the latter decreases rapidly with depth; it is probably limited to the upper 50 m. of the neritique zone of the sea.³ The insignificance of the tides in enclosed parts of the sea as well as in lakes is well known. The Baltic, the Black Sea, the largest part of the European and American Mediterraneans have tides negligible for our purposes;⁴ some, like the Black Sea, none at all.⁵ *Ripples cannot, therefore, be used to distinguish marine and lacustrine sediments.*

A sediment like the Berea Sandstone, which consists largely of fine-grained, almost pure quartz sand and abounds in oscillation-ripples without a trace of current-ripples,⁶ may therefore have originated either in a lake or in a sea free from tidal currents.

A study of map No. 20 of Berghaus' "Atlas der Hydrographie" shows that, so far as recorded, all epicontinental seas which are in open connection with the ocean have rather great tidal ranges and therefore are agitated by tidal currents. In open bays the range is invariably increased. It is only in landlocked bodies of water that

³ "District littoral" of Pruvot (cf. E. Haug, *Traité de Géologie*, 1911, p. 87); "littoral region" of Schuchert (*Historical Geology*, 1915, p. 490).

⁴ Cf. Kruemmel, *Handbuch d. Ozeanographie*, vol. 2, pp. 304 ff., 1911.

⁵ Kindle, in making the generalization that oscillation-ripples are generally found on lake bottoms and current-ripples on sea bottoms (1917, p. 49; see Bibliography, Part I), overlooked the fact that the coast of Nova Scotia with its strong tides offers by no means typical or average conditions for all marine shores or the sea bottom at large.

⁶ J. E. Hyde, *Jour. Geology*, vol. 19, pp. 258-269.

the tide is sufficiently low or lacking entirely. We are, therefore, justified in concluding that the body of water in which, for instance, the Bedford-Berea sediments were laid down, was not in free communication with the sea. That the Mississippian embayment, farther west, had tides is proved by the presence of very large current-ripples, measuring about 180 cm. from crest to crest, in the lower part of the Burlington in southeastern Louisa County, Iowa.⁷ Since sedimentation was probably continuous in this region, the difference in time between the two deposits can not form a serious objection.

b. Occurrence of oscillation and current-ripples in the same formation, on the other hand, indicates deposition alternatingly in quiet water and under the influence of currents (of water or of air). Favorable conditions for such a combination of processes exist:

(1) In shallow seas with tidal currents and wind-drifts⁸ alternating with periods of quiet.

(2) On tidal flats, especially on irregular shores with lagoons and pools.⁹

(3) On alluvial plains where floods leave stagnant lakes, and dust and sand are blown about by the wind, especially in arid regions, where the rivers end in shifting, shallow lakes surrounded by dunes (e. g. Lob-Nur in the Tarim Basin).

In general, the last case offers by far the best chances for the preservation of both types of ripples, especially the large flood plains of semi-arid regions, where the wind, at the approach of the dry season, buries the ripples in stagnant lakes and along the water courses under clouds of silt and sand.

There are practically no data on hand for a comparison of the relative frequency of the two types of ripples in different formations. In a quarry of red Triassic "Buntsandstein" in the German Palatinate, 15 of 23 slabs show symmetrical, the others asymmetrical ripples. (Berthology 1900, p. 181.) A terrestrial origin of this part of the Buntsandstein is almost universally assumed.

⁷ J. A. Udden, *Jour. Geol.*, vol. 24, pp. 123 ff., 1916.

⁸ For a discussion of the effect of wind drifts on tidal currents see W. H. Bucher, *Proc. Nat. Acad. Sci.*, vol. 3, p. 288, 1917 and Chapter III of this paper.

⁹ Oscillation-ripples formed on shores where the tides are high and tidal currents strong, were, for instance, described by Brown, 1911 (Coast of Labrador), and Cornish, 1901 (English Coast).

2. The following relations exist between the dimensions of a water-body and the oscillation ripples formed in it:

(a) A ripple of a given wave-length owes its formation to an oscillating current of definite velocity. The size of the water wave which sets up the oscillation determines the depth at which this velocity would exist and be effective. The relation is very complex and not known quantitatively. As the orbital velocity of the particles of water decreases with depth, we may state in a general way that the greatest depth at which the velocity necessary for the formation of a given set of ripples is found, is the greater the larger the waves creating it.

Any set of oscillation-ripples may, therefore, have been produced in shallow water by smaller, or in deeper water by larger waves.

As was demonstrated by Kindle's observations (p. 188), there exists also a minimum depth for each size of ripples. For each size of oscillation ripples there must exist, therefore, a range of depth within which it may form. This range is very large for small ripples. I have frequently observed oscillation ripples with 1, 5 cm. wave length on the silt of floodplains of the Ohio and Little Miami Rivers, in places where the water could not possibly have been more than a few cm. deep. Udden¹⁰ observed ripples of 6 mm. wave-length in a small water pool in a hollow of the surface of a rock, at a depth of water of but 1 to 2 cm. Siau found oscillation-ripples of small size at the depth of 188 m. off the island of Bourbon. They may form, and certainly do, at any time at any depth in between. From very small ripples, therefore, no inference of any kind can be drawn concerning the dimensions of the waterbody in which they formed. Of statements based on such insufficient evidence, I quote only that of Zimmermann.¹¹ He found small ripples of a little less than 2 cm. wave-length on one of the layers of salt separated by very thin laminae of anhydrite in a drill core from the Zechstein of Hesse. From this he concluded that these ripples could have formed only under a very thin cover of water, perhaps but a few decimeters

¹⁰ J. A. Udden, *Jour. Geol.*, 1916, p. 123.

¹¹ E. Zimmermann, *Steinsaltz mit Wellenfurchen von Schlitz in Hessen*, *Zs. Deutsch. Geol. Ges.*, vol. 60, Monatsber., p. 70, 1908.

deep. They might, of course, have formed just as well at a depth of 100 meters or more.¹²

The range of depth at which ripples may form is, on the other hand, limited for the largest ripples, as the minimum depth is rather great and the maximum small. From the scanty data in table V the former seems to measure a few meters, while the maximum depth is most likely to lie within the littoral region or the upper 40-50m. of the neritic zone of the oceans.

(b) Owing to the fact that the largest ripples possible in one locality have by far the best chance to be preserved, a gradual decrease in the average wave-length of ripples of a sedimentary series should be expected in the direction towards deeper water. The absence of such a decrease over great distance offers a valuable *evidence of uniformity of depth*.

(c) The depth to which the action of waves is felt, that is, the depth of the wave-base, depends on their size, and this, in turn, is determined largely by the fetch of the wind. For each given diameter of a body of water there exists, therefore, a maximum depth to which wave action may extend. For the ratio of *depth* to *width* of the basin, measured along any line, the term "form ratio"¹⁴ might be used. For each basin there exists a minimum and a maximum form ratio, measured along the shortest and the longest diameter. If the latter rises above a certain value, which is different for different widths, a part of the bottom will never be touched by the wave action.¹⁵

On the other hand, if the area of a bay, lagoon or lake is known to have been small, the possible range of the depth at which the largest ripples found in its sediments may have formed, is reduced considerably.

Along the shores of the small, shallow ponds of our parks, on which but small waves can form, ripples are

¹² The same is true, for instance, of small ripples observed in cannel coal (Upper Stinson coal) in Kentucky; cf. White and Thiessen, *The origin of coal*, Bureau of Mines, Bull. 38, p. 42, 1913.

¹³ Note omitted.

¹⁴ This term is used by Gilbert (1914, p. 36) for the ratio of the *depth of stream* to the *width of channel*.

¹⁵ Systematic observations on the vertical distribution of oscillation-ripples on carefully selected portions of the bottoms of various water bodies, might yield valuable data concerning the depth of wave-action, especially if combined with extended measurements of the waves themselves. The photographic camera could probably be adapted to this purpose and lateral illumination be used to distinguish oscillation-ripples.

commonly found but close to the shore. Within half a meter from the shore they disappear at depths measuring in centimeters. On the shores of Lake Geneva, Forel observed ripples down to a depth of nearly 9 meters, which can represent but a relatively narrow zone, as the mean depth of the lake is 154 m.¹⁶

In all sediments deposited in basin-shaped depressions, especially in smaller, more or less enclosed arms of the sea, or bays, such as for instance the sea of Azof, or in lakes, we should expect to find the ripples restricted to a relatively narrow marginal zone, because of too large a form ratio. This explains why lacustrine sediments ordinarily do not show any ripples at all.

It is probable that a compilation of numerous observations on presence or absence of ripples in elastic formations in favorable cases might yield positive results concerning the general trend of the shore line. According to Daly, for instance, ripple marks are absent from the very fine-grained quartzites of the Creston formation of the Purcell Mountain System, while "elsewhere within the Boundary belt these markings were found."¹⁷ Cases like this deserve consideration in detailed stratigraphic studies. The stratigraphic position and dimensions of the ripples of many formations deserve as well a place in the field geologist's notebook as fossils.

(d) There are two observations of ripples on record, which, so far as I know, seem to imply *true shore conditions*,¹⁸ and therefore are of special interest to the paleogeographer. Dawson¹⁹ figures a "rippled surface in Potsdam Sandstone with marks of worms or molluscs arranged in the hollows of the ripples. The marks are simple trails, of that curious circular or chain-like form sometimes observed, and seem to have been made by animals creeping in the furrows between the ridges of the ripple-marks." It is of no little interest to see very similar if not identical tracks confined in the same way to the troughs of ripples figured by Stuchlik (1906; table 8, fig. 3) from the Oligocene Molasse Sandstone of Lechbruck (foot of Bavarian Alps). The conclusion seems to be unavoidable that the animals were concentrated in

¹⁶ A. Supan, *Grundzuege d. phys. Erdkunde*, 1911, p. 753.

¹⁷ Geol. Survey, Canada, *Memoir* 38, Pt. I, p. 123, 1912.

¹⁸ Not necessarily marine, of course.

¹⁹ J. W. Dawson, *On burrows and tracks, etc.*, Q. J. Geol. Soc., London, vol. 46, p. 611, fig. 14, 1890.

the troughs by the receding waters which exposed the crests.

3. The relation existing between the trend of oscillation-ripples and geographical conditions, too, offers a highly complex problem. In practical application it presents itself in this form: Why do the ripples of one formation show a pronounced parallelism, while others do not?

In the case of parallel ripples, others were either not formed or not preserved.

(a) That they were not formed might be due (1) to practical absence of winds from other directions, as under trade wind or monsoon conditions; or (2) that only waves from one direction "touched bottom."

(b) Of the factors favoring the preservation of ripples, outlined, only one may have a selective effect.

If the form ratio of the waterbody is such that only the largest waves stir the bottom sufficiently so as to provide the sediment with which to cover and preserve ripples, the bottom is, for long periods, exposed to the rippling action of the smaller waves. The smaller ripples formed by them, however, will not ordinarily be preserved, because they are nearly always replaced by the larger ones resulting from the action of the exceptional waves. According to Forel's experiments, these, on the other hand, will not be changed, either in wave-length or orientation, by minor agitations of the sea-bottom differing in direction up to 45° from their own and, consequently, are by far the most likely to be preserved.

Along any coast facing the open ocean, the direction from which the largest waves come will always be more or less at right angles to the shore. Even if the direction of greatest fetch of the wind should differ considerably from that of a right angle, the waves would break so far from the shore as to turn them into such a position in shallower water.

In shallow seas of relatively uniform depth and small form-ratio, the bottom of which is reached practically everywhere by most waves, such as probably yielded the largest part of our marine sedimentary record, this breaking and turning of the wave-front is confined in its effects to but a very narrow zone. Throughout the largest portion of the sediments of such large or small embayments and gulfs the length of fetch of the wind would

largely determine the position of the largest water waves and the ripples resulting from them.

4. We are now in a position to discuss the interesting case of the ripples in the Bedford and Berea formations at the base of the Mississippian section of eastern and central Ohio, which were so well described by Hyde.²⁰

The facts entering into this discussion may be summarized as follows:

(1) Where the ripples are most typically developed, both formations consist of fine-grained sandstones interstratified with more or less shaly portions.

(2) The beds are from less than one inch to at most two or three feet thick.

(3) The individual layers are not persistent, pinching out and reappearing at different levels, much like the limestones of the limestone-shale series of the Cincinnati at the type locality.

(4) Where typically developed, almost every layer is rippled.

(5) Only oscillation-ripples are present.

(6) Most of these ripples trend very nearly N 53° W, with subordinate variations in both directions covering an extreme total range of 69°.

(7) Occasionally, smaller ripples intersecting the larger ones at right angles or nearly so, are found.²¹ Only one case of typical interference pattern, produced by the intersection of equally large ripples, has come to my knowledge.

(8) These ripples were observed over an area 115 miles long and 20 miles wide.

From observation (5) we have already concluded the absence of tidal or wind-drift currents from the lower part of the water. The former indicates the absence of free communication with the open sea, the latter a depth sufficiently large in proportion to the area to prevent the action of drift on the bottom. That the limestone-shale series of the Ordovician of the Cincinnati region owes its peculiar character to the stirring action of storms on the sea-bottom and subsequent redistribution of the material thrown into suspension through the action of surface drifts, appears highly probable from an analysis of these

²⁰ Jesse E. Hyde, *Jour. Geol.*, vol. 19, pp. 257-269, 1911.

²¹ Several good specimens are in the collection of Ohio State University.

strata. The similar character of this sandstone-shale series (observations (2) and (3)) suggests a similar origin. In fact, the absence of bottom currents practically necessitates such a process of constant redistribution of the sediments, since the bedding in detail is not regular enough to be interpreted as the sole result of undisturbed sedimentation from above, as, for instance, off the mouth of a large river.

The condition outlined on page 246 explains observation (6), that is, the form ratio of the basin, in which these sediments were deposited, was such as to allow only the larger waves to act vigorously on the bottom, trending NW.—SE. Observation (7) proves that at times waves did form even at right angles of this direction, but they were much weaker than the others. The question then remains: Why were the waves trending northwest to southeast strongest on the Bedford-Berea waters? Either because the wind blew strongest and most frequently from that direction, or because it had by far the greatest fetch in that direction.

Owing to the great difficulties of correlation of the strata involved, no reliable conjectures concerning the geography of that time can be made. One fact, however, will permit us to go one step further in our conclusions. There seems little doubt that a distinct change in the distribution of land and water took place, during Bedford and Berea time. In the north, in Lorain County, Ohio, channels 200 feet deep were cut into the Bedford shale before the Berea sandstone was deposited.²² Farther south the effect of this erosion interval rapidly diminishes, until south of Fairfield County its trace is lost²³ and sedimentation of the Bedford and Berea formations seems to have been more or less continuous.

From this we conclude that, if the constancy of the orientation of the largest waves was due to topographic causes, the fetch of the wind being greatest in this direction, the wind could have come from the southwest only, because the northeast certainly suffered great topographic changes which would necessarily have affected

²² W. H. Burroughs, *The Unconformity between the Bedford and Berea Formations of Northern Ohio*, *Jour. Geol.*, 19, pp. 655-659, 1911.

²³ Jesse E. Hyde, *Stratigraphy of the Waverly Formations of Central and Southern Ohio*, *Jour. Geol.*, 23, p. 663, 1915. Here also additional references on this question.

the formation of waves and thereby the trend of the ripples in the southern portion of the area.

While not impossible, it seems rather improbable that the topographic changes indicated by the erosion channels of northern Ohio should not have influenced the general shape of the basin and incidentally the direction of waves and ripples during the Bedford-Berea time, especially if there should have been no or as little connection with the sea in the southwest and west as indicated by Schuchert's maps.²⁴ The weight of this argument would be great if the ripples in the Bedford and Berea formations of northern Ohio should prove to be parallel to those of central and southern Ohio. In that case we should be compelled to look to climatic causes for an explanation, to winds blowing strongest and most frequently in one or two opposite directions. Of course, as was said before, almost on any coast facing the open sea, the onshore winds, having the greater fetch, are most apt to produce the largest waves. In view of the complete absence of currents, however, we cannot assume such a direct connection with the open ocean. Hyde's conclusions, based on this argument, are therefore untenable.

We must turn then to the only alternative, trade winds or monsoons. In the immediate neighborhood of the great North Atlantic continent to the northeast²⁵ we could not expect to find trade winds in their primitive development. They would necessarily assume the character of monsoons. Monsoon winds blow most frequently and strongest in their typical directions. During the period of reversal, calms are common and the variable winds are much weaker. By way of illustration I reproduce in graphic form (fig. 11) the data contained in a table given by Hann²⁶ for the Arabian Sea. There the mean wind velocities reach their maxima in the summer and winter months, during the typical northeast and southwest monsoons, while they fall off considerably in the intermediate months.²⁷ The means of the wind directions, during the months of greatest wind velocities, show a range of 30°

²⁴ Charles Schuchert, *Paleogeography of North America*, Bull. Geol. Soc. Amer., vol. 20, pl. 78 and 79, 1910.

²⁵ Cf. A. de Lapparent, *Traité de Géologie*, vol. 2, p. 891, 1906. E. Haug, *Traité de Géologie*, vol. 2, 1, 817, 1911.

²⁶ J. Hann, *Handbuch der Klimatologie*, vol. 2, p. 196, 1910.

²⁷ Comp. especially the description of the winds of the Arabic Sea.

(-60)°,²⁸ which compares favorably with that reported for the Bedford-Berea ripples. This is equally true of the monsoon off the western side of Africa²⁹ and especially off the north coast of Australia.³⁰

There are two independent facts which lend additional weight to the assumption that the constancy of the Bedford-Berea ripples is due to the action of monsoon winds.

• FIG. 11.

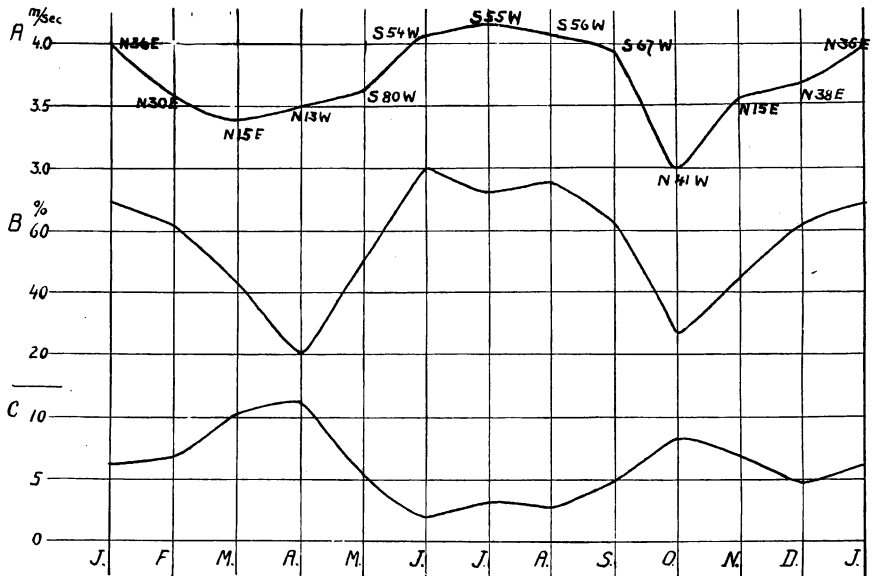


FIG. 11.—Curves showing the relationship between wind velocity and direction of wind for the Monsoon of the Arabian Sea and the northern Indian Ocean.

A = Mean direction and velocity of the wind; B = the number of observations of the mean direction expressed in percent of the total number of observations. C = the number of calms.

(1) The orientation of the ripples (northwest to southeast) harmonizes well with the general assumption of a great land mass, the North Atlantic Continent, to the northeast, and a wide expanse of water in the southwest.

(2) For a later part of Mississippian time Barrell inferred from fundamentally different data a climate of

²⁸ *Ibid.*, p. 200.

²⁹ *Ibid.*, p. 76.

³⁰ *Ibid.*, p. 287; also, J. Barrell, *Origin and Significance of the Mauch Chunk Shale*, Bull. Geol. Soc. Amer., vol. 18, pp. 449-476, esp. 475 f., 1907.

alternating dry and wet seasons for the region lying to the east of the Bedford-Berea sediments.³¹ For the terrestrial sediments in question, the comparison with the monsoon region of the upper Punjab is made, which seems a very happy one. The shallow water marine sediments of our Mississippian seas probably find their closest analogy in the shelf sea north of Australia, where the sea-bottom is largely covered by "a very fine-grained, impalpable, pale olive-green mud, wholly soluble in dilute hydrochloric acid, and therefore essentially carbonate of lime."³² Along the Gulf of Carpentaria the dry winds from the deserts to the south must carry quantities of sand into the sea³³ during the dry season from April to November, while in the remaining months the great floods produced by the northwest monsoon³⁴ must furnish considerable amounts of clastic sediment.

Summary:—It is in a relatively small, more or less detached portion³⁵ of such a gulf that Bedford-Berea sediments were laid down. The parallelism of the ripples formed in it may be due to a peculiar shape, offering the wind a much greater fetch in one direction than in any other. In that case the greater expanse of the water in question must necessarily have been to the southwest, since the north suffered considerable changes during the time of the formation of the ripples.

In view of the distribution especially of the Berea formation and of the improbability attached to the assumption that the waterbody kept its general shape while perhaps as much as one-half of it underwent elevation, erosion, and depression, it appears highly probable that winds of constant direction have caused this remarkable parallelism of ripples. The general trend of these rip-

³¹ See preceding footnote.

³² J. D. Dana, *Corals and Coral Islands*, 3d edit., p. 142, 1890.

³³ Joh. Walther, *Lithogenesis der Gegenwart*, 1894, p. 648.

³⁴ J. Hann, *Handbuch der Klimatologie*, vol. 2, p. 288, 1910.

The Arafura Sea with the Gulf of Carpentaria and the South China Sea with the Java Sea are the only epicontinental seas of the present geologic period offering close analogies to the warm shallow seas of the Paleozoic. A systematic study of their sediments from the point of view of sedimentary petrography is certainly as necessary to a deeper understanding of the problems involved as that of the rocks of the volcanic islands of the adjoining deep sea is to igneous petrography.

³⁵ A recent, larger example of such a detached arm of an epicontinental sea practically without tides is offered by the Baltic Sea, which during the Pleistocene, for a time, was even transformed into a freshwater lake. (Comp. E. Kayser, *Lehrbuch d. Geol. Formationskunde*, 3d edit., p. 650, 1908.)

ples and the testimony of the later deposits of the Mauch Chunk shale, render it probable that they were monsoon winds blowing to and from the large North Atlantic Continent in the northeast.

II. CURRENT-RIPPLES.

1. Description.

Current-ripples are much more common in all kinds of sediments than might be judged from the scarcity of the name or its equivalent in geological literature. It is essential that they should, in all cases, be clearly separated in geological reports from oscillation-ripples.

The current origin of some limestone ripples, especially small ones, is not always easily recognized, as their asymmetry often is not pronounced. A study of a cross-section or a careful determination of the position of the line of greatest depth will, however, reveal their true nature. In most cases, broadly rounded crests lacking any indication of a definite crestline, may be taken as evidence of current origin.

Fossil current-ripples cover the same range of sizes as recent ones. In contrast to oscillation-ripples, they are unfit for the discrimination of upper and lower surfaces in structurally complicated regions, owing to the similarity of crests and troughs.

2. Interpretation.

The following points are of value to the Paleogeographer:

1. *Eolian versus subaqueous ripples.*—If the observations of Cornish and of Kindle (p. 197) prove to hold true in a great majority of cases, at least, ripples of eolian and subaqueous nature may be distinguished by the ratios of their wave-lengths and amplitudes. The absence of the subaqueous type from arenaceous sediments, especially when combined with the typical rounding of grains and the peculiar cross-bedding characteristic of dunes, should be good evidence of their eolian origin. It appears quite doubtful, however, if eolian current-ripples ordinarily can be preserved at all.³⁶

2. *Current-ripples in marine sediments.*—An indication of currents of any kind in marine sediments is always a matter of interest. I have no doubt that, once atten-

³⁶ Cf. p. 269 (Part II).

tion has been called to this matter, current-ripples will be reported from numerous marine formations.

They are rather common on the surfaces of very fine-grained, bluish limestone layers of the Eden and Richmond Groups of Kentucky and Ohio, in the former especially in the fine-grained sandy limestones of the "Garrard Sandstone" of Kentucky.

Such current-ripples may be formed by the wave of translation on the strand, or by wind-drift or tidal currents down to considerable depths. That no information can be expected from marine current-ripples concerning any systems of currents, is made obvious by an inspection of the results of modern marine current measurements, especially those made on the cruises of the "Michael Sars" during the last fifteen years.³⁷ These investigations have shown that the system of currents in such seas as the Norwegian and the North Sea is vastly more complex than was anticipated. By interference of wind-drifts and tidal currents, of these again with reflected tidal waves, along the shore with shore-drift, undertow and freshwater surface currents and their counter currents, a great variety of conditions are produced. These are further complicated by the existence of vortical movements with vertical axes, in the open ocean as well as in coastal waters, and by the fact that in the great majority of cases the bottom currents follow their own laws. In the Skagerack, for instance, "the tidal currents are scarcely noticeable in the upper water layers, whereas they have been met with there down at the very bottom at such great depths as 200 m."³⁸

This raises the question of the maximum depth at which such current-ripples as are found, for instance, in certain marine limestones, might have originated. It can be answered best by a reference to one of the most interesting measurements made on the "Michael Sars." On the edge of the continental slope, about 80 km. northwest of Aalesund on the Norwegian coast,³⁹ *in the open ocean*, not in any channel, the Atlantic current was found running, on the average, parallel with the continental slope,

³⁷ See especially Helland-Hansen, Current Measurements in Norwegian Fiords, the Norwegian Sea and the North Sea, in 1906, Bergen's Museums Aarbog. 1907, No. 15; and Helland-Hansen, and Nansen, The Norwegian Sea, Rept. Norweg. Fishery and Marine Investigations, vol. 2, No. 2, 1909.

³⁸ Report Norweg. Fishery and Marine Investigations, vol. 2, No. 1, p. 79, 1909.

³⁹ 62°50' N. Lat.: 4°47' E. Long.

at times with a velocity of 0.215 m. p. sec. at a depth of 250 m. The lowest velocity observed was 0.059 m.p. sec. "This velocity is so great that the water would move grains of sand, and wash them away from the bottom, which at this place was rocky."⁴⁰

From ripples found in marine sediments, therefore, no other reliable information can be obtained than that there existed currents of some kind which touched the bottom. Since the conditions of preservation are the same for both current and oscillation-ripples, the absence of one or the other type in a sediment must be accounted for in other ways. The Bedford-Berea ripples offered an excellent example for the one case. In the limestone-shale series of the Eden and Richmond Groups of the Cincinnati Anticline current-ripples are common, while I have so far not seen a single case of undoubted oscillation-ripples. While I have no doubt that they will be found, their scarcity is certainly significant and a good evidence of the rather constant current action in these seas, which were shown to have been largely tidal.

3. *Fluviatile current-ripples.*—While in marine sediments the trend of ripples seems of little value to the paleogeographer, its study may yield important results in fluviatile deposits, the true nature and wide distribution of which among the sediments of the past we are just beginning to realize. There are no sediments in which ripples of any kind are of more common occurrence and find better chances of preservation than the sands and muds of alluvial plains.⁴¹

In the deposits of a river obviously a great majority of all ripples should be found facing approximately in the direction of flow of the river. Locally, of course, they can be found facing even in an opposite direction, as along parts of meanders or under the influence of local eddies. Such cases can not, however, seriously affect the average direction obtained from numerous determinations.

This is also true of the ripples on compound alluvial fans. An analysis of the ripples in sediments which are interpreted as alluvial fillings of rift valleys, as, for instance, the Newark series in Connecticut,⁴² should prove especially interesting.

⁴⁰ Helland-Hansen and Nansen, loc. cit., p. 155; cf. also table 1 of Part I of this paper.

⁴¹ Cf. also p. 269 (Part II).

⁴² J. Barrell, Central Connecticut in the Geologic Past, Proc. and Coll. of the Wyoming Hist. and Geol. Soc., vol. 12, pp. 1-30, 1911.

But even in moist climates very complicated conditions may arise which would call for the greatest caution in the analysis of ample data, without which no positive results could be hoped for. The rift valley of the Rhine, *e. g.*, over 160 miles long between Basel to Bingen, was filled to a depth of over 100 m.,⁴³ locally even over 150 m.,⁴⁴ with silt, sand and gravel by the Rhine and its tributaries. The Rhine flows from south to north, but meandered over a large part of the 20 miles width of the valley, and frequently overlapped widely over the fans built by its tributaries, each of which, upon emerging from the bordering horsts, meandered more or less widely over the confines of its fan. An analysis of the ripples of such deposits might well meet with insuperable difficulties. But it deserves to be attempted and may, when combined with careful studies of the composition of the associated gravels and other data, yield reliable results which would substitute definite geographical conceptions for vague notions.

In the Pottsville series of Kentucky, the author observed at several localities shaly sandstones in which the ripples, covering nearly every layer, showed a gradual and continuous change of direction from one level to the next, reflecting clearly the slow shifting of the current in some part of a meandering stream. One mile north-east of Oil Springs, Johnson Co., Ky., for instance, the following six readings were taken on the best exposed surfaces within a thickness of three feet of very thin bedded shaly sandstone:

S 40 E
 S 45 E
 S 50 E
 S 57 E
 S 70 E
 S 90 E

A number of intervening layers showed rippling too, which, in all cases, was in harmony with this general arrangement. The wave-length of the ripples varied between 6.5 and 7.5 cm., and all faced southward.

4. *Current-ripples as evidence of exposure.*—The highly characteristic linguoid ripples, described in Part

⁴³ G. R. Lepsius, *Das Mainzer Becken*, Darmstadt, 1883, p. 156.

⁴⁴ *E. g.* 160 m. at Blodelsheim, in the Upper Alsace: L. Van Werveke, *Uebersicht ü. d. geol. Bau u. d. geol. Entwicklung des Reichslandes Elsass-Lothringen u. d. Grossh. Baden-Strassburg*, 1913, p. 45.

I, have always, as far as I know, been found where the depth of running water was rapidly diminished to complete exposure. They are equally common on tidal flats as on floodplains and therefore can be considered as indicators of this special condition. During the G. S. A. meeting at Albany, New York, there were exhibited excellent specimens of negatives of this type, if I remember correctly, from the Portage Sandstone of New York, together with plaster casts showing their true form. Cox and Dake figure a good specimen from the Roubidoux sandstone of the vicinity of Rolla, Missouri,⁴⁵ and Kindle one from the Carboniferous Sandstone, Joggins section, N. S.⁴⁶ Kindle also called attention to the fact that the laminations of such linguoid ripples, when exposed by erosion, resemble the problematic burrows, described as *Taonurus*. Surfaces like the one figured by him on plate 31 are commonly met with, for instance, in the rocks of the Pottsville group of Kentucky.

The evidence offered by these linguoid ripples is definite and should be used in combination with other data, giving clues to the marine or terrestrial nature of the sediments.

In marine deposits they should be confined to a narrow zone, corresponding to the tidal flats; or they might be found over a wide area in a formation of limited thickness ascending obliquely through the stratigraphic column due to progressive marine overlap pushing the marginal zone forward across the land.

If they are, however, found throughout a considerable thickness of a formation of fixed position in the stratigraphic column, covering a wide area, they offer a strong argument in favor of a terrestrial, fluvial origin.

III. LARGE CURRENT-RIPPLES.

1. Description.

Large current-ripples were described or mentioned from the lower Ordovician dolomites of Illinois⁴⁷ and from the Trenton at a number of localities in New York

⁴⁵ Cox, G. H., and Dake, C. L., Geologic criteria for determining the structural position of sedimentary beds, Bull. School of Mines, Univ. of Missouri, vol. 2, No. 4, pl. IIB, 1916.

⁴⁶ E. M. Kindle, Recent and Fossil Ripple-Marks, Geol. Survey, Canada, Museum Bull. 25, p. 121, 1917.

⁴⁷ Udden, J. A., Jour. Geol., vol. 24, p. 125, 1916.

and Ontario.⁴⁸ They are common in the Eden and in parts of the Richmond Group of the Upper Ordovician in the Cincinnati anticline.⁴⁹ They occur at a number of localities in the Silurian Brassfield formation of Kentucky and Ohio.⁵⁰ They were also reported from younger Silurian limestones in Ohio⁵¹ and New York,⁵² from Devonian limestones in Ohio⁵³ and Ontario,⁵⁴ from the Mississippian limestones of Iowa⁵⁵ and from Waverly conglomerates of Ohio,⁵⁶ and finally from the Comanchean of Texas.⁵⁷

Table VI gives a selected number of measurements for large fossil current-ripples.

In shape they vary from strongly asymmetrical to completely symmetrical; more than half of all large ripples seen in limestones of the Ordovician and Silurian of the Cincinnati Anticline were more or less symmetrical. Their crests are always broadly rounded like the troughs and but rarely show distinct crest lines.

Not one showed any signs of assortment. Shells of *Rafinesquina*, over 5 cm. long and wide, Bryozoans 8 to 10 cm. long and over 1 cm. thick, and, in the Richmond, calices of *Streptelasma*, over 10 cm. long and over 3 cm. wide, are found scattered equally over crests, sides and troughs of the ripples, mixed in almost any proportion with finer shell fragments down to the finest matrix filling the interstices.

It is very important to note that the same utter lack of assortment characterizes the large ripples which are found in the Berne member of the Cuyahoga formation of

⁴⁸ Ruedemann, R., Am. Geol., pp. 367 ff., 1897. Cushing, Bull. N. Y. State Mus. Nat. Hist., 77, p. 34, 1905. Miller, *ibid.*, vol. 135, p. 36, 1910. Kindle, Jour. Geol., 22, pp. 703-713, 1914.

⁴⁹ See Locke, J. (1838); Orton (1873); Linney, W. M. (1882-1887); Knott, W. T. (1885); Perry, N. W. (1889); Shannon, W. P. (1895); Foerste, A. (1895); Moore, J., and Hole (1902); Culbertson, G. (1903); Prosser, Ch. S. (1916).

⁵⁰ Cf. Foerste, Kentucky Geol. Surv., Bull. 7, 1906. Prosser, Ch. S., Jour. Geol., 24, 1916, pp. 465-470.

⁵¹ *Ibid.*, pp. 470-472. Foerste, Jour. Cine. Soc. Nat. Hist., 18, p. 167, 1896.

⁵² Kindle and Taylor, U. S. Geol. Survey, Folio 190, pl. 25, 1913.

⁵³ Stauffer, in "Geol. of the Columbus Quadrangle," Ohio Geol. Surv., 4th Ser., Bull. 14, p. 20, 1911. According to my own measurements, the ripples of the so-called "smooth layer" of the Columbus limestone, here mentioned, have a wave-length of 74 cm. and an amplitude of 2-5 cm. Prosser, *loc. cit.*, pp. 472-475 (2 good fotogr.).

⁵⁴ Kindle, Ottawa Naturalist, vol. 26, pp. 1-3, 112.

⁵⁵ Udden, Jour. Geol., vol. 24, p. 125, 1916.

⁵⁶ To be described presently.

⁵⁷ Udden, *loc. cit.*, p. 126.

TABLE VI.—Data on Ripples observed on limestones chiefly of the Upper Ordovician of Kentucky.

1.	Stratigr. Group.	l^a cm.	a cm.	$\frac{l}{a}$	$\frac{l_1}{l_2}$	material.	
~	Richmond -----	0.4	-----	-----	-----	fine-grained sandy l. s.	C ^b
u.	Richmond (top) ..	1.6	0.07	23	2.7	dense, light yellow dol. l. ..	C
±	Richmond (base) ..	2.5	0.1	25	-----	dense, gray argill. l. s.	C
o.	Richmond -----	3.0	0.2	15	-----	dense, "blue" argill. l. s.	C
o.	Richmond (base) ..	4.0	0.15	27	-----	" " " "	C
±	Richmond -----	7.3	0.25-0.5	14-29	1.8	" " " "	C
o.	Richmond (top) ..	8.0	0.3	26	1.9	" " " "	C
±	Maysville (base) ..	12.5	1.2	10	1.0	" " " "	O?
1	" " " " " " ..	23-30.0	-----	-----	-----	-----	?
0.	Eden (top)	34.3- 50.9	7.6 7.0	4.5 7.3	n. s. ^a	coarse-grained fossilif. l. s. no assortment	P
11.	Richmond -----	40-50	2.5-4.5	15 (av)	n. s.	" " " "	P
12.	Eden -----	60.0	6.5-7.0	9	n. s.	" " " "	P
13.	Eden -----	70- 79	5.7- 8.6	12 9	2.1 ±	" " " "	P
14.	Eden -----	80.0	8.0	10	n. s.	" " " "	P
15.	Eden (top)	74-94	7.6-8.9	8-12	1.2-1.5	" " " "	P
16.	Brassfield -----	83-100	4.6-6.3	18 (av)	n. s.	oolitic rock passing into iron ore	P
17.	Eden -----	95	9.2	10	1.1	coarse-grained fossilif. l. s. no assortment	P
18.	Eden -----	100	10	10	4	" " " "	P
19.	Eden -----	100	5.5	18	n. s.	" " " "	P
20.	Eden -----	110-120	9-10	12	n. s.	" " " "	P
21.	Eden -----	128	7.5	17	n. s.	" " " "	P
22.	Eden -----	75- 130	6.3- 5.7	12- 23	2.2-2.5	" " " "	P
23.	Brassfield -----	134	11	12	1.5	" " " "	P
24.	Eden -----	145	12	12	n. s.	" " " "	P
25.	Brassfield -----	105-160	7.5-10	14 (av)	n. s.	oolitic rock passing into iron ore	P
26.	Eden -----	130- 160	11- 10	11- 15	n. s.- 2.6	coarse cryst. no assortment	P
27.	Lower Burlington	180	15	12	-----	crinoidal l. s. ..	P

^a l = wave-length; a = amplitude; $\frac{l_1}{l_2}$ = horizontal form index (see p. 154, pt. I); n. s. = nearly symmetrical.

^b C = Current-ripples; O = Oscillation-ripples; P = Para-ripples.

LIST OF LOCALITIES REFERRED TO IN TABLE VI.

No. 1: Ky., Casey Co., near Carpenter's Creek. Nos. 2, 7: Ky., Oldham Co., S of Harrods Creek, Lagrange Rd. Nos. 3, 4, 5, 6: Ky., Lincoln Co., Logan Creek. Nos. 8, 9: Ky., Mason Co., between Marshall and Lewisburg. Nos. 12, 14, 19, 20, 21: Ky., Mason Co., creek W of Maysville. Nos. 10, 11, 15: Ky., Garrard Co., Paint Lick. No. 13: Ky., Shelby Co., between Mt. Eden and Southville. Nos. 22, 26: Ky., Shelby Co., between Waddy and Harrisonville. Nos. 16, 25: Ky., Bath Co., about 3 miles N of Olympia. No. 23: Ky., Bath Co., W of Preston. Nos. 17, 18, 24: Ohio, vicinity of Cincinnati. No. 27: Iowa, SE Louisa Co. (Udden, 1916).

Hyde's definition,⁵⁸ who showed me personally two very interesting occurrences in the vicinity of Newark, Ohio, in Quarry Run, south of Newark, and at Toboso, east of it. At the former locality, the broadly rounded, symmetrical crests, 145 cm. apart, have formed on a quartz conglomerate in which pebbles of more or less 0.5 cm.

FIG. 12.



FIG. 12. Asymmetrical para-ripples on limestone in the Eden group, $\frac{1}{4}$ mile above the bridge across Little Beech Creek, on the road from Mt. Eden to Southville, Shelby Co., Ky. (For dimensions see table VI.)

diameter are uniformly mixed with coarse and fine sand without a trace of assortment. Since in the growth of oscillation ripples, the to and fro motion of the oscillating current produced by waves on the bottom of a water body involves a constant tossing of the grains, a sifting and assorting of the grains is unavoidable.

Its absence in the large ripples in question seems to be sufficient proof of their current origin. Besides, it

⁵⁸ J. E. Hyde, *Stratigraphy of the Waverly formations of Central and Southern Ohio*, Jour. Geol. vol. 23, p. 659, 1915.

appears very doubtful, as was pointed out in Part I (March No.), whether ripples of this size can form at all through the action of waves alone. All experimental and observational evidence seems to speak against it.

In the course of a discussion the objection was raised that a current should be expected to "cut through the

FIG. 13.

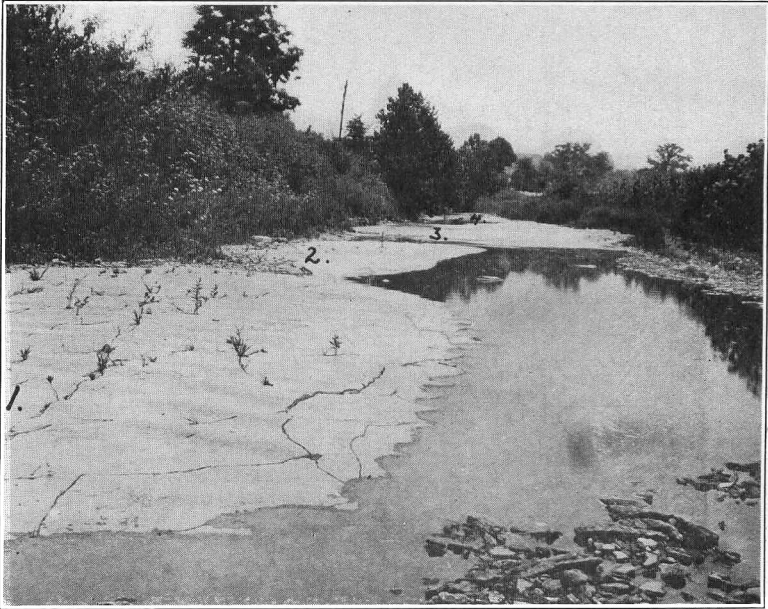


FIG. 13. Para-ripples on limestone in the Richmond group, Blue Bank Creek, above Goddard, Fleming Co., Ky. (See table VI.)

Note that the para-ripples cover undulations of a higher order of magnitude, four of which are seen in the figure (Nos. 1-4). The hammer rests on the second one.

rippled layer into the underlying sediment" in places, while no such case is known at present. This should be indeed the case if there existed local differences in velocity or depth of the current. We have, however, in Part I endeavored to show that the establishment of ripples at the contact of sediment and water serves the very purpose to eliminate any such irregular, local differences and to replace them by a uniform system of flow-lines.

These large current-ripples agree in most points with

the tidal meta-ripples as described in Part I. The essential difference lies in the great number of symmetrical ripples and in the smaller horizontal form-index of the asymmetrical forms. To what extent this difference is due to the fact that the recent tidal ripples were observed after emergence while most fossil cases probably remained under a water cover, I have no means to judge.

Since a neutral name is desired for the large, nearly or completely symmetrical ripples showing no assortment of grain, I suggest the term "*para-ripples.*"

2. Interpretation.

The following discussion of the probable origin of these large ripples of the Upper Ordovician and lower Silurian of the Cincinnati Anticline has already been published elsewhere.⁵⁹ The limited distribution of the other publication, however, makes it appear desirable to embody it in this paper.

a. In Kentucky, the Brassfield formation of the Silurian east of the Cincinnati Anticline shows one or two rippled layers within its 18 feet of thickness. West of it, no traces of ripples were found according to Foerste.⁶⁰

The ferruginous oolitic facies of the same formation is also limited to the east side of the anticline, extending over a distance of nearly 120 miles from Madison County, Kentucky, to Clinton County, Ohio, in a belt running roughly north-south (perhaps slightly east of north). On the west side of the anticline nothing but a salmon-brown color of the limestone betrays the (relative) neighborhood of ferruginous deposits.⁶¹ From this the inference appears justified that the shore-line of the Brassfield sea was somewhere to the east with a general north-south trend.

Of the thirteen measured exposures of rippled layers in the Brassfield, ranging over a distance of nearly 50 miles, twelve showed directions of strike between N 50 W and N 110 W, averaging N 76 W, that is, at right angles to the direction of the assumed shore-line (see fig. 14*b*). The current, therefore, must have been parallel to this shore-line. This excludes the undertow and similar currents from discussion.

⁵⁹ W. H. Bucher, Proc. Nat. Acad. Sci., vol. 3, pp. 285-291, 1917.

⁶⁰ Foerste, The Ordovician-Silurian contact in the Ripley Island area of S. Indiana, this Journal (4), vol. 18, pp. 321-342, 1904.

⁶¹ Foerste's map of the distribution of the facies of the Clinton formation.

b. Large current-ripples are found only on rocks of relatively coarse grain, as conglomeratic sands (Cuyahoga formation) or fragmental limestones, never on fine-grained sediments, that is, on dense blue argillaceous limestones. These are, however, frequently covered with small current-ripples, ranging in wave-length from 1 to 30 cm., and are often interstratified with fragmental limestones of coarse grain covered with large ripples and separated from them only by thin layers of shale. The calcareous layers show delicate tracks of gastropods or trilobites well preserved which practically exclude any current action.

This seems to indicate that the current in question varied in intensity from a maximum to nil, in relatively short intervals. The finer sediments could record only the weaker movements, as stronger currents would have thrown them into suspension.

c. In the Ordovician, I have repeatedly found large asymmetrical ripples on two successive limestones, not more than a foot apart, with nearly the same strike, but with their lee sides facing in opposite directions. The current, therefore, reversed its direction in relatively short intervals.

Observations *b* and *c* exclude ocean currents of larger dimensions, while they point consistently to tidal currents. These, too, are the only marine currents flowing parallel to the shore-line in which velocities of at least 1 m. sec., which seem necessary to produce the effects observed, are found over wide areas.

The great similarity of form existing between these large fossil ripples and some of the tidal para-ripples referred to above goes far to confirm these conclusions. From Cornish's paper on these tidal ripples⁶² we know that on open shores, such as at Mundsley (Norfolk, p. 183) above the mouth of Barmouth Estuary (p. 173), or especially on the Goodwin Sands (p. 189), about six miles off the shore of Kent, these tidal ripples invariably trend at right angles to the shore, often at right angles to the waves. On the open shore, too, their wave-length is the same as that of most large Paleozoic ripples, while those observed in estuaries, where the velocity of the tidal current is greatly increased, have a greater wave-length.

The inference, therefore, seems justified that the large

⁶² Cornish, Sand Waves in Tidal Currents, Geogr. Jour., vol. 18, pp. 170-202, 1901.

current ripples described were produced by tidal currents. Those of the Brassfield formation in Kentucky offer a direct analogy to those of the English Coast.

The ripples of the Lorraine and Richmond Formations, however, offer an additional problem.

1. They are not limited to a relatively narrow zone in the neighborhood of the shore, but formed (probably more or less synchronously) throughout the area of the Cincinnati Anticline, that is, over an area of at least 15,000 square miles and probably much more.

2. They trend in all directions, although a north-south trend is more common than an east-west trend (see fig. 14, *c-k*).

At first sight this seems to offer a serious objection to my interpretation, since in open waters the direction of the current passes through all the points of the compass in the course of twelve hours, which would render the formation of permanent ripples impossible. The following observations, however, offer a clue to this problem.

In 1881 Hunt⁶³ visited the broad open gulf of Torbay on the south shore of Devonshire two weeks after a heavy

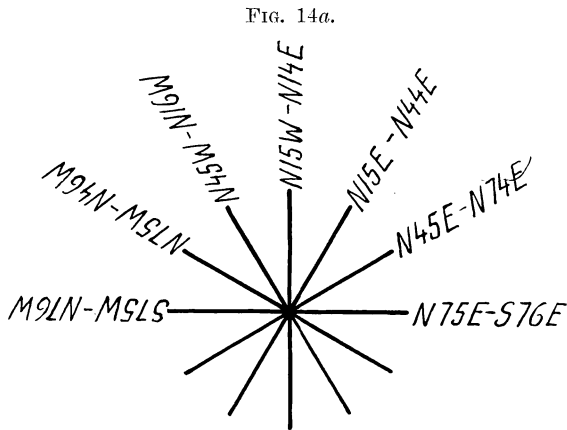
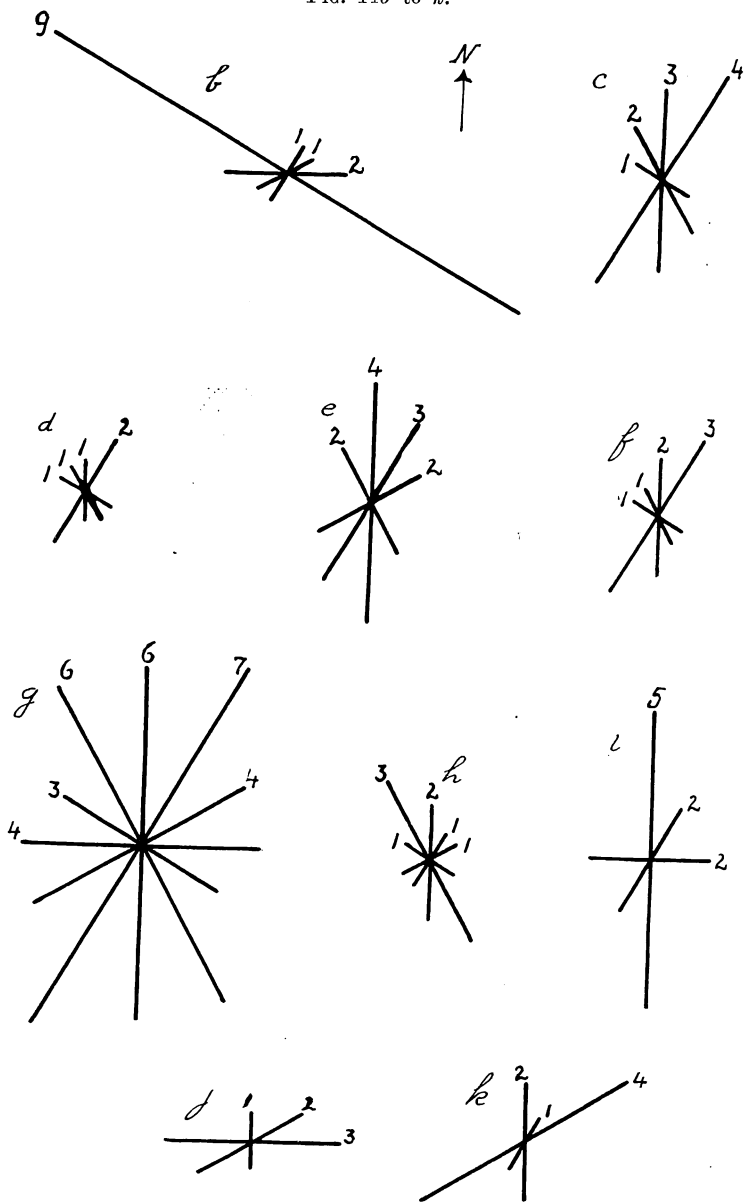


FIGURE 14, *a-k*. Diagram illustrating the relative frequency of the different directions of strike observed in para-ripples of the Brassfield formation (*b*), Eden group (*c-g*), and Richmond group (*h-k*) of the Jessamine dome. FIG. *a* illustrates the method by which the diagrams were constructed. The directions observed were divided into six groups and plotted on six rays, each representing all the directions lying within 15° on either side. The total number of observations in each group is shown, relatively, by the length of the rays, and, absolutely, by the figures at their ends.

⁶³ Hunt, A. R., On the formation of Ripple Marks, Proc. Roy. Soc., vol. 34, p. 4, 1882.

FIG. 14b to k.



Brassfield formation: Fig. b, 13 localities in Bath, Fleming, Powell, and Estill counties, Ky.

Eden group: Fig. c. Valley west of Maysville, Mason Co., Ky.; Fig. d. Paint Lick and tributaries below Paintlick, Madison Co., Ky.; Fig. e. Little Beech Fork and tributaries N of Gravel Switch, Marion Co., Ky.; Fig. f. Headwaters of Big Beech Creek, W of Waddy, Shelby Co., Ky.; Fig. g. Vicinity of Cincinnati, Ohio.

Richmond group: Fig. h. Elkhorn Creek, Adams Co., Ohio, after Foerste, 1895; Fig. i. Between Poplar Plains and Goddard, Fleming Co., Ky.; Fig. j. Tributary of Harrods Creek, N of Lagrange, Oldham Co., Ky.; Fig. k. Jefferson and Wayne counties, Indiana, after Moore and Hole, 1901, and Culbertson, 1902.

storm. In Midbay, at a depth of over 12 meters, where the bottom usually is a soft muddy sand that clogs the dredge in a few minutes, he found the ground hard, producing "not a single shell or a particle of the usual muddy sand." Four weeks after the storm "the ground was still very hard, both the dredge and a fishing-lead tied to a line *bumping along as though over ridges.*" Over six weeks after the gale the same spot had returned to its normal state.

Similarly, Cornish (p. 175) found Pegwell Bay (Kent) in which ordinarily the tide never produces anything but small current-ripples, covered with large tidal ripples after a heavy gale blowing into the bay.

These observations indicate that the drift produced by periods of storms may so strengthen the tidal current as to produce large current-ripples. This I suggest as the probable origin of our large Eden and Richmond ripples.

The ripples observed by Hunt formed at a depth of over 12 meters with a tide of over 2 meters. In open waters the range of the tides and the velocity of the resulting currents would be much smaller than in the channel. With gales of similar strength, therefore, the same mechanical effect of the currents would be possible only at a much smaller depth of water. Allowing, however, for extreme conditions, we may safely say that our Ordovician ripples probably were formed in water less than 25 meters deep rather than more. The Persian Gulf offers an interesting analogy. With an area of about 90,000 square miles, it has a mean depth of but 25 meters.⁶⁴ The tidal range along all its shores is more than 2 meters.⁶⁵

We may summarize the geographic conditions inferred from the large current-ripples of the Upper Ordovician of the Cincinnati Anticline as follows:

1. A sea having sufficient connection with the open ocean to allow relatively high tides.
2. Sufficient area to permit the formation of strong wind-drifts in most directions during periods of storms.
3. A depth small enough to admit of a strong action on the bottom sediments by wind-drift and tidal current combined, probably 25 meters or less on the average.
4. Atmospheric conditions providing for the occurrence of storms, blowing from all points of the compass.

⁶⁴ Supan, A., Grundzüge der physischen Erdkunde, 1911, p. 260.

⁶⁵ Berghaus, Atlas der Hydrographie, 1891, pl. XX.

such as tropical cyclones or, more probably, those of intermediate latitudes.

In the paper referred to, considerable emphasis is laid on a sufficient rate of sedimentation as the chief condition for a preservation of the ripples formed. The discussion, which involves an interpretation of the origin of the more or less rhythmic repetition of shales and limestones in the Upper Ordovician of the Cincinnati Anticline, can not be given here.

The fact that at least four independent factors had to combine for the production of these ripples, namely sufficiently strong tidal action, frequent periods of strong storms, a relatively small depth of water, and a sufficient rate of sedimentation to insure their preservation, explains why such large current-ripples are not found commonly over wide areas in the sedimentary record of other seas.

The large ripples produced along the shores by ordinary tidal currents, also have much poorer chances for preservation than smaller ripples, because they require a thicker cover in order to be preserved. This explains their scarcity in shore deposits. The same is true of fluvial ripples.

In view of the fact that strong tidal currents are found only in waterbodies which are in direct open connection with the sea and not in landlocked seas, whether mediterranean or epicontinental seas, the presence of para-ripples in marine deposits ranging in age from the Lower Ordovician to the Comanchean, all from the United States west of "Appalachia," is of fundamental interest. Many more will be recorded⁶⁶ and will doubtless furnish valuable checks on many lines that will be drawn on future paleogeographic maps.

IV. GENERAL ABSENCE OF RIPPLES IN CERTAIN FORMATIONS.

One question remains to be answered: Why are ripples entirely absent from certain formations, while they are a conspicuous feature throughout others?

The *formation* of ripples is prevented by:

1. Sediments too coarse or too fine in proportion to

⁶⁶ Every occurrence of such large ripples deserves publication. The wavelength, amplitude, degree of asymmetry, direction of trend and a detailed account of the texture of the sediment should be given besides detailed topographic and stratigraphic location.

the existing currents and oscillations. Pure muds can not form ripples at all.

2. The absence of tidal currents, that is, of an open connection with the ocean. (Applies to current-ripples only; cf. p. 243.)

3. A depth too great in proportion to the area of the water body to allow waves and drift currents to touch bottom. (Cf. p. 246.)

The *preservation* of ripples is made impossible by

4. The absence of the conditions favorable for a rapid covering of the ripples, as outlined below.

5. It should be noted especially that in relatively coarse homogeneous sediments, coarse sands for instance, not capable of being carried any distance in suspension and covering extensive areas, the stirring of the sediments does not result in a covering of the ripples formed.

Judging from these points, ripples will be absent from (a) sediments deposited in a landlocked sea or lake with too large a form ratio (points 2 and 3), or, if the form ratio were small enough to cause the action of waves on the bottom, with sediment too coarse or too fine to give rise to ripples (points 1 and 2).

(b) Also from well assorted, coarse sands or other arenites, accumulated in a shallow water body, with or without strong tidal currents and waves, distant from the mouths of streams and of coasts with sand-laden winds (points 4 and 5).

Not one of these points, on the other hand, applies to terrestrial alluvial deposits. There is no reason why ripples of practically all kinds should not be found in profusion in all fluvial deposits, especially in such as were accumulated under more or less arid conditions, with clouds of wind-blown silt and sand settling into the shifting waters.

It appears to be very doubtful, however, if ripples will ordinarily be preserved in dune sands, in view of point 5, which certainly is of equal importance in sub-aërial as in subaqueous sediments. In my own observations of sections of recent dunes, limited to shore dunes, I have never seen ripples preserved in the sands, and they are not mentioned in the descriptions of such typical fossil dune sands as the Sylvania sandstone.⁶⁷

University of Cincinnati,
Cincinnati, Ohio.

⁶⁷ Sherzer, W. H., and Grabau, A. W., Michigan Geological and Biological Survey, Geol. Series, 1, pp. 61-86, 1909.