GRADED BEDDING, WITH OBSERVATIONS ON LOWER PALEOZOIC ROCKS OF BRITAIN

BY

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PREFACE

The present contribution to the problem of graded bedding and its use in paleogeography consists of two parts. The first is based on field work carried out in 1951 and was read before the Geological Society of London in June 1952. Some slight alterations were later made where the discussion showed the author to have been misunderstood. The second part is the outcome of a short visit to the Southern Uplands in 1952 and additional observations made in 1953.

The author would like to emphasize that these papers are not intended primarily to solve local problems in regional geology. That would require more time for detailed fieldwork than the writer has available. Their aim is mainly to contribute to our knowledge concerning the phenomena of sedimentation and to interest colleagues in some new methods which are believed to be useful in the study of geosynclines containing graded sediments.

In the mean time Mr KOPSTEIN has carried out a detailed application of these methods to the Harlech Dome and finds that, in spite of some details still eluding clear understanding, the results lead to a remarkably simple picture of the sedimentary history of this area. This picture is rather different to what British geologists have assumed up to the present. But the author hopes that although he cannot forestall Mr KOPSTEIN's publication by giving any details, colleagues will be interested to hear that a perfectly consistent result is attained in detailed work.

The outcome of a reconnaissance in the Ventura Basin of California and of joint investigations with Mr CAROZZI of Geneva in the Alps are in press.

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PART 1

GRADED BEDDING IN GENERAL AND SOME OBSERVATIONS IN WEST-CENTRAL WALES

Summary

A short visit to the Harlech Dome and the neighbourhood of Aberystwyth enabled the author to study graded bedding in Cambrian and Silurian rocks [1]. Grading was found to occur in most of the subdivisions and to be almost universal in some. A great variety of types was encountered and certain kinds of current bedding and ripple mark were found associated with the grading. The observed phenomena are explained by the action of turbidity currents and some information on the velocity of these currents is deduced. A special investigation was made of "convolute bedding", for which an explanation is here offered.

The time available was much too short to obtain a general picture of the history of the geosyncline in the investigated areas. It is shown, however, that a careful examination of graded bedding and associated phenomena throughout the geosyncline should teach us much concerning its history as to depth, slopes, shape, etc.

One of the main results is that the Harlech sequence of shale and grit groups does not require the assumption at the start of each new group of great changes in depth from deep quiet waters to shallow agitated conditions or back again. On the contrary the trough remained deep throughout, and the coarse grained units may even characterize periods of somewhat greater depth than do the shale groups.

If the proposed explanation is accepted neither coarse grain, occasional shallow water fossils, nor ripple mark and current bedding can be taken as proof of shallow water facies. To constitute proof it must first be shown that these features are not of the type produced by turbidity currents in redeposited beds. Several geosynclines hitherto considered to contain only shallow water deposits will need renewed inspection.

It is argued that Rich underestimates the importance of turbidity flow in his clino and fondo environments. Some modifications of the picture he gives of deep-water sedimentation are proposed.

I. Introduction

In his classical paper on graded bedding, Sir Edward Bailey mentions the occurrence of this type of texture at two localities in Wales, Harlech

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[1] This field work was financed from a grant provided by the Netherlands Organization for Pure Research (Z.W.O.).

and Barmouth. Later O.T. JONES and PUGH stated that the grit beds of the Upper Llandoverian in the Aberystwyth district often show graded bedding. On the other hand later detailed descriptions of the Harlech dome and Harlech grit series contain no references to graded bedding.

The writer visited these parts of Wales in September 1951 to make a special study of sedimentation features. Graded bedding proved to be wide spread and other interesting features were also encountered.

Graded bedding is referred to in a large number of papers but without doubt it is much more common than generally assumed. Usually no other details have been given than thickness of the beds and a rough indication of grain sizes at base and top. SHROCK, in his admirable textbook on sequence in layered rocks, summarized the knowledge gradually accumulated up to 1948 more especially from the Pre-Cambrian formations. For grading has proved to form a fairly trustworthy criterion of bottom and top. By then it had been ascertained that graded bedding tends to be developed in thick series of muddy arenaceous beds of considerable horizontal extent, alternating with lutites, and to be accompanied by small-scale contemporaneous deformations. Cross-bedding and ripple marking had seldom been noted. The graded beds are of the grit or graywacke type and BAILEY had emphasized that graded bedding is typical of muddy deep-water sandstones, while cross-bedding normally belongs to clean, shallow-water sandstones.

Some views on the mechanism by which graded bedding could have been formed were put forward tentatively, but it was not until a couple of years ago that a more serious attempt at solving this problem was made by MIGLIORINI and the present author (KUENEN and MIGLIORINI, 1950). The hypothesis put forward was that turbidity currents are responsible in the majority of cases and it was pointed out why normal marine currents cannot have developed typical graded bedding. An experimental study of turbidity currents showed that this type of flow tends to form graded deposits greatly resembling the natural occurrences, and that the hydrodynamical properties of these currents offer a simple and full explanation of the main features shown by typical series of graded graywackes. The Tertiary macigno sandstones of the Apennines were described in some detail and the hypothesis offered was successfully applied to the vast graded beds of this formation.

Several authors have since accepted this explanation (e.g. PETTIJOHN 1950, DORREEN 1951, COTTON 1951).

In later papers the author treated further the mechanics of turbidity flow (1951*b*), and showed that the deposition of glacial varves can be explained to a large extent by the same mechanism (1951*a*).

In a joint paper with NATLAND (1951) the sedimentary history of a small geosynclinal basin in southern California was elucidated by application of the turbidity current mechanism. NATLAND had formerly shown that the Foraminifera prove great depth of sedimentation for the Ventura

Basin in spite of the occurrence of many coarse sands and some conglomerates. Examination in the field at once brought out that graded bedding is ubiquitous, although not the only type of bedding developed, and that the emplacement of the sands and pebbly beds in great depths is readily explained by assuming slumps changing to turbidity currents. The fact that reworked older Foraminifera and shallow-water types and occasional other shallow-water fossils are found in the sands, while the intervening shales contain only a deep-water fauna supports this view. Pull-apart structures and slump structures testify to relatively steep submarine slopes. The localized intercalation of a thick series of coarse non-graded conglomerates appears to indicate slide deposits off the mouth of streams.

The occurrence was observed of a curious type of contemporaneous deformation, which MIGLIORINI had earlier described under the heading of "crinkled bedding", but the origin remained obscure.

Current bedding and lamination of the upper part of some graded beds was observed, and it was also remarked that the graywacke beds, although evenly bedded, do not appear to cover, individually, very extensive areas.

In a joint paper with MENARD (1952) suggestions have been offered how to account for the absence or poor development of grading in some turbidity current deposits, and features are enumerated by which graded beds resulting from volcanic eruptions etc. can be distinguished from the normal type.

The author had suggested in 1948 (see also KUENEN 1950, p. 240, 360, 366, 370) that deep-sea sands have originated by the transport of shallow-water deposits to far-off deep-sea environments by turbidity currents. This explanation has later been confirmed (SHEPARD 1951, PHLEGER 1951, ERICSON *et al.*, 1951). Deep-sea sands, it was found, are generally graded, although careful examination may be needed to bring this out. They contain shallow water organisms.

It will be shown below that the interval between the deposition of successive graded beds tends to be long. Hence each bed represents the accumulation of sediment at the source over a period of a great many years.

In the author's opinion the combined strength of all this evidence, coming from several entirely different directions, can leave no doubt of the great importance of the turbidity current mechanism in the transport and deposition of sediment in many ancient geosynclines and on the deep-sea floor, and that most cases of graded bedding have been formed in this manner.

The reader wishing for more detail is referred to the papers cited and in the sequel it will be assumed that further proof is not required. However, each occurrence of graded bedding examined so far in greater detail has proved to be characterized by some special features and a lot of work remains to be done before a full picture can be drawn and the significance of each characteristic confidently evaluated.

The reasons for this wide range of properties is not far to seek. The size and declivity of the slopes, the granular composition of materials transported, the volume and manner of origin of the flows all influence the nature of the deposits. In the following an attempt will be made to summarize what is known to date (January, 1952) of features shown by graded beds [1]).

II. Features of graded bedding

A typical graded bed starts at the base with the coarsest grains available (generally sand, in some beds pebbles) and grades upwards continuously to the finest at the top. The graded bed is followed by deposits formed by normal agents in the environment of emplacement, usually fine grained deep-water deposits of lutite (clay or lime) or pelagic planktonic materials. In the most typical examples, cross-bedding, lamination, and ripple mark are absent, but contemporaneous deformations of one kind or another are usual.

Even if the grading is perfect, the degree of sorting in each horizon is only moderate. Only a few (TRASK) sorting coefficients have thus far been determined. These centre around 1.5 to 2.5, which denotes poor sorting compared to beach or river sands of similar median diameters. Where sand or even pebbles occur, these coarse grains are therefore mixed with a smaller or larger amount of finer material. Hence, graded arenaceous beds are muddy and belong to the category of graywackes.

The grading is due to an upward decrease in median diameter. There are beds, however, in which the maximum grain size is about the same at all levels. Then it is the greater concentration of large grains at the base which causes the grading.

Beds range in thickness from minute laminae to mighty beds of 10 meters thickness or more. Although there is a marked tendency for beds in a certain locality to be of uniform thickness, a fairly wide range may often be noted even in a single exposure. In many areas the maximum grain size increases with the thickness of the beds in each exposure. On the other hand some localities are characterized by thin beds with coarse grain, while in other regions even very thick beds contain no grains beyond medium sand sizes.

Another characteristic of graded beds is the great persistance of individual members, resulting in series with bedding of remarkable regularity. In many cases all beds can be traced without cumulative change in thickness as far as the exposure allows, even when only a few cm thick. This holds in spite of local undulations in the bedding planes sometimes observable.

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[1]) Since this paper was read before the Geological Society of London in 1952, the author has made further observations on graded series in the Ventura Basin, the Southern Uplands of Scotland, the Apennines, and jointly with CAROZZI in the surroundings of Geneva. These confirm and amplify the results recorded in the present article.

The greatest extent to which individual beds can be traced is still a matter of conjecture, but MIGLIORINI claimed that some macigno beds can be followed for a matter of several kilometers at least, and CAROZZI has traced beds for 10 kilometers.

Finally it may be noted that evidence of disturbance in the bedding by benthonic life is extremely rare. The fine lamination of the shales between the graded beds tends to be devoid of organic remains or structures, except for worm tracks on some bedding planes and planktonic organisms. This supports the claim for deep-water origin.

A large variety of divergencies from this typical development occur, but in the present stage of investigation it cannot be said to what extent such features are exceptional or common. In a general way, however, it appears that some series tend to show certain abnormalities and in other occurrences different features are again the rule. This indicates that certain features belong to special environments or to special types of source materials.

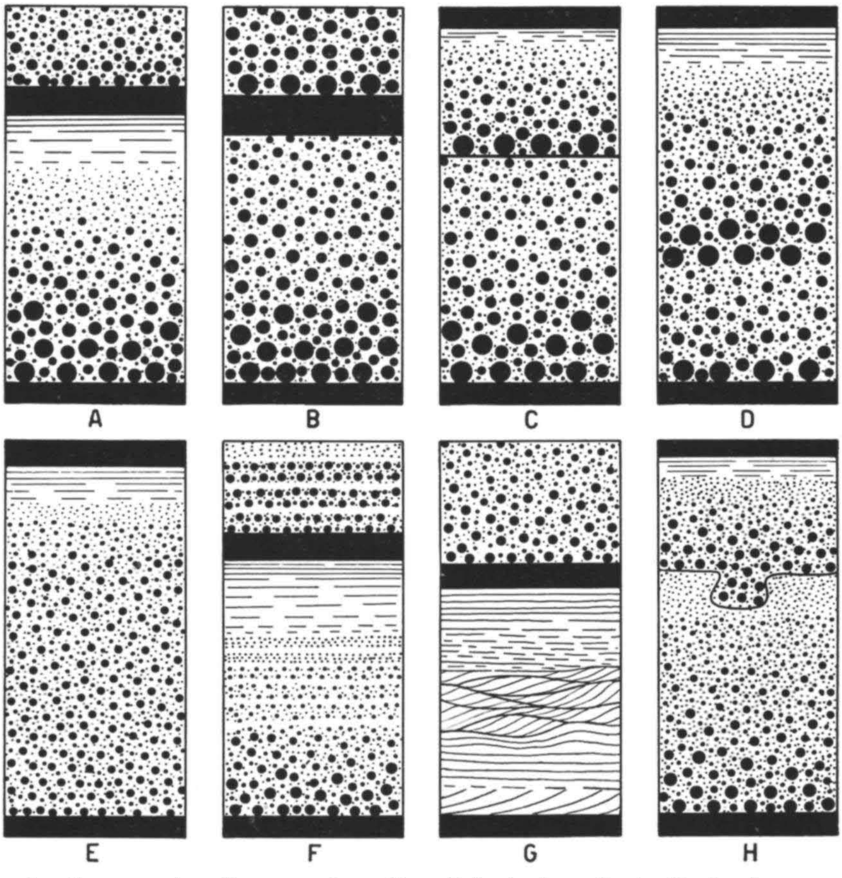

Fig. 1. Comparative diagram of grading. Pelagic deposits in black. A = normal grading, B = top missing below shale, C = top of lower bed missing, D = recurrent grading, E = lower part not graded, F = lamination, G = current and current-ripple bedding, H = flow cast.

The following divergencies from the typical case have been observed.

1) In many occurrences the upper fine parts are missing in all beds or in some. This may have various causes. There may be deep-water sediment between such beds or not.

a) The fine grains are missing in the source materials. This cannot apply where they are present as intergranular mass in the bed itself, the usual case.

b) The fine part has been deposited, but was eroded by the next flow. The graded bed must then be followed directly by the next graded bed, without normal deep-water sediment between (Fig. 1, C).

c) The slope was sufficient for the tail end of the flow to carry its load of fine sediment further away (Fig. 1, B). These conditions must have prevailed in the Ventura Basin and the Welsh geosyncline. The same explanation may possibly apply to the floor of the Atlantic although the slope is very slight (ERICSON *et al.*, 1951).

2) Although well graded, a bed may contain occasional large grains at higher levels. These may be of normal density, but often they are lighter (clay flakes, diatomaceous earth, etc.).

3) Flakes or chunks of fine silt or clay are frequently found included in graded sands. Occasionally these inclusions occur in swarms or along certain horizons all along a graded sand. Sandy inclusions are more rare. The size and shape may vary and angular or rounded fragments may occur together or separately. Bent slabs testify to the unconsolidated state in which the fragments were transported. The oblong pieces are generally oriented parallel to the bedding but occasionally they stand on end.

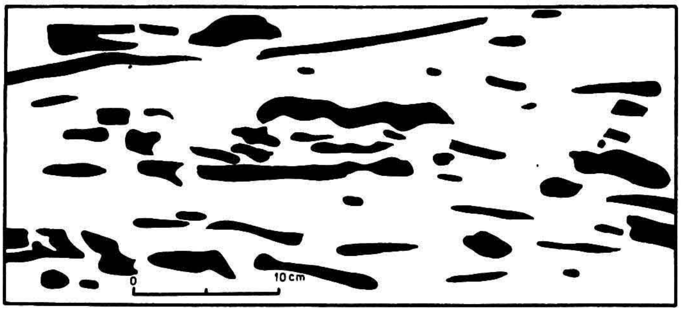

Fig. 2. Swarm of shale inclusions in centre of graded grit 100 cm thick. The swarm is a meter long and tails off to the left and ends abruptly to the right. Old quarry in Barmouth Grits.

In more than one case the author has observed that conspicuous swarms occur in a non-graded, relatively coarse stratum resting with irregular surface on a graded bed. Obviously this represents the result of a local slide which has carried material of older beds along in the wake of a turbidity current.

4) A well graded bed reverts suddenly to coarse, the upward grading starting again from here (Fig. 1, D). This may be due to erosion by the second flow, but more frequently the swift, dense head of the second flow has evidently caught up with the sluggish tail end of the first one, and dived below it, starting to form its own graded bed before the lower bed was completed.

5) Grading is absent in the lower part (Fig. 1, E). This can be accounted for by a turbidity current with a uniform, long continued supply (see KUENEN and MENARD, 1952).

6) The coarsest grain is found a short distance above the base of the bed. The current was probably not yet fully adjusted or the flow showed pulsations.

7) Grading is absent throughout.

a) The source was well sorted sand and only lutite was added during the flow. Careful analyses may bring out slight grading (see ERICSON *et al.*, 1951).

b) The deposition took place so near to the origin that the turbidity current had not yet succeeded in sorting the materials.

c) The deposition was not from a true turbidity current, but from a slump, or

d) from a wedge-shaped stratum moving along below a normal turbidity current (see KUENEN and MENARD, 1952). In the latter three cases the bed was deposited on a relatively steep slope.

8) The bed is laminated (Fig.1, F). Coarse, irregular lamination may be observed in more or less distinctly graded beds which were deposited close to the origin, such as proximal varves. Very regular lamination is not unusual in the fine sandy or silty parts of the graded beds. Thus beds with a coarse lower part may be laminated in the middle or towards the top, and beds starting with fine sand may be laminated throughout or only in the lower parts. The origin of this feature is not yet clear, but is probably due to the traction of grains along the bottom.

9) Current bedding and ripple mark (Fig. 1, G). In laminated beds associated with markedly graded sandstones the lamination may show current bedding. All gradations from slight lensing or long drawn-out wedges to small scale, steeply dipping current bedding are represented, sometimes in combination the one with the other.

In beds exhibiting slight current bedding the grading may still be quite distinct. It is usual for intensively current bedded sands to be poorly graded, except for the finely laminated cover.

Current ripple marks may be detected by the typical type of current bedding or they may show up on bedding planes as asymmetrical subparallel ridges or linguoid ridges.

In the Gamlan Flags of Barmouth and in the Upper Llandoverian of Aberystwyth the following relations are very common. The fine grained beds of a few centimeters thick start with a current bedded basal lamina one or two centimeters thick. The dip of all laminae is roughly the same. Then, in the centre of the bed, the current lamination is of the ripple mark type, consisting of a number of separate units with wavy surfaces, each built up by a sequence of concave wedging laminae. The top of the bed is formed by slightly wavy current bedding with small dips which smooth off the bed upwards. Parallel laminae may mark the end of deposition. Significantly all current bedding in the whole series indicates the same direction of supply and this direction corresponds with the flow marking (see RICH 1950). In an abandoned quarry at the northern outskirts of Aberystwyth a large surface with sub-parallel ripple marks is visible, and, close by, a surface with short-crested ripples, both again indicating roughly the same direction of flow as the flow marks.

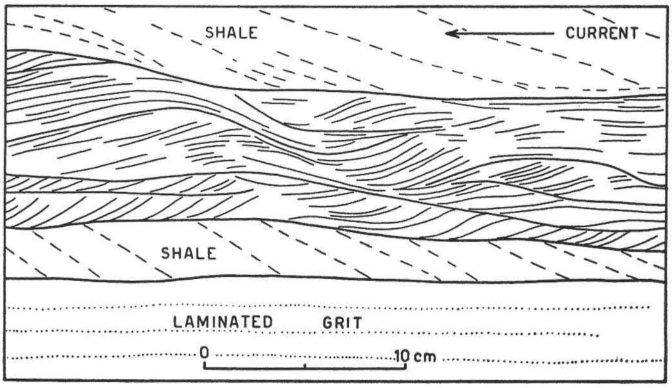

Fig. 3. Ripple bedded, graded fine grit between shales with cleavage (from photograph). Gamlan Flags, Barmouth.

The combination of small scale current bedding and grading in one and the same sequence has been reported by several authors. For instance the Pre-Cambrian Halifax formation of Nova Scotia shows graded bedding and ripple current bedding according to SHROCK (p. 8, 80, 83, 1948). MERRITT reports the combination of cross-bedding with graded bedding in graywackes alternating with shales. The cross-bedding has been slightly deformed, evidently by hydroplastic contemporaneous movements, because only the lamination and not the bedding has been affected. These structures are stated not to be combined in a single bed, as a rule, but the writer found many grits in Wales which are characterized by both. And as early as 1935 HENDERSON already noted small scale current bedding in graded graywackes in the Ordovician (Ardwell Beds) of Scotland. LAMONT (1938) reports the following combinations from County Dublin. Ordovician: graded graywackes, irregular graywacke beds with shale fragments, slump structures. Lower Carboniferous: graded sands and conglomerate beds, ripple mark, graded sand with angular shale fragments and what is evidently convolute bedding towards the top (his Fig. 5) current bedding shown in load casts (his Fig. 4).

VAN STRAATEN (personal communication) observed some small scale current bedding in the macigno of Florence. The writer has later found that this feature is common in these graywackes.

KSIAZKIEWICZ (1948) reported widespread grading with intervening fine grained deposits in the Carpathian Flysch. But current bedding, with uniform direction of supply in a single bed, is likewise common. The attempted explanation of the current bedding by undertow, requiring continual changes in depth to account for the alternation of deep-water graded beds with shallow-water current bedded deposits is far less satisfactory than the simple picture offered by the turbidity current mechanism in which no changes of depth are needed.

In the Ventura Basin ripple marks occur locally and current bedding is ubiquitous.

The reason for occasional development of ripple marking appears to be that ripples are known to be formed only between certain limiting velocities. Where conditions are favourable to lamination and current bedding the bed velocity at a certain point may first be too high for rippling, probably more than 50 cm per second. As the velocity decreases rippling starts, attains a maximum and then falls off again. By the time the tail of the turbidity current is passing the point in question at a velocity below 25 cm per second, rippling stops and the top of the bed is deposited in parallel flat laminae. In the Ventura Basin rippling is mainly restricted to sandy beds between conglomerates evidently formed as foresets to a delta. In this instance a relatively steep slope, and possibly a submarine valley appears to have favoured the development of ripples (NATLAND and KUENEN, 1951).

Here, for the first time, definite information is provided on the velocity of turbidity currents in nature. Assuming that the maximum velocity in the current is double the bed velocity, the grits showing a rippled centre were deposited by currents with a velocity of more than 1 meter per second at the head and less than 50 cm per second towards the tail. These figures, however, are subject to modification if critical velocities for rippling are different in turbidity currents than in clear water.

BAILEY emphasized that current bedding and ripple marking are typical of shallow-water sands and are of little importance in graded graywackes. However, the instances just given show that they are present as small-scale features in almost all graywacke series.

In experimental work they have not yet been produced by turbidity currents but years ago the writer formed current ripples by means of a clear density current of high salinity down a slope under fresh water (KUENEN 1937, Fig. 5, C). It is not improbable that the same may occur with a turbidity current, although concomitant sedimentation may tend to obscure the process.

10) Convolute bedding. This phenomenon will be treated below.

11) Strictly parallel bedding planes are normal, but the upper surface

of some beds undulates and more often the lower surface is found to be irregular.

a) The bed may form irregular pockets in the underlying sediment (Fig. 1, H) as described in detail by Natland and Kuenen (1951) (= load casts).

b) The lower surface undulates slightly and more or less regularly.

c) The lower surface forms sill-like intrusions into underlying, laminated shale or siltstone (Fig. 4).

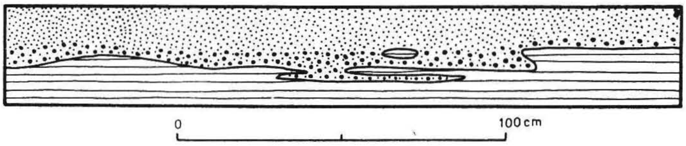

Fig. 4. Irregular lower margin of graded grit showing sill intrusion into underlying shale, part of which has been carried away. Old quarry in Barmouth Grits.

d) The lower bed has been locally disrupted and large slabs are missing. Hence the dividing surface steps up and down across the bedding of the underlying series.

e) Flow markings occur along the base of the graded bed (treated below).

12) Slump structures and pull-aparts. Slump structures resulting from the slipping of beds or series of beds are often found, but do not appear to be nearly as frequent as might be deduced from former descriptions of graded bedding. Many of the structures attributed to slumping are actually convolute bedding in which no (cumulative) horizontal movements have taken place.

Distinction between slump structures and small tectonic structures is sometimes difficult, especially where intensive tectonic movements have later taken place, or when the structure is only partially exposed. Absence of slickensides on bedding planes and of cracks infilled by quartz or other vein material in thick beds of sandstone or limestone may indicate deformation in unconsolidated materials without a heavy overburden. However, the presence of these features is not proof of tectonic origin. They may have been induced later, in a tectonic phase, when movements have been concentrated in slump structures of penecontemporaneous nature.

III. Convolute bedding

Migliorini has observed a curious type of crumpling of certain laminated horizons in many of the graded macigno sandstone beds. The most typical characteristics are firstly that the crumpling increases in intensity upwards in a bed and then gradually dies out again, so that the upper laminae of the same bed are again flat. The length of each successively higher lamination plane between two vertical lines gradually increases to a maximum and then diminishes again without renewed increase. There are cases, however, in which the top of the crumpled zone has been eroded and shale deposited unconformably on the decapitated structure.

Secondly no rupture of laminae has occurred. Therefore individual lamination planes can be traced across a number of undulations. These show rounded distortions without angular nick points.

Thirdly only one bed or one horizon in a bed is affected at a time, and there is only one system of distortions in a single bed. But the disturbance can be traced with extreme regularity for great distances over the bed in all directions.

Fourthly the affected bed shows no external irregularities in thickness. Finally the degree of distortion is in many case of almost equal intensity in two planes, one parallel the other at right angles to the original slope.

Typical examples are exposed on the abraded shore south of the Afon Ystwyth (Fig. 5). Individual beds can be traced for 120 meters with constant thickness and degree of convolution. They are separated from grits without internal deformation above and below by only a few centimeters of shale.

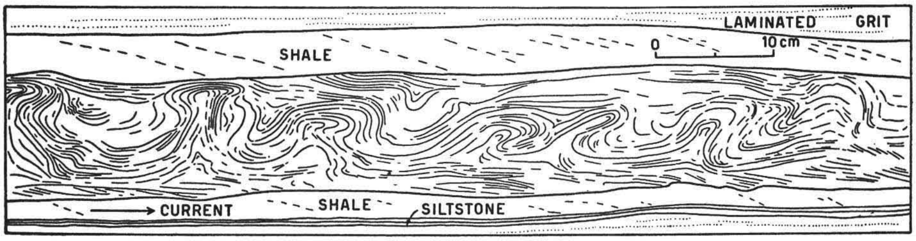

Fig. 5. Convolute bedding in fine grit with undisturbed, current bedded base lying between shales with cleavage. Section about parallel to slope (from two combined photographs). Upper Llandoverian, south of Aberystwyth.

Undisturbed current bedding or lamination may occur below in the same bed and the undulations may be smoothed off in the same manner before the deposition of the bed came to an end. Hence the deformation took place during sedimentation by the turbidity current and this process cannot have occupied more than a few hours, probably much less. The structure is therefore contemporaneous in the most strict sense.

MIGLIORINI has applied the term "crinkled bedding" to this curious structure. FEARNSIDES and other British authors have earlier referred to this phenomenon as "curled bedding", but as far as the writer is aware without closer description. ALLAN spoke of "crenulated bedding" when describing the same structure from an early Pre-Cambrian graded graywacke series (SHROCK 1948, p. 81). KSIAZKIEWICZ (1950) used the terms slipbedding and corrugation in describing structures from the Carpathian Flysch, part of which are evidently convolute bedding. NATLAND and

KUENEN encountered this structure in the Ventura Basin. JONES and PUGH mention the structure as "twisted and contorted laminae" from Aberystwyth and RICH later on gave a detailed description calling them intra-stratal contortions or crumplings.

The present author proposes the term "convolute bedding" to indicate the most typical properties of distorted lamination planes without rupture of the laminae, and of rounded as opposed to angular distortions.

MIGLIORINI attributed the structure to compaction and extrusion of enclosed water during the accumulation. NATLAND and KUENEN took exception to this view and pointed out several objections to MIGLIORINI's suggestion. RICH, on the other hand, believed that sliding, after the covering bed had been deposited would explain the dying out upwards and downwards of the folds. The required larger-scale adjustments in the strata somewhere farther down the slope at the time of crumpling he believed to have traced in disturbed zones of pseudo-tectonic(?) nature, which occur here and there in the Aberystwyth area.

For several reasons this explanation cannot be accepted.

1) The crumplings continue through the large-scale structures without any change in intensity. Evidently the convolute bedding was fully developed before the large structures were formed.

2) Several dozens of beds are folded together and in the same degree in the large structures. This means there was no differential movement between them to account for the convolute bedding.

3) In some convolute beds the anticlines are cut off and end with a clean-cut surface against the overlying shale, or upper laminated part of the bed itself.

4) In a few beds the structure shows that after an undulating surface had developed the troughs were filled up with cross-bedded laminae until the bed obtained a flat upper bedding plane.

5) The convolute beds are of wide extent. Therefore the thin covering clay stratum cannot have been held in place. It must have slid down at least as far as the underlying slumping sand. Hence it should have been pulled apart at the higher end and folded or overthrust lower down. It is typical of the shales, however, that the beds are of extreme regularity without any of the complicating structures of the directly adjoining convolute bed.

The enumerated arguments clearly show that no horizontal mass movements accompanied the deformation of the lamination planes. Hence one must agree with MIGLIORINI that the whole structure was ready by the time the bed had been built up.

The following was found by examination of the convolute bedding in the Upper Llandoverian of the Aberystwyth district. Besides beds with plane-parallel lamination there are several fine grained grits with concave, wedging lamination of the type associated with ripple mark, as described above (Fig. 3).

In a number of beds internal plastic movements started during the rippling but these left the lower part of the bed undeformed (Figs 6 and 7). RICH thought the entire bed was affected, but this is generally not the case. This plastic movement is demonstrated by the current bedding showing dips that are partly too steep or dipping the wrong way, although the wedging indicates that originally they dipped down current. This may go further until vertical or overturned lamina are developed. Soon the movements began to die out again, while low-angle ripple bedding continued to develop on top. The synclines filled up and the surface became smooth. If sedimentation continued, a cover of parallel or only slightly current bedded laminae finished the building of the bed.

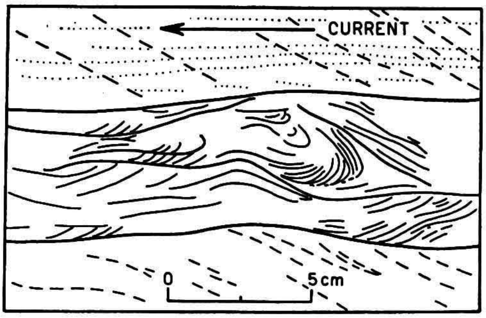

Fig. 6. Current bedding overturned by slight convolution (from photograph). Gamlan Flags, Barmouth.

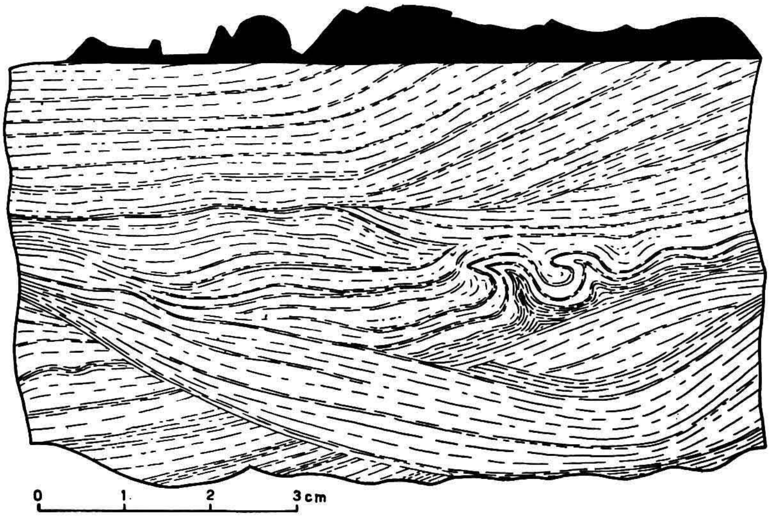

Fig. 7. Cross-section of fine grit at right angles to bottom slope. Flow marking at base. Current bedding with minute convolution. Covered abruptly by shale. Aberystwyth.

More commonly the current bedding is less clearly developed. Although the sequence of events is then less obvious, one can still trace how the plastic deformation was gradually intensified, while at the same time each successive lamina tended to level off the surface again by showing a greater thickness in the troughs than on the ridges. This thickness cannot be attributed to post-depositional diapiric sinking of the synclines and raising of the anticlines, because in that case the laminae must have been thickened in the core by flowage from the limbs and crests. In the evident absence of lateral compression with convolute bedding such a process appears to be impossible in materials of uniform composition (Fig. 8).

Careful examination shows that although many laminae cross the ridges in a thin film, there are also many ridges over which the laminae are absent. Slight current bedding in the upper few laminae often obscures the true relations.

Less frequently but by no means exceptionally the anticlinal crests have undergone erosion during this development, which may be followed by the deposition of slightly current bedded laminae.

These observations lead to the following picture. The sandy deposits forming by a turbidity current are in a highly mobile condition like quicksand or saturated beach sand that is patted with a flat object. The development of pockets in nature and in the experiments testifies to this mobility. In this quasi-liquid state very small forces will suffice to cause plastic deformations. If the velocity of the turbidity current sinks below the upper limiting value for ripple marking and a ripple pattern starts to develop, internal forces are set up in the bed and it reacts by plastic deformation.

Two possibilities can be imagined. One is that the crests form a load and settle downwards pressing up the troughs. But because of further accumulation the process proceeds until the current drops below the lower rippling velocity, whereafter a series of parallel laminae can be laid down on top. Shrock (1948, p. 157) suggested this mechanism to explain some types of load casts.

The other explanation is, that after ripples have formed pressure is exerted by the water in the troughs and suction on the ridges (apart from the hydrostatic pressure) in the same manner as by wind blowing over waves. The difference in pressure would cause the initial deformation. The deepening of the troughs will lead to deposition. Thus pressure and loading will work hand in hand to cause further deformation. The process ends for the same reasons as given above.

The writer is inclined to favour the latter view because he found several instances in which the ripple bedding is overturned on the up-current side of the synclinal depression. This shows that the structural syncline formed a concave surface (a ripple trough) at an early stage of development. If the synclinal depressions had formed below a convexity of the surface (a ripple ridge) the ripple bedding could only be developed on the down-current side of the ripple crest, that is on the down current side of the syncline also. Conceivably both cases occur in nature, dependent for instance on the steepness of the ripples forming.

The observed decapitation of the anticlinal crests happened in final stages, when the rippling was dying out and when erosion in the ripple troughs is highly improbable. This, again, shows that the structural crest formed below ripple crests and not from ripple troughs.

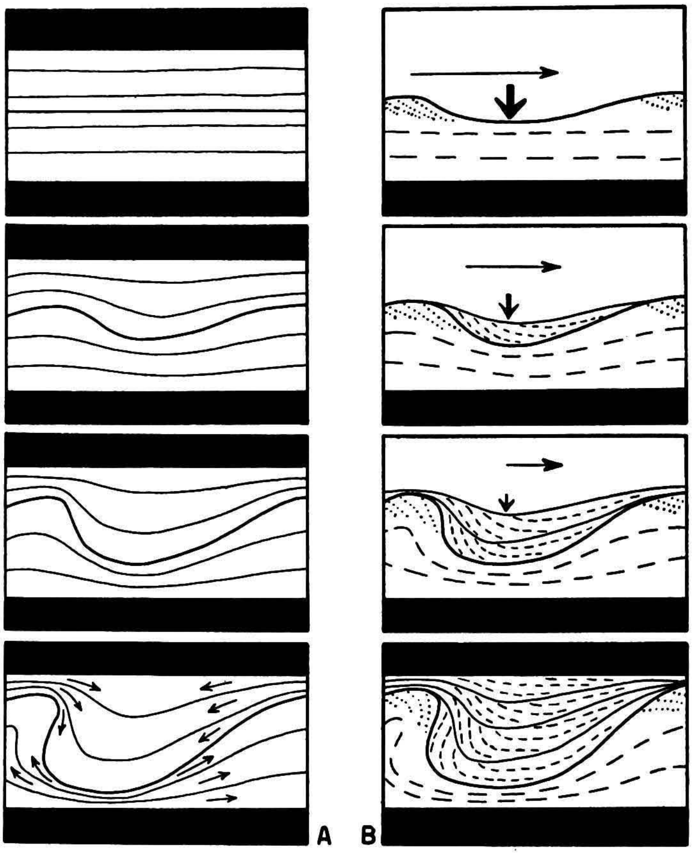

Fig. 8. A. Thinning and thickening in laminae of bed required if convolute bedding is explained by post-depositional diapiric movements without horizontal compression.
B. Development of convolute bedding from ripple mark by downpressing and infilling of troughs. Overturned current bedding on up-current side of structural trough.

Finally reference to Fig. 5 will show that the structural troughs are broader than the ridges. This accords with the greater breadth of ripple troughs than ripple crests. One cannot easily imagine how the sinking of narrow ripple crests could build broad structural troughs and the rising of broad ripple troughs lead to narrow mushroomed anticlines.

From a quantitative point of view the proposed explanation appears possible. Prof. THIJSSE of Delft kindly informs the writer that with a current flowing over a ripple the dynamical difference in pressure between trough and crest is proportional to the square of the velocity. With a velocity of 60 cm per second, measured 25 cm above the crest of a ripple, 12 times longer than high, this pressure difference may be estimated at 2.5 gr per cm^2. This is the velocity believed to correspond with the development of the ripples. If the density of the mobile, water-logged deposit is estimated at 2 (under water 1) the ripple crests will represent a hydrostatic overburden of 1 gr per cm^2 for every centimeter of elevation. In our case the ripple length was about 15 cm and the height may be estimated at 1.25 cm. Hence the dynamical pressure should not only have carried the weight of the ridges, but have tended to press down the trough floors. Given sufficient mobility of the deposit hydrodynamics therefore favour the explanation offered.

Whether the deposit was sufficiently mobile to react to this pressure cannot be proved. But at any rate the crests could not sink by their weight.

The close connection between rippling and convolute bedding in the studied rocks is brought out by examination of partly abraded beds. Some of the beds on the shore off Constitution Hill and the surface of many of the huge blocks that have tumbled down the cliffs south of the Afon Ystwyth (Plate A, 1) have been abraded by waves in such a manner that the laminated silt at the top has disappeared. The horizontal section through the top of the convolutions thus produced presents a pattern strongly recalling ripple marking, both in shape and in size. The crests are oblong in some slabs with the longer axes parallel. Interchanging is seen just like that of ripple marks. On other surfaces the pattern is more or less regular but with short-crested ridges resembling some types of linguoid current ripple mark formed in shallow currents. As far as the author has observed the crests are roughly at right angles to the deduced direction of the turbidity currents. In a number of beds the anticlines heel over in the down-current direction. Conversely this might help to show the direction of slope if other data are lacking.

The explanation of convolute bedding by the action of ripple marking thus accounts logically for the high degree of deformation in many beds in directions both parallel and at right angles to the original slope (Fig. 9). This type of convolution evidently belongs to short-crested (linguoid) ripple marking.

Further investigation will have to show whether all instances of convolute bedding in other areas can be accounted for by the intervention of rippling. The "corrugations" described and illustrated by KSIAZKIEWICZ (1950) strongly recall our convolute bedding and are also associated with graded bedding, current bedding, and slump structures. The horizontal pattern recalls ripple mark. Whether, in this case, a sharp line can be drawn between real slumping (upper half of his fig. 3) and convolutions without horizontal slip (lower half of his fig. 3) is doubtful. There appears to have been more erosion towards the end of the turbidity flows in the Carpathian Flysch and in the Ventura Basin.

In the macigno sandstones the large scale of some of the convolutions might be interpreted as the result of rippling above the third critical current velocity when large ripples are formed. A later smaller generation of convolutions should develop below the second critical current velocity. However that may be, it seems highly probable that some slight cause started the plastic deformation during the sedimentation and concomitant sedimentation caused the movements to continue. Once the excessive mobility of the deposits *in statu nescendi* is admitted, one can conceive of differential movements being initiated and bringing about the fantastic contortions known to occur.

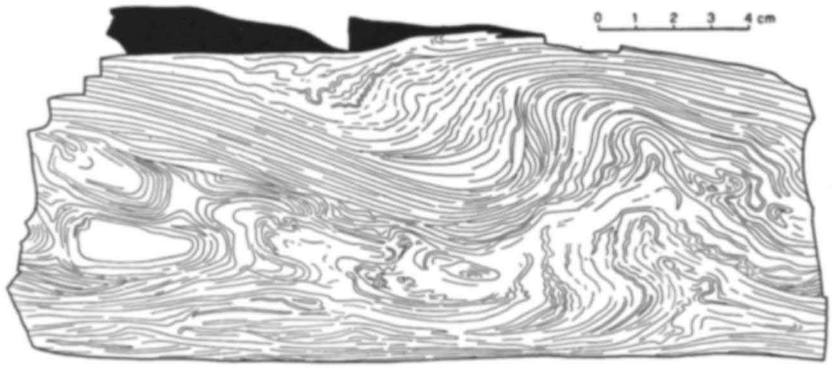

Fig. 9. Convolute bedding in graded bed. Section nearly at right angles to the slope shows strong movements. Same bed as Fig. 5.

A *conditio sine qua non* for the development of convolute bedding is excessive mobility of the deposit while it is being formed. Clean sand probably does not acquire this high degree of plasticity when being deposited from a normal current. It appears likely that the muddy character of sandy or silty beds forming from a turbidity current render them prone to internal distortions. Muddy sands formed under other conditions are rare. The sand with faecal pellets of mud flats is not very mobile. Hence, it may be that convolute bedding is restricted to graded series.

If the explanation by rippling is correct, there is yet another reason for this restriction. For it is only in turbidity currents that the combination occurs of relatively high current velocity with deposition of fine grain. If future search for convolute bedding shows that this type of deformation is restricted to graded series, the above conjectures will find confirmation.

IV. Pre-consolidation structures

For a clear understanding of convolute bedding it is necessary to realize the differences with some other contemporaneous and penecontemporaneous deformations which they somewhat resemble, more especially slump structures and load casts.

A typical slump structure is formed by the sliding of one or more beds *after* the deposition. Hence it is a *structure* and not a type of bedding.

True slumps are characterized by one or more of the following features: occurrence between undisturbed beds, rupture of the beds at the higher end (pull-apart structures, generally not exposed or not obvious), piling up or thickening of beds at the lower end, beheading of anticlines, the dying out downward of the deformation, less seldom also upwards, balled-up structures of sandy or calcareous beds surrounded by more plastic material (clay or lime mud), sliding planes, faults, general irregularity of structures often showing similar intensity in sections parallel and at right angles to the slope, internal rupture of bedding planes, brecciated masses, abrupt changes in thickness of beds, the partaking of more than one bed in the movements, irregular surface sometimes smoothed off by a graded bed or by infilling with laminated deposits, the duplication of beds on top of each other.

Baldrey and Brown have made out a strong case for the occurrence

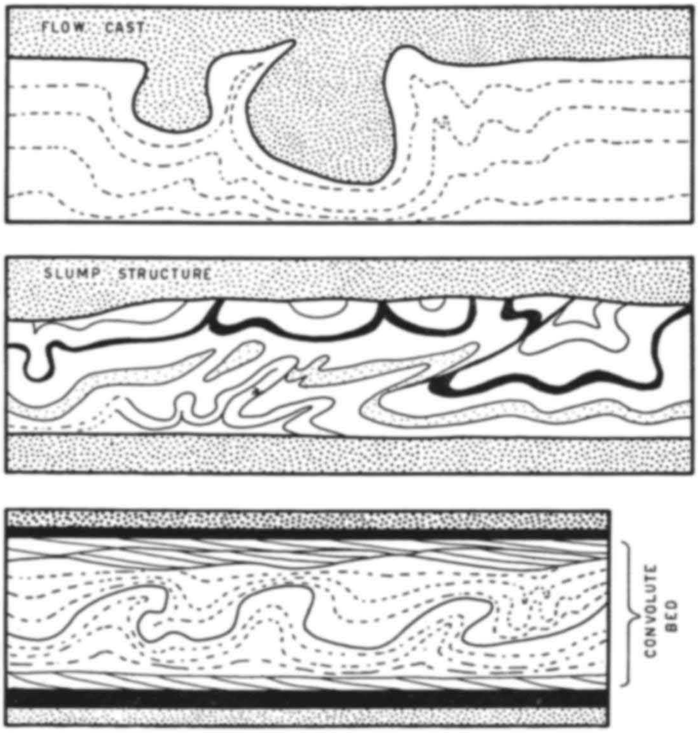

Fig. 10. Diagram showing some soft-rock deformation types: 1) load cast, developed by plastic deformation of a bed under a later load (formerly called flow cast); 2) slump structures due to horizontal movement of beds after deposition; 3) convolute bedding developed during deposition of the bed without horizontal mass movement.

of gravity sliding on a much larger scale involving sediments hundreds or even thousands of feet thick. The latter author and CHALINOR have advocated the possibility of processes of intermediate size in semi-consolidated rocks.

It is also probable that some types of gravity slumping resemble subaqueous creep, occurring slowly over long periods during which sedimentation continues.

The essential difference between slump structures and convolute bedding is the horizontal movement in the former.

In the "flow casts" [1]) described by SHROCK the deformation is caused by loading of a hydroplastic deposit, generally by sand. The maximum deformation of the load is at its base and dies out upwards, in many cases already close to its bottom. The usual shape is of rounded bags with the plastic substratum wedging up between. The deformation usually dies out in the plastic substratum from its upper surface downwards, but in other cases the greatest complexity is at somewhat lower levels. The substratum tends to show more angular bending, slipping and variable thickness of its laminae. The difference between load casts and convolute bedding is that in the former the plasticity is due to the substratum with different mechanical properties. With the convolute bedding the cause lies in the plasticity of the mechanically uniform bed itself. [2])

Load casts tend to be more irregularly distributed and of variable size, often occurring as a single separate structure, while convolute bedding is characterized by its regularity in size and shape occupying the entire extent of the bed.

Both types differ from slump structures by the absence of horizontal mass movement. In all three types the structure is usually non-directional or at least less directional than in tectonic folds.

Matters are complicated by combinations occurring. Superficial erosion of convolute bedding is not unusual. Also the folds are asymmetrical in some beds, evidently due to drag by the current and to down-current wandering of the ripples. In the example of load casts given by SORBY (see SHROCK, Fig. 118) a slight lateral shift has deformed the casts. The current has nothing to do directly with the structure because the wavelike deformations developed under a covering of sand. But this sand (ash) moved by gravity and probably by drag of the depositing flow. The writer collected samples from the same locality, one showing a slump structure

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[1]) The term refers to the filling of the negative features produced by the flowage of the soft underlying sediment, not to the flow or slumping by which the load was brought into place. The term "load casts" is more appropriate.

[2]) VAN STRAATEN has noted (personal communication) several cases of pre-consolidation deformation greatly resembling normal load casting, but upside down, with the sand forming rounded pockets upwards into clay or peat. Some of these are associated with perma-frost structures (ice wedges). Classification of these deformations must await a clearer understanding of their genesis.

(flow breccia), another erosion of the load cast structure by a current, before the following beds were deposited, and again a load cast with some covering laminae deformed in a second period of larger scale load casting.

Long ago FUCHS described "Fliesswülste" from the Alpine Flysch which are identical with certain types of load cast described by SHROCK. FUCHS was able to reproduce these forms in all detail by allowing plaster of Paris or cement with sand to flow over hydroplastic clay. This is strong evidence that the natural "flow ridges" he described were produced along the base of the load during lateral creep.

BROWN (1938) described ridges on the under surface of sandstones, which eventually became detached and rolled over in the shale below. This is much the same process as MACAR and ANTUN found by careful analysis of "pseudo nodules", a combination of the load cast mechanism with slow creeping slump.

The conclusion is warranted that the essential condition for the production of load casts is the loading of hydroplastic sediment by an overburden, but that when this burden moves laterally during or after deposition the process is intensified and rendered more complicated.

Cryoturbate (frozen ground) structures are partly due to solifluxion and then belong in the same class as slump structures. In other instances the type of deformation is that of load casting without horizontal movement. In both cases the mobility is a result of the poor drainage in the permanently frozen subsoil. It appears likely, however, that the pressure due to freezing of groundwater has often played a part in cryoturbate structures. The movements have little to do with the conditions of sedimentation and might be termed post-contemporaneous in contrast to pene-contemporaneous sliding, contemporaneous load casting, and ultra-contemporaneous convolute bedding.

Ice wedges, polygonal soils, etc. are not considered here.

V. Flow markings in the Aberystwyth area

JONES and PUGH had already observed curious markings on the lower surface of the Llandoverian grits around Aberystwyth.

Since RICH (1950) has described them no detailed account need be given here. But it may be recorded that the present author found a sample exactly similar to the photograph reproduced by RICH depicting flow markings in the Berea Sandstone (his fig. 6).

It also greatly resembles the "lobate rill marks" of SHROCK's fig. 92 from the Devonian Portage sandstone of New York. The "groove casts" shown by the same author in fig. 121 are also represented occasionally at Aberystwyth.

Some hesitation may be felt in accepting RICH's explanation of these markings by current erosion. The remarkable degree of parallelism over wide areas both north and south of Aberystwyth and through thick series of beds always with the deep end pointing south southwest and the tapering end towards the north northeast, and the similarity to stream fluting in limestone are admittedly strong evidence in favour of the proposed explanation.

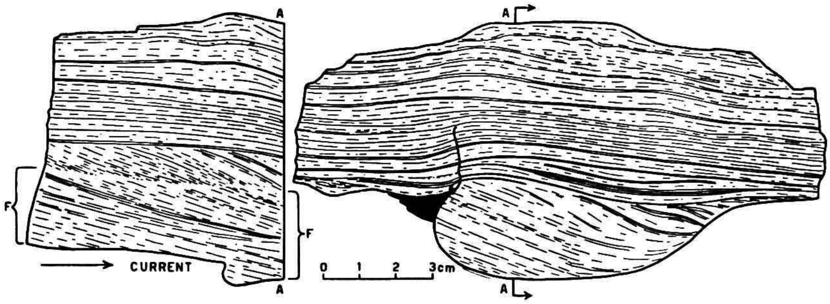

Fig. 11. Cross-section of flow marking on the right, longitudinal section on the left. Current bedded fill. Lower part of coarse grit from old quarry at northern end of Aberystwyth.

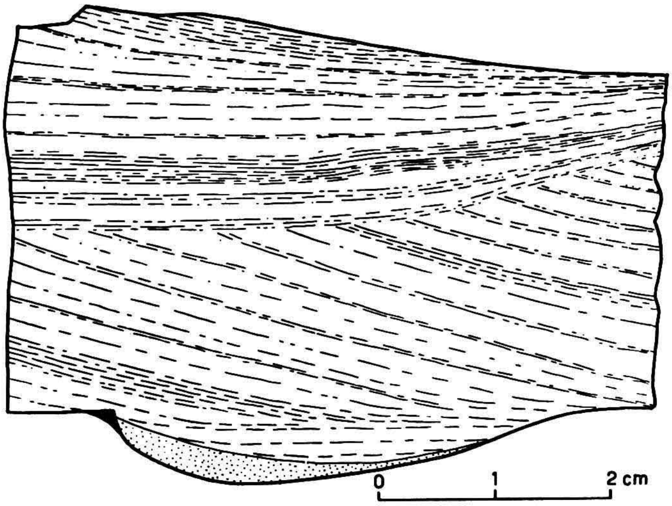

Fig. 12. Section of flow marking with coarse grains at bottom and current bedded cover. Lower part of fine grit from old quarry at northern end of Aberystwyth.

During the present investigation further support of this explanation was supplied. Firstly the evidence for turbidity currents deriving from the graded bedding, and therefore that swift flow actually did sweep over the marked bedding planes. Secondly the current bedding indicating roughly the same north northeasterly direction of flow. Thirdly the observation that the grooves in the shales were filled by fore-set laminated sand before the next bed was deposited, but this sand forming part of the covering bed (Fig. 11). In other flow marks some abnormally coarse sand collected in the hollows before infilling (Fig. 12). This shows that the markings were not developed by some process after deposition of the covering grit.

As the two ends of the grooves are of a different shape, all with the deep one pointing south south west-wards one cannot assume that they were formed at right angles to the current. Moreover, the ripple marks and current bedding provide convincing evidence that the beds around Aberystwyth were deposited by currents flowing towards the north northeast. The intermittent nature of the currents excludes the action of normal ocean currents. Therefore the conclusion cannot be avoided that it was the slope that directed the currents to the north northeast.

It is significant that the same feature was illustrated by Rich from the Talara shale of Peru and that Dorreen has since shown these beds to be typically graded. It remains to be seen whether all flow markings of this type are associated with graded sands and are characteristic of turbidity current action.

VI. Observations on grading in the Welsh geosyncline

The time available to the writer was insufficient to make a regional study of the occurrence and nature of graded bedding and associated structures, even in the small part of the Welsh geosyncline visited. The writer hopes, nevertheless, that the following account of his observations will help to convince others of the importance of noting these features as routine field practice. To go out and collect this type of data separately over wide areas is a formidable task. On the other hand, without additional effort during the mapping it would have been possible to cover a map of the whole Harlech dome with arrows denoting the direction of supply, and to ascertain much as to the relative steepness of submarine slopes.

For the Harlech dome conclusions to date were that depth had varied greatly and that pebbles have come from the east, although there is also some evidence for a westerly source.

The following preliminary results can be recorded.

Cambrian of the Harlech dome

Dolwen Grits. Bedding in these generally extremely fine grained grits is usually poorly developed and no grading was observed.

Rhenog Grits. In some exposures, as below Harlech Castle and in a small quarry just south of Parsel (north of Barmouth) the bedding is regular, the grits varying in thickness from a few centimeters to 2 m, the majority

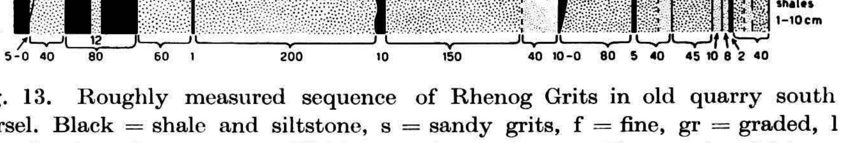

Fig. 13. Roughly measured sequence of Rhenog Grits in old quarry south of Parsel. Black = shale and siltstone, s = sandy grits, f = fine, gr = graded, l = laminated, c = coarse. Thicknesses in centimeters. Top at the right.

well graded from very fine gravel to silty sand, and with thin shales between. Fig. 13 shows the roughly measured sequence exposed in the quarry south of Parsel.

In other localities the grits are less regular, attaining up to 5 meters in thickness, but owing to poorly developed shales the bedding is indistinct. This appears to be the greatest thickness of individual beds anywhere in the Harlech dome. Grading is usually poorly developed; the maximum grain size is upwards of 10 mm. This type occurs along the road 4 miles south of Trawsfynydd, on the slopes above Parsel, and along the road north of Harlech. The exposures examined at the northern outskirts of Barmouth and further along the road, and those in the Afon Gamlan represent intermediate cases.

Manganese Group. The grits exposed in the Afon Gamlan are moderately well graded. In one, 40 cm thick, the base contains pebbles of 5 mm, the top coarse sand of 1–2 mm. Along the road north of Harlech the grading of the grits just above the ore bed is poorly developed. In the shales ripple bedding is shown.

Barmouth Grits. Along the footpath running to BwlchyLlan and around Cell-fawr on the higher slope above Barmouth the grits are thick and very coarse with pebbles up to 3 cm. The bedding is irregular and sometimes indistinct owing to poorly developed shales. The grading is mostly poor, but several beds are well graded. Load casts are frequent.

In the old quarry at Barmouth the bedding is very regular. A tectonic (?) complication crosses the quarry. The grading of most grits is highly conspicuous with pebbles up to 8 mm in the base of some, the top being formed by medium or fine sand, sometimes laminated. Some beds show recurrent grading. The thickness of the beds varies from 100 cm down to a few centimeters. Inclusions of shale occur in several beds. Many pockets, "sills", undulating bases etc. are found. The thin grits show ripple bedding with a southerly direction of supply and convolute bedding. The upper grit in the quarry wedges out to the south and shows a complicated base and internal structure (Fig. 4). At the eastern side of the former entrance a remarkable slump structure occurs (Fig. 14).

Along the road north of Harlech the grits are intermediate between the

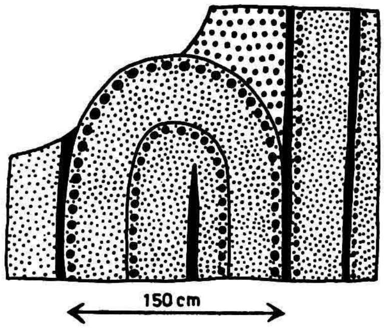

Fig. 14. Diagrammatic horizontal section of slump structure in Barmouth Grits. Old quarry in Barmouth.

two former types. East of the quarry and in the Afon Gamlan the same type is found as in the quarry.

Gamlan Flags and Grits. The best grading found in the Harlech dome by the writer was developed in the Gamlan grits. Only very few show no grading and the great majority range from coarse sand (2 mm) or fine pebbles (8 mm) to very fine sand or silt. Along the shore at Barmouth a series of 60 meters thick is perfectly exposed. There are two dozen grits of 15 to 60 cm thick. Only two or three of these show poor grading. One of the latter is formed of a graded lower part and a non-graded upper part containing many large inclusions of shale. One bed of 22 cm thick consists of two parts, each graded with a highly irregular boundary, the upper part with convolute bedding. Convolute bedding is also developed in a thick grit with the anticlinal crests dragged slightly in a down-current direction, the crests eroded and the material carried away before the cover was laid down. This proves that the drag is not of a tectonic nature, although the bed as a whole is bent in an anticlinal shape.

Judging by the average thickness of the Cambrian in this area these beds were deposited in two million years. Hence the time interval between the deposition of the grits was of the order of 100,000 years. A rough estimate for the Aberystwyth grits is 1000 to 2000 years.

For the Ordovician and Silurian graded graywackes of the Southern Uplands of Scotland the average works out at 1000 to 2000 years per graded bed (see HENDERSON, 1935). It is well to realize how exceptional an occurrence was the development of a major turbidity current.

Between the thicker grits of the exposure described a larger number of finer grits less than 15 cm thick are intercalated. Many of these show very distinct ripple cross-lamination with supply from the S.E. Convolute bedding is also frequent.

At the eastern end of the exposure a folded structure is found, which is also seen in the road cutting some 30 meters inland. The writer is inclined to assume it is not tectonic but a slump structure, mainly because of the great variations in thickness over short distances shown by the massive grits without internal rupture, the (total?) absence of slickensiding on bedding planes, the equal competency of grits and shales, and finally the proximity to the slump structure in the underlying Barmouth Grits, mentioned above, because this shows there was sufficient slope.

In the Afon Gamlan the grits are somewhat thicker, less regular, and coarser (grains up to 10 mm). The grading of some beds is poor.

Cefn Coch Grits. In the Afon Gamlan the grits are well bedded from 20 to 40 cm thick. The grading is inconspicuous in some, well developed in others. The grain size varies from coarse sand to silt.

Clogau Shales. No grits were seen in these beds.

Vigra Flags. Fine-grained grits were seen during a hasty examination of these beds, many with ripple mark and convolute bedding, along the road east of Barmouth and at the rapids of the Afon Mawddack north of Tyn-y-Groes Hotel. Grading was not definitely observed, but suspected here and there.

Penrhos Shales. No grits were seen in these beds.

Ordovician and Silurian between Machynlleth and Aberystwyth.

Upper Bala. The Upper Bala south-west of Machynlleth contains some fine grits. Some doubtful grading was observed in these.

Llandoverian. In the neighbourhood of Machynlleth thin laminated fine grits with lensing laminae, wavy current bedding, worm tracks, and typical convolute bedding were observed. The grits are thinner and finer grained than around Aberystwyth, which may be due to greater distance from the source, or to presence of a different stratigraphic horizon.

The Llandoverian exposed in the cliffs from the first bay north of Aberystwyth to two miles south of the town are of remarkably uniform character. It cannot be said how thick is the stratigraphic sequence represented but it must be hundreds of feet at the least.

The thicker grits range up to 50 centimeters and these are also the coarser ones. They show excellent grading from grains of one or two mm to fine silty shale. Lamination is usual and convolute bedding is sometimes found towards the top. The medium grits, in beds of 5 to 20 cm thick, are graded in many cases. Current bedding, ripple bedding, and convolute bedding though absent in some beds are generally specially well developed. The grading then tends to be inconspicuous. Here and there the bedding is coloured from light grey in silts with a sharp lower margin grading in laminae up into black shale, each of these rhythms 10 to 15 cm thick. In other, similar cases the variations in colour are less systematic.

A few slump structures were noted, one with slump balls, one in which a couple of grits had been overthrust 2 meters.

Fig. 15. Irregular bedding due to pull-apart (bed B, with current bedding) and slump structure (bed C with current bedding, etc.), convolute bedding (bed A), in alternating shales, siltstones and fine grits (from photograph). Upper Llandoverian south of Aberystwyth.

The flow markings are highly characteristic. The direction of the current deduced by RICH is N 25°E and this was entirely confirmed by the ripple mark, and current bedding.

In the bay one mile north of Aberystwyth a few thick lenses with cone-in-cone structure were encountered and elsewhere sand lenses are met with.

CHALLINOR and RICH have described somewhat larger contorted structures from this area, which they attribute to slumping. The present author is inclined to agree with this opinion, partly because of the strongly localized mode of occurrence, partly because of the absence of slickensiding on bedding planes and rupture even in strongly twisted thick-bedded grits. However, there is some quartz and siderite veining in cracks in and around these structures. This shows that movements occurred after consolidation in some depth. This may have taken place, however, long after the structures had been formed, merely because the later tectonic stresses found relief in these structural irregularities. It was pointed out above that these structures can have nothing to do, as RICH suggested, with the convolute bedding.

VII. Use of graded bedding and associated features in paleogeography [1])

However meagre the recorded results for the Welsh geosyncline may appear, some significant conclusions of general importance can be drawn from this type of evidence as to depth, slope, and direction of supply.

The first point to be examined is the direction from which materials were supplied.

Up to the present the source or direction of supply of sedimentary particles is deduced partly by their petrographic nature (pebbles) or mineralogical properties (sand grains), partly by noting the direction of change in size of grains or thickness of beds. In some terrestrial or shallow water deposits cross-bedding has been used (ILLIES 1947). Other sources of information are sometimes available, such as regional heavy mineral analysis, or knowledge of where land masses were present.

But it can safely be said that for deep geosynclines the available evidence is extremely scarce. It is therefore of some importance that several new sources of information can now be added: ripple marking, flow marking, current bedding, orientation of pebbles, convolute bedding and properties of graded beds.

The most useful of these is current bedding due to turbidity currents. Most of the groups examined by the writer in Wales and elsewhere showed current bedding and he feels confident there is sufficient evidence in almost all good exposures for roughly establishing the direction of flow. Direction of supply and direction of dip on the sea floor can thus be clearly established.

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1) A more general treatment has been given elsewhere, KUENEN 1952.

In some localities in graded graywacke series all the current fore-setting on a flat vertical rock face points in the same direction. But usually one can find an odd bed here or there in which the direction is opposite in one or a few small patches. However, as far as the author has observed these reversed dips never amount to more than a few per cent of the total.

When two or more rock faces are combined to find the orientation of the current in space rather wide variations are found. The reason is that the ripple crests are sinuous or linguoid. Hence the fore-set laminae must show variable directions of dip even when the current was steady. Probably vortices also formed, adding to the variation in direction of dip. Then, on slight slopes or close to the origin of turbidity currents successive flows will have fanned out. Overlapping edges of the deposits must then show different directions of supply. Hence it is no surprise to find that the fore-set laminae are somewhat variable in orientation. But in most cases the direction of slope of the former sea floor can be ascertained to well within a quadrant or even more accurately.

Mr KOPSTEIN has found (personal communication) that in coarse beds the average direction of the longest axes of pebbles is parallel to the direction of flow and in small areas the variation in orientation seldom exceeds 10° to 20°.

Flow markings give even more accurate data, because they can be measured with greater precision. The ripple markings are likewise excellent pointers for direction of flow. Both features, however, are much less frequent than current bedding in the examined part of the Welsh geosyncline and hence only of local importance.

The information that can be gathered from the grading is less helpful. Individual beds can seldom be traced far enough to show direction of thinning or direction in which the grains become finer. But if evidence were available throughout the examined area it might help to round off the picture.

Coming to the question of depths it is now obvious that the floor of the Cambrian Welsh geosyncline has shown much smaller vertical movements than geologists have been inclined to assume. The entire Cambrian in the Harlech dome is conformable, but the repeated alternation of the fine grained shale groups with the coarse grit groups had been attributed to great changes in depth. Ripple mark appeared to confirm periods of shallow water. The fact that between the grits are similar shales, while the shale groups contain grit horizons does not fit into this picture. Logically one would have to assume great change in depth from each bed to the next.

By attributing the grits and ripple marking to the action of turbidity currents the necessity for assuming small depths during their deposition no longer exists.

The change in character from one group to another can be accounted for in several ways. Uplift around the geosyncline could result in the supply of more and coarser sediment. The slope may have changed through geosynclinal subsidence or fill. Eustatic movements or earthquakes may have favoured the generation of currents more at one time than at another. Without more detailed knowledge of the regional distribution of the various features the correct answer cannot be given.

In the mean time one may guess that epirogenic rejuvenation of relief (glacial influence is excluded) caused steeper slopes to develop together with more abundant supply of coarser sediment leading to the formation of the grit groups. Each grit represents the sum of near-shore accumulation during centuries, carried by a submarine flash flood to the muddy environment, but without change in depths of the sea floor.

The shale groups would mark periods when fill had reduced slopes and denudation had led to a fall in supply of sand and gravel. But the abruptness with which some of the shale groups set in, suggests that the supply of coarse sediment was cut off suddenly in these cases.

This brings us to the problem of slopes. If the above analysis is correct the grit groups tend to mark periods of greater slopes below and above sea level and hence in general of greater depths of water. This would be contrary to what is generally assumed and the reader may feel inclined to reject this conclusion. But it should be realized that the classical conception of clay settling in deep water and sand in shallow water does not apply to graded grits and graywackes. The graded sands and even coarse shell beds recently sampled on the ocean floor form striking examples of coarse deep-water deposits.

On the other hand it is true that in a given stratigraphical unit the turbidity current deposits should tend to be finer at greater distances from the source and hence in greater depths.

Also coarse grain tends to go with poor grading, irregular bedding, and absence of fine tops to the beds or absence of shales in between. The combination should indicate proximity to the source and steep slopes.

Evidently the appearance of coarse grain in a series of graded beds may indicate the development of smaller depths. But below the levels at which waves and tidal currents sweep the bottom conclusions as to depths cannot be based on grain size alone. A paleogeographic analysis is first required on a regional scale.

VIII. Interpretation of facies

In recent papers Rich (1950, 1951) has started a development in the interpretation of facies, which may well prove of fundamental importance. Briefly, he distinguishes the unda-, clino-, and fondo environments. In the unda environment waves and normal ocean currents are the dominant factors in transport and deposition. The sediment is coarse and clean. The clino environment starts at a break in slope and lies below the action of waves and normal currents. Deposition is dominated by settling from stagnant water and occasional turbidity current action with scouring effects. Sediment is fine in distinct even bedding. In the fondo environments pelagic sedimentation of clay and planktonic organisms prevails with occasional non-scouring turbidity flows.

Although agreeing with most of this the present author is of opinion that more stress should be laid on the importance of turbidity currents. Two fundamental concepts then take on a rather different aspect.

Firstly, beyond the unda environment coarse grain is nothing unusual. RICH expected fine sediment, and in his type example of clino beds, the Aberystwyth Silurian, he talks only of "silt-stone". But local workers use the term "grits" for these graded beds because the medium sized ones contain a large proportion of sand grains and the thicker ones grains exceeding 1 mm. The coarse deep-sea sands of the present ocean bed demonstrate how, even in the fondo environment, turbidity currents can supply thick beds of sand over vast areas.

It appears that in addition to the characteristics mentioned by RICH as typical of clino and fondo beds there should be added that where psammitic beds occur these should tend to be graded graywackes, grits, or detrital limestones.

An important group of clino deposits, like those of the Ventura Basin or the Harlech dome, should be added to the types distinguished by RICH. In these, flow markings are rare or absent. On the other hand ripple mark and current bedding, excellent features on which to determine direction of slope and of supply, are much more frequent than RICH assumes.

The other respect in which the picture drawn by RICH is modified by emphasis on turbidity flow is the distinction between the clino and fondo environments. The contrast between the two can only be retained during sedimentation as long as they show a fundamental difference in the process of deposition. Conditions under which a slope can be built out into a basin while maintaining a (rounded) break in slope at the lower end are only present where particles tumble down the slope individually (maximum angle of repose on a coarse delta front), where much of the sediment is wafted only to limited distances beyond the upper break in slope, or where slumping prevails. Where the sediment is carried down the slope in currents the tendency must be to establish a concave profile of equilibrium approaching gradually to the horizontal bottom at the far side of the basin or at the centre. Only if the sediment consists of two contrasting size grades, clay and coarse sand for instance, can currents produce and maintain an profile of equilibrium with a moderately sharp bend.

Because pelagic sedimentation combined with normal currents does not much modify the bottom shapes except for leveling the floor, the turbidity currents are left to establish their profile of equilibrium. This means that the upper end of the clino form is built out relatively steeply from the unda form, and may be repeatedly modified by submarine land sliding.

Beyond, there should be a gradual decrease in slope with a concomitant decrease in grain size and thickness of the deposits. It is not yet known on which part of the slope the slump structures and flow markings attain maximum development. Probably the type of sediment is important. But beyond the region of maximum development of these features a gradual decrease may be expected.

The origin of the break in slope at the edge of the continental shelf is still an open question, and off large rivers it is usually very indistinct. It must therefore be left to future research to ascertain how abrupt is the passage from unda form to clino form under various conditions. The smaller the scale the sharper it probably is.

The conditions leading to the development of turbidity currents are not yet established. But the wide distribution of graded bedding in deeper water indicates that a great number of basins reaching below the unda environment are filled by turbidity currents combined with deposits of pelagic nature. In these basins the distinction between clino and fondo environments is without much real meaning. For instance, a topographic high on the basin floor would be bypassed by turbidity currents and rise as an isolated mound of fondo beds from the surrounding clino beds. Only if the basin is so small that the turbidity currents are ponded, a fondo environment could be distinguished below ponding level in which the standing clouds deposit their load. Even then these fondo deposits would tend to alternate with coarse graded sands carried by turbidity currents from surrounding shallow regions.

In very wide basins that are only a few hundred feet deeper than wave base the contribution by turbidity currents could be slight and restricted to lutite grades outward from a short distance beyond the slope. Although slope and floor would merge imperceptibly there would still be ample justification for distinguishing clino and fondo deposits.

As pointed out above the convolute bedding of the Aberystwyth area is not due to slumping and slump structures are very rare. The argument for interpreting the rocks as clino beds is thus greatly weakened. The slope necessary for the development of flow markings is not yet known and may be quite small. The writer is inclined to assume that the depositional slope was very slight as compared to those in the Ventura Basin and the Harlech dome on the evidence of more slumping, coarser tops to graded sandstones, and less even bedding in the latter areas.

IX. Concluding remarks

Recent oceanographical work, especially bottom photography, has shown that ripple mark (in part, at least, of the wave type) occurs in great depths on the ocean floor. The present study has shown that current ripple mark and current bedding are found associated with graded bedding much more frequently than was formerly supposed. Careful examination will almost certainly show that, in graywacke series, these features are quite common although perhaps indistinct [1]).

Turbidity currents are known to transport shallow water organisms and deposit them together with the sand. Hence their enclosure in graded beds cannot be used as evidence of a shallow water environment.

Thus it transpires that three of the features most widely used to prove small depths of deposition, coarse grain, ripple mark, and cross-bedding, cannot always be relied upon and that even faunal evidence must be used with circumspection.

The most obvious types of rock among which a search for deep water deposits from turbidity currents may prove successful, is any major sequence showing regularly alternating and even bedding (rhythmic bedding). Many types of flysch, and similar formations belong to this class.

The conditions leading to rhythmic bedding in which shale and limestone alternate, are hard to explain by shallow water processes. But if the two materials accumulated in a deep and a shallow environment and the shallow deposit was carried by turbidity flow to the deep environment, the abrupt alternation becomes comprehensible. If the lime is graded the shale represents the autochthonous material (e.g. calcareous deposits between deep-sea lutites on the present ocean floor). If the shale is sandy and graded it has been carried to a deep with autochthonous lime sediments.

In conclusion the author would like to emphasize the ambiguity of the evidence on depth derived from the above features when insufficiently examined and contrast this with the great help to paleogeographic reconstructions which they may afford when carefully studied in the field. It is likewise obvious that earlier conclusions as to small depth of deposition will have to be reconsidered, when the only evidence used is coarse grain, ripple mark, cross-bedding or occasional shallow water organisms.

The writer does not intend to imply that the majority of rocks, hitherto believed to have been deposited in shallow water, will prove to show bathyal or abyssal facies. It is mainly in geosynclinal prisms that one is likely to find deep-water deposits and even here they are surely exceptional. On the other hand the history of some geosynclines, in which great depths are believed to have alternated repeatedly with shallow water conditions, such as the Harlech geosyncline, will prove to have had a much simpler history.

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[1]) The writer has found current bedding in practically every good exposure of the many graded series examined.

PART 2

PROBABLE DEEP-WATER ORIGIN OF SOME SOUTHERN UPLAND ROCKS

Summary

A reconnaissance of the coast south of Girvan and at Portpatrick provided some evidence indicating that the conglomeratic beds and most of the non-bedded graywackes are due to sliding on the sea floor into deep water ("bathyal" depths). It is suggested as working hypothesis that the graded graywackes and graded limestones were deposited from turbidity currents. Some fossiliferous limestones occur as blocks which slid into deep water. Shallower conditions prevailed in part of the Ardmillan Series at Girvan. The presumable unconformity at Shalloch mentioned by Lapworth is here interpreted as the result of slipping of conglomerate onto deep-water shales. The direction of supply has been mainly from the northwest but a local supply from the southeast was established for some time in both regions. Part of the time the depositing currents were flowing towards the southwest.

The author hopes these tentative interpretations may stimulate others to undertake the detailed investigations necessary for arriving at a final conclusion on the questions raised.

I. Introduction

The emplacement of graded graywackes by the action of turbidity currents was first suggested in a joint paper by the present author and MIGLIORINI (1950). NATLAND and the present writer (1951) then applied this explanation to the unconsolidated Pliocene graywackes of the Ventura Basin, California. The great depth at which some of these rocks were deposited had already been established by NATLAND, using a number of still living Foraminifera as plumb lines. The coarse, non-graded conglomerates were interpreted as due to sliding, the sandstones on account of the excellent grading to turbidity currents. The foraminiferal shales between represent the autochthonous clay.

The author then studied the graded grits of the Cambrian around Harlech and of the Silurian at Aberystwyth (Part 1 of this publication). He found additional evidence of turbidity currents in the form of unidirectional, small-scale current bedding and associated ripple mark. RICH (1950, 1951) had already explained markings on the lower surface of the coarser beds around Aberystwyth by currents, presumably of the turbidity type. All these three kinds of pointer are mutually confirmative as to the direction of the currents. This means in the case of graded graywackes the direction of bottom slope. Over large areas and through great thicknesses the direction of the slopes was found to vary but little. Thus they offer a valuable tool for paleogeographic reconstructions (KUENEN 1952). On revisiting the Ventura Basin in 1952 the writer found that the same features can be used there also for determining the former submarine slopes (KUENEN 1953).

In the mean time E. K. WALTON had independently discovered the value of current bedding for ascertaining the direction of the slope down which the turbidity currents had carried the graywacke materials (WALTON, in preparation). In the Silurian of the Peebles area studied by him the supply came from the northwest.

Mr KOPSTEIN, a pupil of the author, is now engaged on paleogeographic field work in the Harlech dome. He has discovered that in addition to current bedding, ripple mark, and flow markings, the orientation of pebbles is a useful feature. The average direction of the longest axes varies only a few degrees in adjacent localities and coincides with the direction of the currents.

In the areas studied up to the present the explanation of the graded rocks by turbidity current activity has proved satisfactory. The intercalated lutites represent in part the product of very slow turbidity flow, in part autochthonous deposits settled from above.

There are other areas, however, where to judge by earlier accounts graywackes are found in close association with rocks of shallow-water origin. After consultation with Mr WALTON it was therefore decided to make a short joint trip to Girvan at the western end of the Southern Uplands to test the new ideas preliminarily in one of these critical areas. A few additional observations were made in the spring of 1953 1). The coast here offers good exposures in a Lower Paleozoic sequence containing graywackes, conglomerates, fossiliferous limestones, and shales, with supposed unconformities. As far as the writer is aware this sequence has always been looked upon as one of typical shallow-water, geosynclinal conditions (PEACH and HORNE, 1889, HENDERSON 1935, p. 489).

In the present paper a different interpretation will be offered as a working hypothesis. It will be suggested that the majority of the rocks was deposited in deep water. By deep is meant depths well below wind-wave base and the action of swift tidal currents. This implies that sand and pebbles cannot have been carried by normal agents and that their transportation must be attributed to the action of turbidity currents or sliding.

Although confident that the deep-water nature of the graywackes in the examined areas is well established, it is realized that a considerable

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1) The travel expenses of the author were defrayed from a grant given by the Netherlands Organization for Pure Research (Z.W.O.).

The writer wishes to express his sincere gratitude to Mr E. K. WALTON for acting as guide and for stimulating discussions of the observed phenomena.

amount of additional fieldwork, also reaching inland, is required before an adequate picture could be drawn.

A short visit was also made by the author to the coastal sections on the western shore of the Rinns of Galloway.

II. The Girvan Area

The lowest member investigated was the *Benan Conglomerate* of Ordovician age at Kennedy's Pass. It consists of a thick series of bedded, polymict graywacke conglomerates with boulders up to one foot across. The bedding is distinct but not very regular. There is no grading, but the internal structure is of a streaky nature, without cross-bedding. There are no primary voids between the pebbles and cobbles, and imbrication is absent or at least inconspicuous. In these respects the conglomerates differ from most beach and river conglomerates. Between the conglomerates highly laminated graywackes of medium grain, without visible grading are present.

These rocks are tentatively interpreted as beds on a slope building out at maximum angle of permanent repose. The materials have come down in repeated slides, not as individual particles. The term "slide conglomerate" appears suitable. Similar conglomerates occur here and there in the Ventura Basin, interbedded with graded sands and pelagic lutites. The depth of accumulation in these latter cases varied from 1000 to 6000 feet of water. All that can be said concerning the depth of accumulation of the Benan Conglomerate is that, in all probability, it was below the surf zone.

According to HENDERSON there are unconformities below and above the Benan Conglomerate.

The Benan Conglomerate is succeeded along the coast by the *Ardwell Group*, the Balclatchic Group being absent.

The Ardwell Group is represented by graded graywackes 1) alternating with strongly laminated shales and flagstones. One bed, for example, could be followed about 250 feet across some minor faults. It was 2 feet thick, graded and laminated with shale fragments and small pebbles up to half an inch in diameter at the base.

The spectacular slump structures of the Ardwell have formerly been described and excellently illustrated by HENDERSON (1935). The somewhat larger crumply folds, a few feet across, are probably of tectonic nature because some of them affect thicknesses of 150 feet of strata in a single sharp, similar fold ("similar"in the sense that all beds show the same shape, as opposed to "parallel" with sharper bending in the core). They nearly all pitch to the northeast.

Numerous instances of pull-aparts are found, usually in the occasional calcareous beds. They vary from angular fragments still nearly in contact

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1) The many features characterizing series of graded graywackes are listed in a forthcoming joint paper with CAROZZI.

with each other to chunks dragged far apart. These should not be confused with the abundant calcareous concretions.

A more advanced stage in pulling apart is represented by the chaotic breccia beds of contemporaneous sediments described in such detail by HENDERSON. A modification is here suggested of this author's explanation. Instead of invoking the action of tsunamis and the shattering in situ to form breccias, the phenomena are here attributed to slumping and turbidity currents. A powerful argument in favour of this view is, that the small scale current bedding everywhere points in one direction. With tsunamis which are waves, there should be equal development of opposing current directions.

The disturbances of the breaking-wave shape (HENDERSON, Plate II, Fig. 3) are believed to represent load casts and convolute bedding.

Convolute bedding (see Part I) is another frequent phenomenon.

Here, as in all typical graded graywacke series, each bed tends to show its own characteristics along the strike as far as the bed can be traced. These characteristics result from variations as to lamination, convolute bedding, shale inclusions, current bedding at the surface, load casting at the base (KUENEN 1952), repeated grading, grain size, thickness.

Again, as in many other occurrences, there is a general though not very marked tendency for the coarser grain to occur in the thicker beds. This point is in favour of turbidity flow, because in shallow-water transport there is no such coincidence. It is logical that the swifter turbidity current, able to carry coarser grains, is also the larger one; hence depositing a thicker bed.

The direction of supply obtained from a few dozen rough measurements was from the north northwest.

The Ardwell is followed by the *Whitehouse Group*. The lower part of the latter consists of shales with gritty calcareous bands (4–12 inches thick). Many of these are graded and contain corals and brachiopods (displaced?). There are slump structures, very marked convolute bedding, and unidirectional, but rather variable current bedding, some of it overturned. The direction of supply had changed and was from the southeast. This series appears to have been formed on a slope from shallow water into slightly greater depths by small turbidity currents. Compared to the Ardwell the supply of minerogenous matter was small and the depth insignificant.

Higher up in the sequence the Whitehouse Group consists of alternating thin green grits and shales. The bedding in the former is less regular than in the typical deep-water graywackes. There is no systematic grading and there is current bedding which may cut right across a bed 6 inches thick and minor convolute bedding. These rocks are interpreted as shallow-water deposits.

At two points along the coast (Port Cardloch and Myoch Bay) there occur small exposures of massive graywacke grits which Lapworth (1882) equates and places in the Lower Whitehouse Group. They are poorly and irregularly bedded, with coarse current bedding through thicknesses of one foot at a time. Some parts are crowded with angular fragments of shale resembling that of the surrounding rocks. The thickness varies considerably over short distances. Along the strike these masses are cut off by complicated oblique faults, or pass under the raised beach. At Port Cardloch the supply was from the west northwest.

These masses are diagnosed as filled-in wash-out channels and this confirms the conclusion that the accompanying green rocks are a shallow-water deposit. Upwards these rocks pass into purple mudstone, bright green along the joints. On account of the colouring resembling that of Devonian and Triassic shallow-water shales, these beds are also interpreted as of shallow origin.

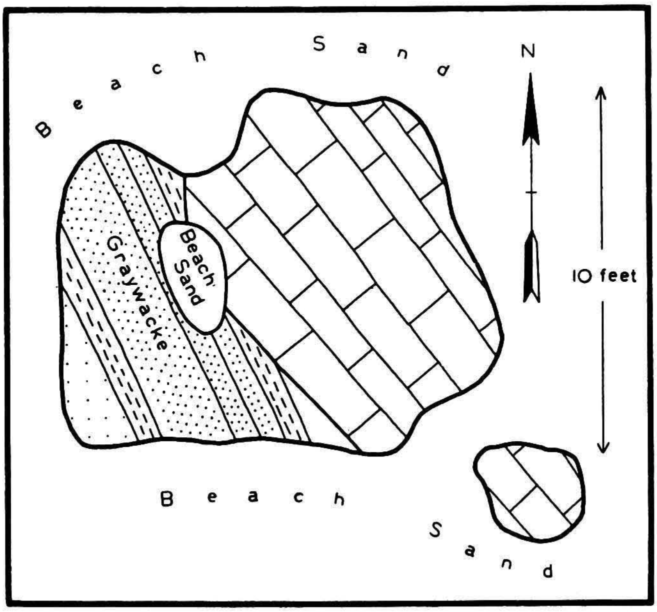

Fig. 16. Rough sketch of limestone block in graded graywackes exposed on shore at Shalloch.

The purple shales are followed by a series of graded graywackes which comprise both the upper part of the Whitehouse Group and the Barren Flagstones, the former with isolated lenses of calcareous grit. The lower part is fine grained and judging by the current bedding the supply was from the west northwest. A few dozen feet higher up in the succession the graywackes show an abundance of flow markings denoting a supply from the northeast.

The *Craigskelly Conglomerate* at Craigskelly and Horse rock is associated above and below with well graded graywackes of the normal deep-water type, interbedded with shales. The conglomerate is polymict and very coarse with boulders up to one foot in diameter. It encloses some chunks of the graywacke several feet across. The water must have been deep and the graywackes were deposited by turbidity currents, the conglomerate is of the slide type.

Next in ascending order come shales and limestones. At Woodland Point no evidence was gained on depth and mode of accumulation, but the fauna does not appear to be in position of growth. Between Horse and Cow Rocks at Shalloch the limestone appears to occur, as far as exposure among beach sand shows, in a chunk of 10 by 15 odd feet, lying slightly oblique to the bedding of a normal deep-water graywacke (Fig. 16). The contact is not tectonic, nor of a normal unconformable nature. It is almost certain that the limestone mass has slid down a slope to its present position as a more or less consolidated block. There is another chunk visible, but whether it forms a separate slide block, or is joined with the other could not be ascertained owing to sand cover.

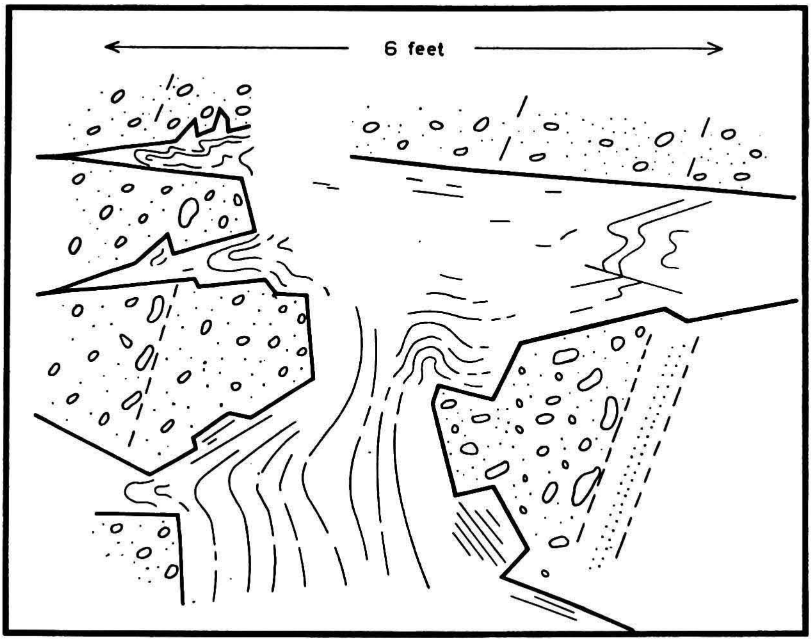

Fig. 17. Rough sketch of laminated deep-water lutites flowing into contemporaneous crevices in overlying slide conglomerate, seen from above. Beach at Shalloch.

Along the graywackes and slide blocks there must be a fault obscured by beach sand. Within a few yards a large mass appears of finely laminated siltstones and shales (*Gregarius Shales*) covered by the *Quarz Conglomerate*, another typical polymict slide conglomerate. The contact is also of great interest. LAPWORTH suggested a discordance complicated by faulting. However he writes "....the two formations are dovetailed into eachother in a most intricate manner, rendering the detection of their natural relationship more a matter of speculation than of absolute certainty".

Closer inspections shows that the conglomerate is cracked and split open towards the contact at its base thus forming large angular fragments. The underlying siltstones and shales have flowed into the wedge-shaped openings in intricate crumplings (Figs 17 and 18). There are also chunks of the shale encorporated in the conglomerate and tongues of conglomerate wedging into the shale bedding.

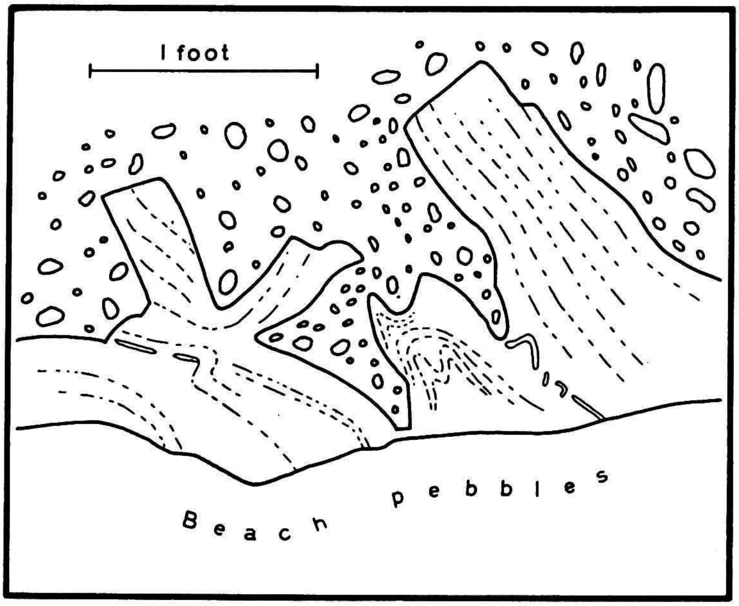

Fig. 18. Rough sketch of contact between split conglomerate lying on laminated deep-water lutites in steep scarplet. Beach at Shalloch.

These features are the opposite to what they should be at the unconformable contact of a basal conglomerate on older rocks.

The puzzle can be accounted for by assuming a deep environment in which the shales accumulated in situ. Into this the mass of conglomeratic material came sliding down. Then part of the mass thus formed pushed out further in the same manner but not from so far up the slope as had happened somewhat earlier with the limestone blocks. It is obvious that the materials did not roll separately down the slope to their present position, because the cobbles have not sunk individually into the soft mud. Before the final movement some measure of consolidation must already have taken place to account for the splitting up the conglomerate and the shale.

The writer thus ventures to suggest that part of LAPWORTH's intricate faulting is merely an example of contemporaneous cracking and that no shallowing of the area need be assumed to account for a discordance. Presumably there is also a fault along the western contact with the shale.

At Woodland Point the same quartziferous conglomerate is extremely coarse with occasional boulders reaching two feet across. The lower beds contain numerous angular fragments of limestone. Here again these conglomerates are of the slide type: non-graded, with some gravelly beds tending towards grading. The internal structure is streaky without cross bedding.

Going upwards the grain size rapidly decreases and excellent grading sets in. Beds range upwards to 7 feet in thickness. They contain fine to medium gravel at the base and grade to fine silty sand at the top. Thin shales form partings and the bedding is highly regular. There is also a slump sheet of one foot thick in the middle of these graywackes (Fig. 19). Flow markings and some current bedding show that the supply was from the east.

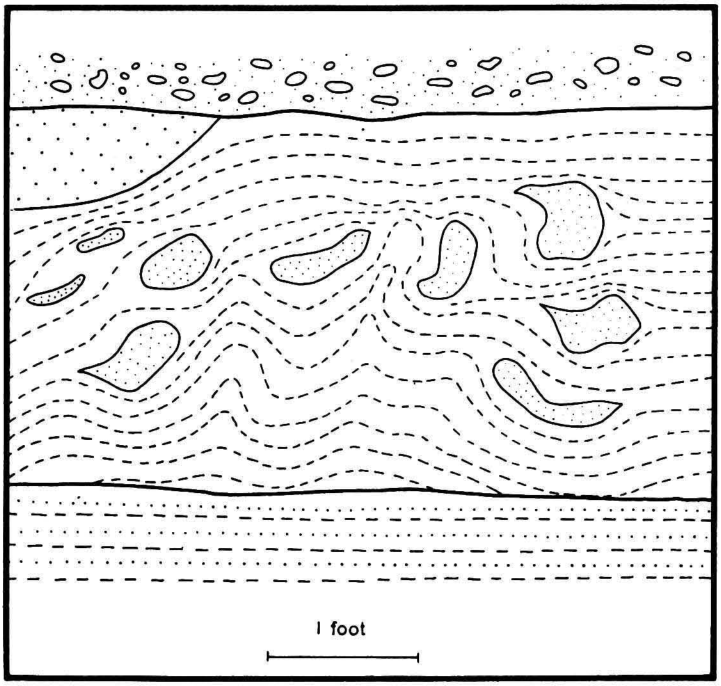

Fig. 19. Rough sketch of slump sheet between graded graywackes, Woodland Point.

These rocks are likewise diagnosed as slide conglomerates covered by beds deposited from turbidity currents. The thick beds with grading show that the turbidity currents had travelled far enough down slope to have gathered the coarse particles at their noses. It is imagined the depth must have been several hundreds of feet at the least.

The foregoing account of the rocks exposed along the Girvan shore will show that if the present interpretation is correct both deep and shallow water deposits are represented. The Ardwell Group was formed in deep water with a source to the northwest. During the earlier part of the Whitehouse Group a shallowing is indicated and the supply was reversed to the southeast comprising also calcareous detritus. The rising of a secondary ridge in the geosyncline is thus suggested. The calcareous detritus was soon suppressed although reappearing spasmodically later. Shallow conditions prevailed till near the end of Whitehouse times. Gradually the water deepened and graded graywackes with a supply from the northwest appeared. To be followed by the same material, somewhat coarser and coming from the northeast. At Shalloch, the Craigskelly Conglomerate, the graywackes and slide blocks of limestone, the shales and the quartz conglomerate are all of deep-water origin. At Woodland Point the depth is doubtful for the limestone, but the quartz conglomerate and covering graywackes are of deep facies. The paleogeographic history of the geosyncline is thus found to be complicated by reversal of submarine slopes and variations in depth.

III. The Rinns of Galloway

In addition a few remarks may be added on rocks of the west coast of the *Rinns of Galloway.* On a quick reconnaissance the author found that the graywacke sequence from Portobello Bay to a few hundred yards northwards shows the normal combination of features for deep-water graded graywackes. The supply, shown from abundant current bedding and ripple bedding (Plate B, 1), varied from south to nearly west and nearly east. At a point 150 yards north of the bay an occurrence of flow markings (Plate B, 2), confirmed the evidence given by immediately adjacent current bedding which indicated a supply coming from the west southwest.

From Larbrax to Morroch Bay south of Portpatric the graywackes tend to occur in thick masses, much jointed, with some lamination, but generally without shale beds to mark the bedding planes. Grading is absent or at least very inconspicuous in this type of deposit. In the absence of clear bedding it would be hard to find anyhow. However, the grain is not particularly coarse. It is important to note that these graywackes are quite different from normal shallow-water sandstones in that there is no current bedding, no wave ripple mark, no channel scour, and the fact that fossils are completely absent. The composition is very uniform, no sorting of the lutites or sands has been occasioned by wafting currents. These combined properties exclude in the author's opinion the possibility that such massive graywackes accumulate in shallow-water environments.

The close relation to normal graded graywacke is proven by their being decidedly "dirty" and containing occasional shale fragments. Every here and there along the coast one comes across a well bedded patch in which grading is usually conspicuously developed. Such portions are indistinguishable from normal graded graywackes. These occurrences seem to indicate the temporary development of a suitable slope and other conditions requisite for the production of true turbidity currents. The massive portions can be attributed to watery slides without the development of true turbidity currents and following each other so quickly that time was lacking for the settling of clay in separate beds.

Occasional contorted beds of shale in which lie embedded irregular, lensing slabs of graywacke (Plate A, 2) can be explained as slump structures, although a tectonic origin is not excluded.

Close to the north of Black Head Lighthouse current bedding indicates supply from the southeast. At the semaphore a coarser bed with many small fragments of shale crops out. The thick, bedded, medium grained graywackes at the northern end of Morroch Bay contain a few laminated siltstones with current ripple bedding. The supply was from the northwest. The associated rocks, dark shales and radiolarian cherts, can all be confidently attributed to deep-water accumulation.

It thus appears that the examined rocks along the coast of the Rinns of Galloway were laid down well below wind wave base on steep to moderately steep submarine slopes. Sliding and turbidity currents were both active. The history of the geosyncline was complicated by oscillation of the slope and deep floor, the turbidity currents being directed now to the north, now to the south.

A point of tectonic interest is that as far as noted all along this coastal section the bottom of the graded beds which strike east—west lies on their southern side. The northern limbs of the isoclinal structures appear to be entirely suppressed.

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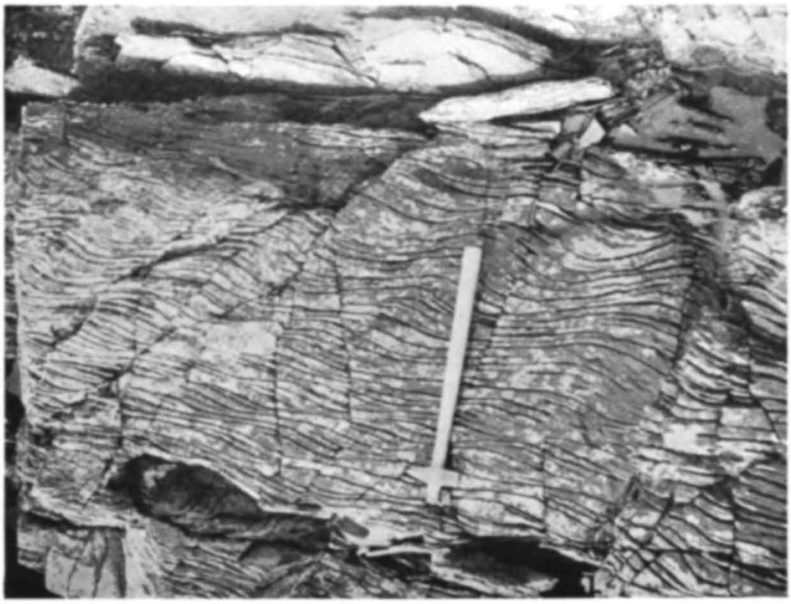
Photograph 1. Convolute bedding as seen on slightly abraded slab. Note that general arrangement resembles pattern of ripple mark. Shore south of Afon Ystwyth.

Photograph 2. Presumable slump structure in graywackes interbedded with shales. Knock Bay, Rinns of Galloway.



Photograph 1. Regular, small-scale current ripple mark exposed in section. The deposit was built up while the ripples moved down-stream (to the right). North of Portobello Bay, Rinns of Galloway.

Photograph 2. Flow markings on lower surface of graywacke. The current came from the upper left hand corner. North of Portobello Bay, Rinns of Galloway.