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Turbidity Currents and Organisms [1])

by PH. H. KUENEN[2])

With 1 figure in the text

ABSTRACT

The conditions for life and for the preservation of organic remains in environments where turbidity currents occurred are sketched on the basis, first, of inorganic evidence. The vast scale on which such currents have acted in the recent past in the oceans is emphasized. The principal features shown by the deposits (= turbidites) – both positive and negative – are briefly summarized. The same characteristics are shown by the sandstones of normal flysch-type formations. Lamination, rate of deposition, diagnosis of pelagic beds, the origin of shell pavements, ponding and depth are passed in review. The main arguments are listed for more than neritic depth, both those based on inorganic and on organic evidence.

A plea is made for further search for trace fossils in the Precambrian. The low organic content usual for flysch and the high values for turbidite formations of Southern California are explained on the basis of oceanographical observations off California where upwelling fertilizes the surface waters, and in the Adritic where nutrients are scarce. In most respects the conclusion of KSIAZKIEWICZ is accepted that absence of oil in flysch is due to adverse conditions for phytoplankton. Circumstances for benthonic life including that of burrowers are listed. Evidence is lacking that plant detritus plays an important part as source of food.

Introduction

The subject of my address can be approached from the mechanical or the biological side. Although the biological aspects are the most important to your group, I have nevertheless chosen the physical approach, that means starting from the turbidity currents themselves, because this subject-matter is more familiar to me. It must also form the foundation for the interpretation of the organic evidence.

First a picture must be drawn of the mechanism of these submarine flows, based on a combination of experiments, of findings in the present oceans, and of observations in flysch-type deposits. Opinions differ on the role played by turbidity currents as on so many geological matters. We are still far from understanding all aspects of the mechanisms involved. However, compared to the puzzles of much older subjects, like evolution, the origin of granite, the formation of nappes, or the cause of ice ages, the problems concerning turbidity currents are perhaps less baffling. Rapid advance is at least still being made by the interplay of geological fieldwork, oceanological observa-

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tion, and experiment. Paleontology has made an important contribution, but there are still general biological questions unanswered and countless regional problems to be solved by the study of fossils.

In the sequel an attempt will be made to offer an integrated picture of the action of turbidity currents. But to summarize the contents of many hundreds of papers in a few pages necessitates extreme simplification, and also the ignoring of exceptions and controversies. Mainly the personal opinion of the speaker will be offered and no attempt will be made to do full justice to divergent views held by others. I will also omit acknowledging the sources of information for the inorganic aspects. A more detailed picture can be obtained from the references listed at the end. I would like to draw attention specially to DZULYNSKI and WALTON (1965), KUENEN (1964a, 1967).

The mechanism

A suspension of sediment in water has a higher density than clear water. If a submarine slide, storm waves, or a very heavily loaded river produce such a suspension locally, the heavy liquid will be propelled by gravity and start to flow under the clear stagnant water. It will run down any available slope, or spread out on a horizontal bottom. Velocity increases with the root of (1) excess density over that of clear water, (2) slope, (3) thickness of the current. The motive force disappears by degrees with the loss of sediment as it settles out of the current to the bottom, and the flow is thus dissipated somewhat like a cloud of dust left behind by a car on an untarred road. The higher the velocity the more turbulent the flow and the smaller the loss of suspended matter. On a steep slope it is possible that erosion by the fast nose of the current is greater than the loss from the more sluggish tail, causing the current to grow and accelerate. But on a small slope the current will lose sediment. The deposit always tends to smooth the bottom.

From work at sea, it has been established that turbidity currents can attain gigantic dimensions, carrying up to one or two hundreds of cubic kilometres of sediment (HEEZEN et al., 1955), building beds several metres thick (so-called graded deep-sea sands) and extending for many hundreds of kilometres from the origin. They have produced fans at the lower end of submarine canyons 50–100 kilometres wide and sloping to the abyssal floor at one degree. These deep-sea fans are continued in abyssal plains with less than 0.1 degree slope forming the floor of wide oceanic basins or of deep-sea trenches. The oceanic turbidity currents have carried shallow benthonic organisms like *Halimeda* (calcareous alga) and thick shells, or pebbles to distances of hundreds of kilometres across plains lying at 5000 metres depth.

To simplify discussion the term 'turbidite' has been introduced, meaning a deposit attributed to a recent or ancient turbidity current. An analogy can be drawn with other terms denoting a mode of origin like eolianite, lava, or tillite. In case of doubt as to the origin of a bed one can substitute a descriptive term like deep-sea sand, graded marine graywacke, graded calcarenite, or flysch-type sand bed. The term 'fluxoturbidite' refers to similar beds that were presumably deposited by a turbidity current unable to carry all sediment in suspension, so that a watery slide produced a stratum showing less obvious grading or sole markings, but plenty of shale pebbles and also coarser grain than accompanying turbidites.

The study of ancient rocks, partly on the basis of experimental turbidites has shown that one can expect more than a dozen sedimentological features in a turbidite formation, which are also common to graded deep-sea sands. They include graded bedding, current ripple lamination between co-sets of horizontal lamination, convolute lamination, sole markings due to violent current action, some fine matrix contained in coarser parts of the sands, very regular bedding extending over wide areas with a sharp lower boundary and a top grading into lutite. No less important are the 'negative' characteristics, such as absence of all shallow-water features like wave ripple mark, plants in situ, beach phenomena, reefs, etc.

It should be emphasized that no single feature can establish the turbidite nature of a bed, but the larger the number of typical properties encountered the greater the confidence with which one can infer this origin. Neither will any bed – not even a whole formation – show all of the normal characteristics combined.

Every turbidite formation presents special aspects that may change gradually in a horizontal or vertical sense. Thus the bed-thickness may be abnormally large or small, sole marking may be largely restricted to flutings or to grooving, convolution may be absent or common, pelagic clays between the turbidites may be absent or exceptionally thick. The mineralogical composition can also vary from non-calcareous formations to pure calcarenites between calcilutites. There may occur calcareous turbidites or precipitated calcilutites between quartz turbidites. Older quartziferous turbidites are usually changed to graywackes, presumably by slight metamorphism.

Turbidity currents occur at a given spot at large intervals to be measured in hundreds or many thousands of years. Normal pelagic or hemi-pelagic sedimentation of lutum occurs in between. The next current churns up the watery surface of this fine mud, incorporating it so that this same material is deposited again from the tail as top of the bed. In this manner pelagic mud is transformed to turbidite mud. The current produces various types of markings by turbulent scour and by dragging objects over the bottom. It is uncertain how long (minutes?) it takes for deposition from the current to start covering and thus preserving the sole markings. By this time the pelagic mud may have been partly or entirely removed. Sole markings are useful because the direction of the current can be ascertained from them.

It is now firmly established that the alternation fo sandy beds with shales, typical of normal flysch, is the result of turbidity currents. Conversely, most of the formations built of such a sequence of turbidites have been called flysch by at least some authors. But owing to the uncertainty as to the best definition of the term flysch, it is safer from the point of view of dynamical sedimentology to use the expression 'flysch-type' sand beds or turbidites. Thus one can avoid the controversy as to whether a slight lime content is a necessary requirement, and whether the macigno of the Apennines is a flysch, or whether a given turbidite sequence belongs to a flysch or to a molasse. For it should always be held in mind that the term turbidite means exclusively that the author is convinced that a turbidity current produced the bed. Hence, it refers to a mechanism of emplacement that may have involved a wide range of compositions, but that it has no implications as to age, orogenic role, or geosynclinal environment. On the other hand terms like flysch, molasse, and 'Kulm' (=Lower Carboniferous in Germany) are applied to formations, not beds, and among the criteria handled, are orogenic age, thickness, and compositional factors. Mode of emplacement was not taken into account when defining these latter formations and there was only a vague notion that most flysch shows regular rhythmic bedding of lutite alternating with arenite and that molasse tends to be partly non-marine and less regularly stratified.

What has gradually transpired is that nearly all normal, typical flysch consists of turbidites, fluxo-turbidites, with additional slumps, whereas in molasse turbidites, slide conglomerates and slumps are rare. In 'Wildflysch' slumping is important and usually involves some separately slid blocks.

The mechanism of turbidity currents has not been restricted to geosynclines or flysch-like formations. Otherwise these currents could not have acted in the present oceanic basins. Various kinds of basins have received occasional or even frequent turbidites. However, the conditions necessary for the generation of turbidity currents were wide-spread at certain stages of geosynclinal development, whereas they occurred only by way of exception in other structural units. Hence, turbidites appear massively at certain periods in geosynclinal histories, and these are the times of flysch sedimentation.

Measurement of current direction from sole markings has shown that in more than half the cases studied the flow has been predominantly in a longitudinal direction in ancient trenches. Other cases are known in which direction measurements showed lateral or oblique supply. Paleogeography and local coarse deposits have been invoked as evidence that the main supply has come from internal or external cordilleras. That would mean that the supply was chiefly lateral, but that the sole markings were formed mostly after the currents had turned to a longitudinal direction. This aspect is in urgent need of clarification, partly because it is hard to explain why flysch produced from small, steep areas is nevertheless poor in pebbles.

Several authors have found slump structures with the axes of the folds parallel to the sole markings of the distorted turbidites. This has been claimed as evidence that the depositing currents flowed not down the slope – as it is indicated by the slump direction – but followed the depth curves. Some geologists have even gone so far as to discredit the whole concept of turbidity currents on this one difficulty, ignoring the mighty body of evidence compelling us to accept it. However, there is a logical explanation involving supply by turbidity currents. There must be a reason why beds, first deposited from a current, have later been mobilized when consolidation should have rendered them firmer than during sedimentation, not more mobile. The cause was almost certainly an earthquake or tilting. As we are dealing with active, subsiding trenches it is probable that there were longitudinal faults. Movement on these should produce a local flexure on the sea floor and if slumps were triggered these would move at right angles to the trench axis. In this picture the slumps do indicate paleo-slope, but only a temporary local one, perpendicular to the general longitudinal slope that guided the turbidity currents. The temporary cross-slope was quickly obliterated by the slumps and deposition, whereby the original flat floor sloping slightly in a longitudinal direction was restored.

Turbidity currents have also contributed to the sediments of ancient basins that were dominantly filled by other kinds of deposits. In this manner they have introduced foreign material into otherwise uniform environments, such as reef detritus into pelagic lutites, or mixed volcanic detritus into shales or marls.

Insight into the concept of turbidity currents and turbidites stems from experiments, from study of the present oceans, from theoretical considerations and from ancient rocks. Experiments have shown that the mechanism is a physical reality and give valuable information on the limits in density, on the viscosity, on the transporting power and on the origin of depositional structures. The present oceans reveal the enormous scale on which the mechanism can act and its astounding capacity for transportation. Conditions as to slope, depth, distance, bed thickness, and distribution of material can be accurately ascertained. Hydrodynamic theory, although not fully developed for this mechanism, should lead to a better understanding of its action. Another, highly effective line of approach is the study of ancient turbidite formations. These provide more than a historical and regional application. The features of the beds, such as sole markings, grain orientation, internal structures, current directions, time intervals, are better displayed for study than on the deep-sea floor. Possible alterations with time as basins developed are shown in hard-rock exposures, but are beyond the reach of coring instruments in the sea bed. In the near future the plans to drill in the deep-sea floor will bring to light much evidence of the history of present deep-sea basins thus presumably helping to complete the picture.

In addition there is another reason, why field work in ancient basins is necessary. Although much information can be gleaned from experiments and the investigation of recent turbidites, there can be no doubt that conditions in ancient flysch troughs and other turbidite basins differed fundamentally from most of the present seas. Sedimentation was faster, isolation from the wide oceans and tectonic activity were both more pronounced, extent was relatively small and depth presumably varied within wide limits. The present helps to guide speculation as to the happenings in ancient basins. But the application of oceanological findings is more in the nature of suggestions for the field geologist to use as elements from which to construct an overall picture of the past. For each ancient basin a separate evaluation of shape, depth, supply and development has to be made. However, if the field geologist or paleontologist is not well acquainted with the conclusions arrived at through the study of experiments and the oceans, he will be in great danger of evolving a distorted picture of the past. Too often field geologists and sedimentologists who have come across a single turbidite formation, have ventured to express far-reaching conclusions concerning the concept without taking the trouble of confronting their ideas with the findings of others.

In the same manner the nature of ammonites could not have been deduced without knowledge of the recent cephalopods. Conversely, biologists could not have had an inkling of the vast expansion and diversification of ammonite life in the past, if the geological record had not been available.

Factors involving time

Lamination. An important problem is the nature of the lamination found in turbidite formations. The lower parts with medium to coarse sand seldom show lamination, but the fine sandy and silty levels are almost always laminated. This has been attributed to various causes, from separate flows (even yearly ones) to clouds or pulsations in the current. I have shown experimentally (KUENEN, 1966a) that any decelerating suspension current develops lamination except if the deposition happens faster than at one centimetre per one or two minutes. Another exception is a current with too high a content of lutum for sand grains to be able to separate out and accumulate on the bottom. Otherwise laminae develop as long as there are particles above clay size.

It should be borne in mind that there is yet another source of lamination in turbidite formations. After the sediment of a current has been deposited a long period of quiet ensues. During this interval wind, surface spreading of river run-off, plankton bloom, invasions of new sea water, convective currents, or volcanic ash can produce laminae. Even a distant turbidity current can waft some fine sediment to the area in question. For this reason the pelagic sediment covering a turbidite hardly ever lacks lamination entirely. This is one of the reasons for the difficulty to find where the turbidite merges into the pelagic bed.

There is no reason to make a separate category of 'laminites' as proposed by LOMBARD (1963). No special mechanism of transport or a different source of material are involved in the passage from the unlaminated lower to the laminated upper part of a turbidite. Neither is a thin turbidite with lamination throughout due to a set of conditions differing from those causing an unlaminated coarse bottom part. The term is also inappropriate for a formation in which the beds themselves are so thin as to suggest laminae, because laterally they probably grow in thickness beyond what can still be termed laminae.

It is confusing to give a separate name to the upper part of a homogeneously deposited graded bed. A bed lacking the unlaminated part below is in all respects equivalent to the top part of one with a graded unit at the bottom. It is more useful to speak of laminated turbidites or of a thin-bedded (turbidite) formation, as the case may be.

There are laminated formations like varves, fluviatile sequences, tidal flat deposits, volcanic sequences, and certain wind deposits, that have an entirely different origin from laminated turbidites. In my opinion introduction of the term 'laminites' offers no gain and can only lead to confusions.

Rate of sedimentation. A fair estimate of the sedimentation rate between the advent of turbidity currents in the present wide ocean basins is 1 to 10 cm per 1000 years, an average about 5 cm. After compaction to shale this average would be about $1^1/_2$ cm. The basins off Southern California show values of 10 to 90 g/sq.cm/1000 years. This is about 3 to 30 cm per 1000 years in the form of shale, the average roughly 10 cm (data from EMERY, 1960). In the deep basin of the Adriatic the accumulation amounts to 24 cm per 1000 years (VAN STRAATEN, 1966, p. 442) the equivalent of 7 cm shale. There is naturally a wide variation in rates of sedimentation in marine basins according to conditions of supply.

The sole markings prove that the currents cause a certain amount of erosion. These markings are possibly formed after many centimetres of watery sediment have first been removed, but it is also conceivable that they tend to develop immediately on the sea bed so that erosion does not exceed the normal relief of the sole markings, that is a depth of one or two centimetres. Considering that first an uncertain amount of erosion and then an additional amount of compaction have reduced the initial thickness of lutum in ancient deposits, the original thickness of pelagic deposit was presumably in most cases three to four times the amount one now measures.

The average rate of accumulation due to the addition of the turbidites is a separate question. In the present wide oceans the activity was greatly increased during the low sea levels of the Ice Age because transportation of detritus to the outer edge of the shelf was enormously stimulated. It was much retarded, in fact almost stopped, in the Post-glacial because vast amounts of sedimentary matter are trapped in estuaries and on the shelf and therefore little is available for the development of turbidity currents. An exception is found at the narrow shelf off California. Sand drifted along the coast is trapped in the canyons that head close to the shore. This material moves down the canyons. At intervals it produces turbidity currents on the basin floors.

In the basins off California turbidites account for about 14 % of the total accumulation, varying between 34 % and less than 1 %. In most flysch formations the turbidites predominate entirely over the pelagic intervals. This means that the majority of the currents swept away all the pelagic sediment that had accumulated during the foregoing interval. This clay was then redeposited as upper lutum level of the turbidite.

The maximum rate of sedimentation in ancient geosynclines averaged over long periods is 7.5 cm (KUENEN, 1966b) and over short periods 20 cm, the average over long periods of the whole geosyncline is 2.5 cm. Some of the higher values must represent flysch-type formations. The rate for flysch-type formations is generally admitted to be very high. A recent estimate for the early Pliocene of the Los Angeles basin is a maximum of 20 cm (compacted) per 1000 years (CONREY, 1967), and as much as 70 cm holds for the Ventura Basin (EMERY, 1960). The maximum in the oceanic basins is about 50 cm, but locally up to several metres, unconsolidated (EMERY, 1960) 15 cm as shale.

Problem of pelagic sediment. As stated above it is difficult to ascertain how much of the lutum forms part of the turbidite and how much is pelagic. Where present, the fossil content offers a source of information.

In most turbidite formations the sandy beds are rather poor in fossils, and the majority of the latter are evidently carried in from shallow regions by the currents themselves. An additional source of shells comes from the eroded inter-current deposits and consists of planktonic and benthonic forms. At a certain level in the lutite a sudden change in fossil content has here and there been noted and is attributable to the end of swift turbidity current deposition and the onset of slow pelagic sedimentation. At the same time re-population of the basin floor should start after the current has disrupted the benthonic life. There may be an additional change in colour or an increase in lime content. In other cases there is an alteration in the type of sand grains scattered through the lutite. The thickness of this pelagic interval is commonly presumed to be insignificant (for a summary see KUENEN, 1964b). But it is too early to draw general conclusions before a number of formations have been carefully studied paleontologically according to the knowledge summarized in Fig. 1.

An excellent summary of the distribution of fossil remains in turbidite formations has been compiled recently by WEIDMANN (1967). The elements carried by the current are graded according to transportability. The larger massive ones come to rest in the coarse sands below; the finer spicules and small planktonic shells in the laminated fine sandy and silty parts; pollen etc. in the muddy top of the turbidites. In the pelagic mud are concentrated benthonic foraminifera of the Rhabdammina micro-fauna, pelagic foraminifera (we can add pteropods), nannoplankton both calcareous and composed of organic matter (dinoflagellates, acritarchs, etc.), radiolaria and diatoms, fish remains and ichno fossils. WEIDMANN showed that the swift transition from the current-deposited clay to the pelagic deposit on top is most clearly defined by the replacement of the reworked terrestrial spores, pollen, etc. by marine microfossils.

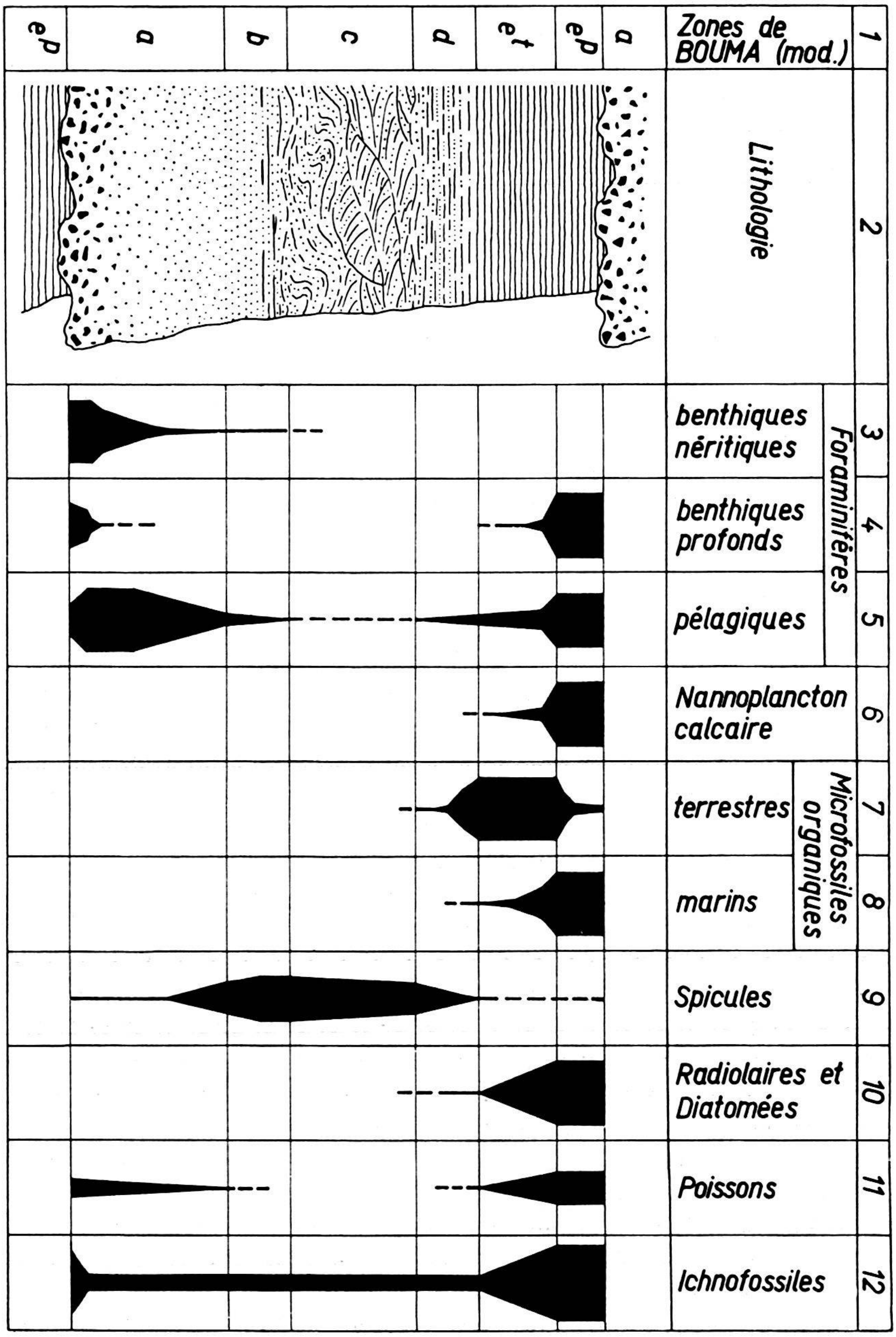

Diagram of the relative frequencies of various groups of fossils in a flysch turbidite (after WEIDMANN, 1967).

Rhythm frequency. In the middle of the inshore basins off California the interval between turbidity currents was 400 years (GORSLINE & EMERY, 1959, p. 288). An estimate of the time interval between turbidites in a flysch formation can be based on the thickness of the pelagic lutite compared to measurements of recent sedimentation. The best results will be obtained by using gr/sq.cm.

The chief difficulty with the application of this method to flysch formations is to ascertain which part of the shale is pelagic as pointed out above. It is also possible that 'pelagic' sedimentation in flysch troughs tended to be much faster than in the recent basins examined. If one adds the uncertainty as to the thickness washed away by the turbidity currents, it is obvious that this line of approach is far from satisfactory.

However, there is also a different method, that of dividing the total time represented by a formation by the number of beds. For ancient basins the shortest estimate so far obtained is a century (Ventura Basin, California), for some Paleozoic formations one to many thousand years appears to be normal, while a million years may hold for some pelagic formations (Nappe de Morcles).

The possibility must be allowed that a flysch formation represents only a part of the time between deposition of the underlying and overlying beds. The remainder of the time gap (=diastems) could be filled by emergence or non-deposition. This would render the interval between the advent of successive currents shorter than calculated in the manner just explained. The writer very much doubts that the flysch basins can have shown periods of non-deposition sufficiently long to seriously affect the calculation of current intervals.

Ponding

The picture originally suggested by MIGLIORINI (1944, and personal communication, see also KUENEN & MIGLIORINI, 1950) was that the current will form a pond of turbid water in the deep part of the basin, from which the graded bed is produced by settling. The experimental turbidity currents of the present author later demonstrated that the current itself is a far more efficient mechanism for depositing a graded bed of somewhat muddy character. However, some currents must be so large that they are ponded at the far end of the basin. This follows from the demonstration that some marine basins have been filled to the lowest gap in their surrounding wall. The currents then started to flow over this spillway and have begun to fill the neighbouring basin. Obviously prior to this overflow, part of the currents must have reached the far wall and been ponded. HERSEY (1965) recently claimed that the bulk of turbidite deposition in the present oceans happens after ponding, but this is most unlikely. It is incompatible with the enormous extent of abyssal plains and the range in depth from proximal to distal parts of such a plain. It is also contradicted by horizontal grading from coarse to fine with distance from source. In the much smaller flysch basins this phenomenon may have played a larger part.

The settling rate of the flocculated marine suspensions is relatively high. Assuming densities between 10 and 30 gr clay per litre of sea water the surface of a stagnant suspension will sink, according to experiments, at one to several millimetres per minute. Theoretically this limits the ponding effect, for the level of the pond must be raised faster than the sediment can settle. But the discharge of a turbidity current is so large that only in very extensive ocean basins will settling gain on the supply.

As the water is not brought to a standstill but is diverted in another direction starting to circulate in the pond, one might conclude that the upper parts of the beds will then be built from currents of variable direction. But this is presumably an entirely wrong conclusion. The incoming current should always tend to flow in contact with the bottom because its density is higher than of the earlier parts that have already lost the coarser elements of their load. The bottom will be shielded from the random eddies of the ponded water by the denser inflow. No sole markings or depositional structures will be formed by the ponded water. It seems likely that the effect of ponding will be limited to providing an additional thickness of structureless turbidite lutite above the level produced directly from the turbidity current itself.

Depth of deposition

Inorganic evidence. The principal reasons for assuming that turbidites are formed in 'deep' water are the following.

(1) All undoubted examples of turbidites extending for significant distances on the present sea floors have been encountered in depths exceeding several hundreds of metres. Apart from a few local occurrences on marine deltas, the sediments of the shelf are obviously not turbidites nor even remotely like them.

(2) The generation of a turbidity current is usually visualized as starting with a slide on a slope. The slide plain below a large volume must show considerable depth at its outer edge, otherwise the necessary slope would be lacking. The ensuing current must be generated below that level on the sea floor. It seeks the steepest gradient and will tend to produce its turbidite in the deepest parts of the basin that it can reach by following down-slope all the way. In experiments the suspension is produced by the unnatural process of stirring before release. But it is logical to postulate a slope of some extent to generate a turbidity current in the oceans. Hence, the expectation is that the subsequent depositing process will take place below a considerable depth of water.

(3) Admittedly it is conceivable that conditions favourable to the generation of turbidity currents might occasionally develop in small depths resulting in the production of a shallow-water flow. As turbidity currents can flow for hundreds of kilometres on bottom slopes of less than 1/1000 a current generated in shallow water, should be able to transport and deposit its load in neritic depths.

The question then arises whether a part of the ancient turbidites could not be attributed to small depths? However, the shallow marine beds found up to the present that may be turbidites are of very slight extent and merely an abnormal admixture to deltaic deposits. This argues against them being represented in any flysch-type formation, because indications of fluviatile conditions and delta deposits are extremely rare if not entirely absent in flysch-type sequences. The common presence of plant remains in flysch means nothing in this respect, for vegetable matter is often encountered in the deep-sea sands at 5000 metres depth. Water-logged debris can be transported as far away as the silt, that means hundreds of kilometres from the land.

(4) Examples have been found of flysch formations divided by a submarine ridge with reduced thicknesses of sediment (e.g. BROQUET & MASCLE, 1968). In such cases the flysch is the deeper of the two types of marine sediment.

(5) Examination of countless flysch and flysch-like formations has shown that wave ripple mark, beach features, and alternations with terrestrial formations are absent. This evidently holds even for the areas and for the times of maximum sediment supply. In fact, one of the few aspects on which all flysch specialists appear to agree, is that flysch is purely marine. Hence, even during maximum rate of deposition flysch sediments have not been able to build up to the surface.

(6) In some flysch formations the current direction is found to have been away from the area of greatest thickness, which may be as much as 2000 metres. This implies an original depth of the basin that must have been about as much as that thickness. In shallow water the movement cannot be otherwise than in the opposite direction towards the area of greatest thickness, where subsidence provides the necessary space (KUENEN, 1959).

These are the main reasons based on inorganic features for assuming more than neritic depth for flysch. The presence in contemporaneous deep-sea trenches of normal turbidites shows that the mechanism is quite as effective in abyssal depths and is not affected by pressure.

It is true that foot prints of birds have been reported from formations claimed to be flysch. However, accompanying them were other features highly unusual in flysch such as symmetrical wave ripple mark, ripple impressions on the sole of the sandy beds, salt pseudomorphs, a mixed type of fauna. Most geologists appear to agree that the tracks of land animals are limited to molasse-like formations or transitions from flysch to molasse. Although the sandy beds associated with the bird tracks show a marked resemblance to normal turbidites, there are sufficient reasons for assuming a somewhat different mechanism of transport, probably a sheet flood in a semi-arid coastal zone.

It has been contended that some Miocene turbidites of the Northern Apennines were deposited in water a few dozen metres deep. The chief argument was based on grain size distribution, but is not convincing. No mechanical reasons can be given why the grain size distribution in question should be linked to small depth. Doubts are strengthened because the fauna appears to indicate greater depth, about 500 m (VAN STRAATEN, personal communication).

Organic evidence. The fossil evidence on the origin of turbidites includes a rich display of tracks and trails. The fossils in turbidites are not randomly scattered throughout the beds, but are sorted, like the graded mineral grains, according to their transportability. Solid fragments are associated with mineral grains of equal size, whereas hollow tests tend to occur amidst smaller grains. But there are everywhere smaller particles deposited between the larger ones in turbidites and here and there an exceptionally big one. Because microfossils tend to show a restricted range in size there is a tendency for them to be more abundant in certain horizons than in others. Some of the remains are supplied from shallow water at the origin of the current. But erosion along the basin floor by the current can have added shells of organisms that had been deposited in deep water.

Most flysch-type formations are poor in fossil remains. But even in calcarenite beds they cannot show what the depth of deposition was, because the great majority obviously has been re-deposited. This follows from the fact that the fossils are graded according to size and are not in position of life.

The finding of micro and macro shallow-water shells in the present deep-sea sands in over 4000 m depth confirms the view that the fauna of re-deposited beds cannot be used to find a maximum depth, only a minimum might be deduced from suitable finds. But even in this respect there is a danger, because some turbidites are rich in fossils of greater age (= reworked). These fossil remains have probably first been elevated to smaller depths before resedimentation, rendering them unsuitable as fossil depth recorders.

Clearly, the only reliable evidence can be obtained from organic remains in the pelagic parts between the turbidites. Both trace fossils and true fossils could prove useful. The enclosing lutum shows that no current was involved that could have carried in shells from far off. However, plant debris and most pelagic fossils drop in from the surface and naturally are useless for depth recording.

Trace fossils. It is well known that many of the trace fossils in flysch-type formations are of a very specialized character, which has remained unchanged from the Lower Paleozoic to the youngest representatives (SEILACHER, 1964, 1967). The majority of these traces are not encountered in any other type of formation. This in itself strongly suggests that we are dealing with an environment radically differing from normal sites of sedimentation such as deltas, lagoons, neritic seas. This abnormal combination of trace fossils might be caused by low temperature, absence of light, scarcity of food, turbid bottom water, spasmodic sedimentation, or stagnant conditions. On the other hand the main factor could be great depth. Any single one of these conditions cannot offer an explanation. Surface temperatures in the European or Californian Tertiary were not low. Absence of light would in itself mean more than neritic depth. Scarcity of food has occurred without the development of the characteristic burrowings. Stagnant conditions in shallow water frequently lead to high organic content and are normally associated with absence of sand beds.

On the other hand bathyal depth might be the primary cause, because it would automatically ensure some of the other factors. A deep basin will tend to have moderate to low bottom temperatures, absence of light, and quiet to stagnant bottom waters. The food chain would depend on settling from above because there could be no production in the dark. The supply of nourishment might be insufficient, especially if turbidity at the surface were high enough to hamper photosynthesis. If occasional surface spreading of fresh water occurred and the basin were more or less land-locked this would have a deleterious effect on marine life.

The excellent preservation of the burrowings and feeding patterns suggests a rather low intensity of life. In thickly populated bottom areas the deposits are ploughed over and over again, resulting in a large number of mutually erasing disturbances. But in flysch beds one is struck by the high percentage of rather complete traces combined with preserved depositional lamination. If the rate of sedimentation is 40 cm per 1000 years and if each spot on the sea floor is visited once in 200 years the burrows will have about 8 cm depth available before starting to efface eachother, after compaction 3 cm. If each burrow is occupied for a month, then the mutual distance of the live animals would average 50 diameters of the burrows. Deep-sea photographs in such an environment would show perhaps one larger and a few smaller traces in process of formation. But if the burrows were being developed *in* and not *on* the bottom the pictures would show no activity (see HERSEY, 1967).

SEILACHER (1967) distinguished half a dozen trace fossil communities that appear to be governed by depth. Two appear to have lived in deep quiet water, the Zoophycus facies and the more extreme Nereites facies. The latter is typical of the lutites between turbidites.

Only a few examples have been recorded of flysch-type burrows on photographs of the deep-sea floor. This can be attributed to wide spacing or to difficulty of detection. It is not unlikely that the circumstances in orogenic flysch basins tended to differ from those shown by present ocean deeps. Comparison should be restricted to deep-sea trenches and basins of moderate extent. But presumably flysch basins were more landlocked and turbid with a higher rate of sedimentation than the majority of recent basins.

SEILACHER pointed out that the photographs of recent Nereites markings were obtained at 3500 metres and deeper. He suggested that the flysch formations in which the Nereites facies is lacking may have been deposited in depths too small to accomodate this ichnocoenosis. Personally I am more inclined to assume that these Nereites traces will in future also be encountered in the present oceans or inland seas in lesser depth. The absence in some flysch formations can also be explained by failure of the animals in questions to reach the basin.

Precambrian trace fossils have not yet been recorded. But there are turbidites of great age showing remarkably slight metamorphism. These contain excellently preserved inorganic markings and if trace fossils are absent this must be a primary feature. Perhaps closer inspection will as yet reveal organic markings. From the evolutionary point of view it is a question of the utmost importance to ascertain which kind of trace makes the first appearance and in rocks of what age the various types of trace start to appear.

Here lies a chance of making a stride forward in understanding the course and the timing of evolutionary stages which escape us because no shelly parts are preserved. The problem is urgently recommended for study.

True fossils. The fauna found in the pelagic beds between the turbidites are of two kinds, planktonic and benthonic. Where the planktonic remains are plentiful, there has been only slight dilution by land-derived lutum and considerable production. The cause could be respectively an appreciable distance from land or upwelling of nutrient-rich water.

Where plentiful benthonic shells are found these indicate that both ventilation of the bottom water and supply of food from above have been ample. Usually, however, even the pelagic beds of flysch-type sequences appear to be rather barren of life. Although this can be in part attributed to failure in identifying and sampling such beds, it seems probable that flysch basins were in general not very suitable for life either on the bottom or near the surface. This is one of the conclusions arrived at by KSIAZKIEWICZ (1961), a stratigrapher who has paid special attention to the paleontology of flysch, especially in the Carpathians. This point needs further study in all flysch-type formations by careful search for fossil horizons.

The most credible case reported so far of modest (= shallow-neritic) depth is that of a Pyrenean flysch containing a.o. beds of calcareous algae alternating with normal flysch sandstones (MANGIN, 1959). Even if this evidence is fully accepted, the case is so highly exceptional that there is all the more reason for recognizing the almost complete absence of calcareous algae in situ in normal flysch-like formations as negative evidence favouring more than neritic depths. This conclusion is confirmed by absence of all kinds of reefs or plant roots in situ. It has also been suggested that the algal beds described by MANGIN formed during temporary lessening of depth, due to crustal movements, to 150 metres, the maximum at which algae can grow.

The clearest fossil evidence on depth comes from the Ventura Basin in Southern California. NATLAND demonstrated long ago (see NATLAND & KUENEN, 1951) that the foraminifera indicate depths of more than 1000 metres. Later studies (CROUCH, 1952; NATLAND, 1963; CONREY, 1967), have confirmed his results and provided a more detailed picture. The only modification was to show that temperature was more significant than pressure. But in view of clear proof by fossil plants of a warm climate on the adjacent land, low temperature of the bottom water must be equated with considerable depths.

A very extensive study by BROUWER (1965, 1967) has shown that flysch-type formations are characterized by an autochthonous agglutinating foraminiferal assemblage ('Rhabdammina fauna') that differs characteristically from the associations encountered in deposits that evidently formed in neritic environments. The principal elements of the flysch fauna are found in the present oceans at bathyal to abyssal depths.

This conclusion has recently been challenged by PFLAUMANN (1967). In the shales between the turbidites of the flysch in southern Germany he noted scarcity and small size of planktonic foraminifera and relative abundance of agglutinating forms. Eleven of the latter belong to recent species and he tabulated depth ranges in the present oceans, as recorded in the literature. He concluded that the basin was warm and shallow, and swept by muddy currents. In the table a prominent part is played by the data of LACROIX (1929), whose identifications for the fauna collected off Monaco are criticized nowadays. If these data are struck from the table then half of the species determined by PFLAUMANN are only known from bathyal depths. All the eleven species have been found in depths exceeding 1000 m, and for two the minimum is 700 m. The average for all is 1600 m (inclusive of LACROIX's data 1500 m). Seen in this light PFLAUMANN's results are convincing evidence for bathyal depths, probably 1000 m or more.

Strong support for this interpretation comes from the absence of shallow benthonic foraminifera. Accompanying turbidite beds according to PFLAUMANN contain a rich fauna with large foraminifera indicating clear, shallow water. The contrast in conditions under which the resedimented turbidite fauna originally flourished and those prevailing in the same basin at the place where deposition of the lutite and redeposited sand beds took place cannot be accounted for, except by entirely different environments for life. The only logical interpretation is much greater depth in situ where the lutite fauna lived and shallow agitated waters where the turbidite-enclosed fossils thrived prior to transportation.

MYERS and COLE (1957) pointed out that benthonic shallow-water species can be distributed by attachment to floating weeds. Therefore an occasional shallow fossil in the shales of flysch formations cannot prove small depths. More weight must be given to the testimony of the much commoner deep-water benthonic remains.

CLARKSON (1967) studied the problem of blind trilobites in the trough of the Variscan geosyncline. His conclusion was that depths of hundreds of metres are the most probable.

Pavements

A noteworthy feature of some deep-sea sands is the presence of a stratum at the base consisting of planktonic shells, one shell thick (NESTEROFF, 1963). Originally this was attributed by NESTEROFF to deposition from the tail of the current. Any subsequent pelagic deposit had been washed away by the next turbidity current, so as to lay bare this stratum of shells. This second current then built its graded bed on top. It was noted that these shell laminae occur only below fine-grained deep-sea sands, but that where coarser-grained beds indicate higher current velocities the shells have been washed away by the flow supplying the covering sand.

There are several arguments opposed to this explanation (KUENEN, 1964) and it is more logical to assume that the feature is a self-made pavement below a new current. The assumption is that the current was fast enough to winnow the clay from the pelagic deposit, but unable to displace the enclosed pelagic shells. These were thus concentrated until forming a protective cover to the underlying pelagic lutum. Erosion should come to a standstill at the moment a stratum of juxtapositioned particles one shell thick has been produced.

This is the picture actually observed by NESTEROFF. Complications might arise if ripples form. The author is not aware of the finding of fossil pavements, but they doubtless exist. In searching for microfossils in turbidite formation particular attention should be paid to the base of finer grained turbidites where a rich one-millimetre deposit of planktonic and deep-benthonic life might be found.

Organic matter in turbidite formations

The great majority of flysch formations are remarkably poor in fossils, as KSIAZKIEWICZ (1961) has re-emphasized in an excellent survey of this subject. It is therefore not surprizing that they are usually also poor in organic matter, although the two features are by no means always directly correlated in sedimentary beds, not even in source rocks. Where plentiful plant detritus in the shape of coal films – as for instance in some flysch-type 'Kulm' deposits and many Tertiary flysch beds – denote an original organic content there is nevertheless no oil or gas preserved. On the other hand the turbidite-filled basins of Los Angeles and Ventura in Southern California are among the richest oil fields of the world (EMERY, 1960). Evidently the mechanism of turbidity currents is not adverse to the production of an oil pool, but in most flysch basins conditions were unfavourable to accumulation. This remarkable difference in productivity between turbidite formations cannot be correlated with a particularly high density of fossil remains in the Californian basins. The proportion of fossils is not spectacularly high compared to Alpine, Carpathian, or Pyrenean flysch but the fauna is much less specialized. One could suggest that the tectonism of the Californian basins is so mild compared to that of the flysch formations mentioned, that the contrast results from leakage or metamorphism in the European basins. However, the barren Apennine macigno and marnoso arenacea are not more disturbed than the Ventura Basin. Neither is the consolidation of the marnoso arenacea in an advanced stage.

Some oil geologists maintain that the underlying Monterey Shales are the source rock in Southern California. A different opinion was expressed by EMERY (1960). He confirmed an earlier conclusion of TRASK (1932) that the sediments forming at present in the basins off Southern California contain the exceptionally high amount of 7% organic matter at the surface and 4% at 3 m depth. The Pliocene rocks of the Los Angeles Basin contain 2.6% and are closely similar to the recent sediments. It is logical to suppose with EMERY that the oil in the fossil sediments represents the equivalent of the organic matter in the recent sediments, somewhat reduced with time. EMERY's conclusion is stated in the subtitle of his book 'The sea off Southern California: a modern habitat of petroleum'. Where organic matter is enclosed in sediments in the form of non-fossilizing debris such as algae and animals lacking a durable skeleton, high percentages need not be reflected in high fossil content.

The modest fossil content of the Ventura Basin is therefore no compelling reason for seeking the source in the underlying Monterey Shales. The latter view would mean, first total loss of organic matter from the Upper Tertiary rocks which – by analogy with the recent basins – was originally abundant, and then replenishment from the underlying shales. This complicated hypothesis is hardly warranted.

It is also important to note that this high organic content in the recent sediments is not coupled with anoxic bottom waters. Oxygen values of 0.2 to 2 ml/litre are found which are admittedly well below the 6 ml/litre found at the surface, but about equal to the content in the open ocean at sill depth (EMERY, 1960, p. 108).

HEDBERG (1964, p. 1770) claimed that 'a reducing environment seems a cardinal necessity for petroleum genesis', but this can only be conceded for conditions *in* the bottom and not for the bottom water of the basin. However, as the vast majority of lutum sediments are reducing below a thin oxidized surface layer, there is nothing distinctive about the reformulated rule. Provided production is vigorous the organic content of basin sediments can be high, high enough for them to act as source-beds, in spite of a modest amount of oxygen in the bottom water.

The contention that one of the prime factors in the production of petroleum is upwelling of water rich in nutrients causing plankton bloom was expressed by TRASK (1932) and afterwards in more detail by BRONGERSMA-SANDERS (1948, 1966). The latter authoress made this claim mainly in connection with open shelves, estuaries, and embayments. But as follows from the analysis given by EMERY of the situation off Southern California it can evidently be equally effective in basins of medium depth.

An instructive comparison can be drawn between the Californian basins and the deep part of the Adriatic. The basins of southern California range in depth from 600 to 2500 m, and the average percentage of organic matter at the surface of the sediment is 6.9. This figure is roughly equal irrespective of distance off-shore or rate of accumulation. The deep part of the Adriatic is only a few times larger than the average for the Californian basins. It is within their range of depth (1200 m), and shows the same rate of sedimentation: 24 cm per 1000 years (VAN STRAATEN, 1966, p. 442) against an average of 30 cm per 1000 years (EMERY, 1960, Table 19). But the deposits in the deep of the Adriatic contain 1.0% organic matter and, in the small basin to the north west 300 m deep the average is 1.2% (unpublished data, supplied by VAN STRAATEN). These figures are quite low, lower than of many normal marine sediments that are evidently not potential source beds.

Low productivity is typical of the whole present Mediterranean and results from the type of circulation in the Straits of Gibraltar, incoming at the surface and outgoing along the bottom (so-called anti-estuarine circulation). The Adratic basin shows the same type of circulation with respect to the eastern Mediterranean, due to winter cooling and vertical convection. The bottom water is very high in oxygen ($>$5.0 ml/litre) and this may contribute to the low organic content of the sediment.

The paleogeography of the Tertiary geosynclinal flysch basins of Europe can hardly have allowed of upwelling comparable to that occurring off Southern California because they were too far removed from the open oceans.

Another possibility for high productivity would be estuarine circulation of the kind shown by the Black Sea. But that requires special conditions in the form of a very narrow and shallow outlet. Wherever the sill depth of a larger basin in a warm climate is more than about 200 m, as in the Moluccan basins, there is anti-estuarine exchange and low productivity. The average organic content of Moluccan sediments is 1.5% in spite of rather low oxygen content of the bottom waters ($\pm$2–3 ml/litre).

For basins far inland from the continental borders the conditions for shallow and limited water exchange with the ocean by estuarine type of circulation are more likely to be developed, witness the Black Sea. Also in the much shallower molasse troughs the anti-estuarine circulation was less likely to develop, hence more chance for productivity.

The tentative conclusion is that the scarcity of petroleum in most flysch formations is primary and due to lack of nutrients and hence poor phytoplankton. Neither upwelling nor estuarine circulation are likely to have played a prominent part. High oxygen content of the deep water caused by vertical circulation as in the Adriatic may have been an additional factor.

In his discussion of the rather general scarcity of fossils in flysch KSIAZKIEWICZ (1961) considered more especially the Carpathian geosyncline. In the neritic zone life may have been impeded by great influx of terrigenous material, especially during periods that clastics were particularly abundantly supplied. But he seeks the chief cause of sterility of the flysch basins in lack of nutrients. This lack he attributed to:

(1) The small area of land draining into the Carpathian and other flysch basins according to the paleogeographic map for Cretaceous and Lower Tertiary times.

(2) Poor communications with the epi-continental seas in the vicinity. Although true euxinic conditions (H_2S in bottom water) were reached only once in the history of the Carpathian geosyncline, the connections with the open sea tended to be narrow and shallow. Only surface water, already depleted in phosphates and nitrates, could be introduced.

(3) Even if vertical mixing took place, the paucity of decaying organic matter on the bottom, provided hardly any nutrients to fertilize the euphotic zone.

This analysis by KSIAZKIEWICZ is very much to the point. But two aspects call for clarification. A distinction must be made between fossil remains and organic matter. If strong vertical convection carries oxygen to the bottom, then the nutrients can be returned to the surface. Dense life and fossiliferous deposits could thus be maintained without other supply to the basin than of lime and silica. But the deposits would be poor in organic matter. If only the organic matter is considered then KSIAZKIEWICZ's treatment of regeneration would show elements of a circular reasoning. For he claimed that the observed lack of organic remains on the basin floor is due to low density of life in the euphotic zone. And the latter is in turn related to the scarcity of organic matter decomposing on the bottom producing fertilizers to be carried back to the surface.

The manufacture of plentiful organic matter for burial in the sediment requires an outside source of nutrients. This is illustrated in a negative sense by the planktonic deficiency in the Adriatic where unfertile Mediterranean water flows in and sinks to the bottom, producing oxidizing bottom water and low organic content of the deposits. Off Southern California, on the other hand, upwelling of fertile water under similar climatic and bathymetric conditions, results, in plankton bloom and deposits rich in organic matter.

The possibility must be examined whether the low organic content of flysch sediment can have been occasioned, not by low productivity of the overlying water, but by dilution consequent on a high rate of sedimentation. The combination in the inshore basins off Southern California of high organic content (6%) and high rate of sedimentation (60 cm/1000 years = 75 mg/sq cm/year) shows that this line of speculation is unsatisfactory.

Life conditions for the benthos

The conditions for life on flysch basin floors visited by turbidity currents appear to have been as follows. Darkness, rather low temperatures, normal salinity, a continuous slow rain of lutum, insignificant current action, low supply of organic matter, in some cases a low – and in others a reasonable supply of oxygen, but anaerobic conditions *in* the bottom.

Once in a while, but at intervals, of a hundred to many thousands of years, a turbidity current swept the bottom clean of all benthos except a few deep burrowers. The damage sustained by this displaced fauna is unknown. Possibly wide extents of abyssal plains had to be repopulated from the edges and far end, but individuals may have been dropped from the tail of the current, perhaps one or two hundred kilometres down-current from the spot where they were engulfed. It seems to the author unlikely that repopulation took up a large proportion of the interval between the advent of successive currents.

The behaviour of the more deeply burrowing animals is different to what might be expected. During the long periods between the advent of turbidity currents the floor was formed of lutum. In sections it can be observed that burrows seldom reach deeper into the top of the turbidites than about 5 to 10 cm and have not disturbed the sedimentary structures of the fine sand ripples or even of the silty cover on the ripples. When a turbidity current arrived some animals were so deeply positioned that they remained in situ while the turbidite was deposited on top of them. This process can be estimated to have taken one to several hours inclusive of the level containing the ripples.

One would expect a mud feeder entrapped below a coarse sandy bed of half a metre or more in thickness to be unable to escape. In fact in some cases one does find so-called 'worm burrows' that appear to follow below the lower surface of the covering sand as if the animal had sought to escape but had been frustrated in this attempt. But there are also some beds of which the sandy lower metre is particularly crowded with burrowings as if the animal preferred the new diet of coarse sand to its usual meal of lutum. It seems most unlikely that a sand-eating animal was imported from shallow water by the current itself, because of the entirely different pressure. Was the turbidite perhaps richer in oxygen or in food to tempt the burrower? Lack of preference for a fine-grained environment, as shown by some of these mud feeders, is illustrated by the finding of cases in which a burrower has gone right through a large shale pebble in the sand, evidently undeterred by whether it encountered sand or fine mud. These phenomena are so rare, however, that it will be difficult to find the correct explanation.

Some turbidity currents have carried large amounts of vegetable matter to the floors of basins. It has been suggested (HEEZEN et al., 1955) that this supply forms an important source of food for deep benthos. However, there is so little disturbance of the lamination in recent and ancient turbidites rich in vegetable debris that this conclusion is open to doubt. Perhaps the debris carried in the currents had already lost its nutrient value for multi-cellular animals.

In a recent paper MEISCHNER (1967) discussed the Ooser Plattenkalk-sequence and suggested that calcareous turbidity currents may cause precipitation of carbonate and a higher oxygen-content of the bottom water. This would temporarily allow more exacting epibenthos to replace the normal endobenthos. However, the present author imagines diffusion and currents will dissipate this oxygen in the course of a few weeks, allowing little time for a change in fauna.

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