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ESTIMATED SIZE OF THE GRAND BANKS TURBIDITY CURRENT

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ABSTRACT. The observed velocity of what Heezen and Ewing have shown to be the Grand Banks turbidity current is used as a basis for estimating the size and sediment content. The volume of the original slides and the extent of the deposit are also evaluated. It is shown that a consistent picture of the whole process can be built up to fit the available data. The scale, though unexpectedly large, is by no means impossible as might at first sight be supposed. This supports the explanation of the cable breaks proposed by Heezen and Ewing. It also carries us a step further in understanding the emplacement of deep-sea sands and fossil graded beds. Needless to say the figures arrived at are merely suggested as a first approximation. It is argued that a slide of recent marine deposits may change to a turbulent flow without inmixing of water. They contain an ample supply of water to allow of turbulent flow once the thixotropic strength has been destroyed.

Whatever the result of future determination of volume for the deposit, it would be unreasonable to suppose this single case represents the upper limit in size ever attained in nature. A multiple of the area and thickness must be possible. If coring or examination of fossil graded beds should lead to volumes of dozens or even hundreds of cubic kilometers, this size can no longer be used as an argument against explaining the emplacement by turbidity flow.

IN the preceding enlightening article Heezen and Ewing show convincingly that the progressive sequence of breaks in cables accompanying the Grand Banks earthquake of 1929 cannot be explained by the direct action of the earth shocks or by undermining through slides. Neither do tsunamic waves account satisfactorily for the observed time lag between the first and last ruptures. The explanation they propose is that a gigantic turbidity current, resulting from slumps set off by the shock, caused the later cable breaks.

Although Bailey had suggested some time ago (1938), in connection with the erosion of canyons, that submarine slides could readily merge into submarine mud-rivers and Kuenen and Migliorini (1950) had invoked the same process to explain graded bedding and the emplacement of deep-sea sands (Kuenen, 1947 and 1950), while Kuenen (1950, p. 239) had attributed some other cable breaks tentatively to turibidity currents, no one had yet realized that here nature had carried out a vast experiment along these lines, accurately timed and located by the cable companies. Neither had anyone conceived of turbidity currents, let alone experiments, on such an enormous scale.

The marshaled evidence appears to allow of no other interpretation and the picture offered is logical. Nevertheless many will feel doubt whether velocities of 100 km per hour and travel over hundreds of miles on an almost level bottom are within reasonable bounds of speculation. In the following the writer will attempt to show that this intuitive feeling is unfounded. When the size of the current and the amount of sediment involved are computed from the velocity, figures are obtained which are quite reasonable. The data will be seen to fit into an entirely consistent picture of what happened and this should strengthen confidence in the proposed explanation.

So little is yet known of turbidity currents in nature that no one can say offhand whether the thickness of the inferred current was to be measured in meters or hundreds of meters, whether the amount of sediment involved was a small fraction or a high multiple of a cubic kilometer, or whether the deposited bed should extend any distance beyond the farthest break or, finally, whether the deposit should be a few centimeters or dozens of meters thick. The writer hopes this will excuse a crude attempt to arrive at a first approximation and that it will be realized from the outset that the present results are not claimed to be more than tentative.

Before going any further it should first be examined whether a pure submarine slide could account for the observed phenomena not by undermining, but by impact. Two arguments appear to exclude this possibility. Firstly the slope at the lower end was so slight (less than 1/30 of a degree) that a slide would have stopped long before reaching the furthest breaking points. Secondly a slide cannot result in a graded deposit. Although deep-sea coring has revealed a great number of graded deep-sea sands, only a few small beds of unsorted coarse sediment have been found which are evidently due to local slides on rather steep slopes. If slides could attain the size indicated by the delayed cable breaks, deep-sea sampling should already have encountered many non-graded beds of uncorable thickness. Hence one may conclude that if the delayed breaks are due to sediment transport, this must have taken place in the shape of a turbidity current.

However, it might be conjectured that the breaks do not correspond to the velocity of the current, but occurred later by gradual abrasion ("sand blasting") in the current. The active part of the current passed any point in a matter of minutes and the breaking must have occurred soon or not at all. The timing therefore cannot be changed significantly. Moreover, it would only mean having to assume even greater velocities. It appears safe to assume that the breaks occurred almost immediately after the current reached them.

On the basis of experiments and data on turbidity currents in reservoirs the present writer has attempted in earlier papers to deduce the relation between velocity on the one hand and size, density, and slope on the other. It was found, as Daly predicted, that the formula used for calculating the velocity of rivers $V = C\sqrt{m \times s \times d}$ ($V =$ velocity, $C =$ a constant, $m =$ hydraulic mean depth, $s =$ slope, $d =$ effective density) holds also for turbidity currents. These results will now be applied to the Grand Banks turbidity current.

The constant C is related to the internal and external friction and for turbidity currents the value must be lower than for rivers. In the centimeter-gram-second system C for large rivers is 700-800. For our case a value larger than 600 is out of the question.

In discussing his experiments the writer concluded (Kuenen, 1951) that C must be 125, but reconsideration has since led him to assume that the density in the experimental flows was smaller than supposed and hence C larger, probably about 200. The figure deduced for the turbidity currents in reservoirs was 400.

The highest density at which turbulent flow is possible is of the order of 2. But for an arbitrary mixture of grain sizes and as an average for the entire thickness of the flow it must necessarily be less.

Moreover, recent marine sediments contain from 60 to 80 per cent water by volume. A density of the current higher than that of the original sediment cannot be postulated. Hence it will be assumed that 60 per cent water by volume is the minimum, and this means a maximum density of 1.6 (effective density, $d = 0.6$).

As the currents appear to have been very broad the hydraulic mean depth is half the thickness of the current. In table 1 the thickness is calculated for various points along the bottom and for $C = 400$ and $D = 0.6$.

TABLE 1

	Depth range in fathoms	Distance in miles	Slope	Velocity at end: knots	Velocity at end: meters/sec	in meters: Hydr. m. d.	in meters: Thickness
Cable H*	....	...	1:170	55	28.3	137	270
Cable H I	2160-2640	105	1:220	45	23.1	121	240
Cable I J	2640-2760	130	1:1080	16	8.2	77	150
Cable J K	2760-2773	20	1:1080	14	7.2	81	160
Cable K L	2773-2800	40	1:1500	12	6.2	61	120
Cable H L	2160-2800	295	1:440	32	16.4	123	240

C 400 d 0.6

* For lettering of cables see the preceding article.

In table 2 various values for C and d are tested for the entire run from breaking points H-L.

TABLE 2

	C	d	slope	m/sec	Hydr. m. d.	Thickness
On basis of experiments	200	0.3	1:440	16.4	973	1940
Maximum possible	600	0.8	1:440	16.4	41	80
Most probable	400	0.6	1:440	16.4	123	240

From table 2 it follows that the values for C and d deduced from the experiments are much too low because they lead to an impossible size for the current. The minimum thickness possible is 80 meters. But if a figure of this magnitude has to be admitted it appears more likely C and d were less extreme and the thickness still greater.

Two significant points can be made here. If we are forced to assume a high average density the vertical component of the turbulence must be high to hold the sediment in suspension. This fits the enormous velocity established because turbulent velocities are related to velocity of flow. From the necessarily high value of C it follows that the surface of the flow experienced relatively light friction with the covering stagnant water. This, in turn, is a *conditio sine qua non* for maintaining the high density.

This result is confirmed by the figures in table 1. These show that the gradual decrease in velocity between Cables H to L must be attributed mainly to the diminishing grade. Only a moderate additional loss either in density or in thickness must have taken place. The table is based on the assumption of constant density. However, thinning due to lateral spreading is likely to have occurred. Some loss of sediment by deposition especially towards the far end is also probable. Obviously dilution by mixing cannot have been intensive, otherwise the current could not have maintained the observed velocity.

Doubt has been expressed whether the writer's former attempts to extrapolate from his experimental results to the dimension of turbidity currents in nature was permissible. It was suggested the higher velocities might result in increased friction and a much lower value for C. It now appears as if the opposite may be true and that the friction and dilution in the small scale experiments are *relatively* higher than with larger dimensions and swifter currents. For those who admit that graded beds of vast extent in fossil basins and on the ocean floor have been deposited from turbidity currents the above conclusion appears to be warranted. For only if friction and inmixing are limited can the phenomenon of turbidity flow attain the gigantic horizontal proportions which they are forced to assume.

Heezen and Ewing deduce the velocity of 55 knots at the first breaking point from the time-distance curve of their figure 3. An attempt can be made to estimate where the current started and what its velocity was before reaching Cable H. The writer is inclined to assume that the original slides produced by the earth shock attained a high velocity and changed to turbidity currents almost immediately and that this took place on local steeper parts of the slope, somewhere around 1000 fathoms depth.

A slide without friction on a slope of 1 in 10 will attain a velocity of 30 m/sec in half a minute. The turbidity current is launched in a few minutes, or not at all, it may be assumed. We are further led to suppose that the sediment lying on the sea floor already contains all the water necessary for turbulent flow. The thixotropy of the clay and the loose packing of the sand account for the high porosity combined with a certain, though small, strength. The earthquake causes a large mass to start sliding and this movement then breaks down the internal strength. Thus the entire mass suddenly changes to a liquid. At this moment a turbulent turbidity current is launched.

This supposition was tested on some deep-sea samples of blue mud and tidal flat deposits. It was found that fine deep-sea lutite with 77 volume per cent water (density 1.33) if violently shaken in a bottle is soon mobilized. It runs like a watery liquid, but is pastelike when at rest due to strong thixotropy. The same is true of firm sandy muds from a tidal flat containing 58 volume per cent water and showing a density of 1.62. In the experiments it was also noted that a current with slight internal friction results when a viscous liquid starts to flow turbulently. Addition of an equal amount of sand to the lutite of the above deep-sea samples does not change the physical properties, except that the density is raised to 1.6. This mixture is the supposed composition of the Grand Banks slides.

Realization of the circumstance that the sediment requires no inmixing of water but only a physical treatment, to produce a liquid state clarifies an aspect of turbidity flow which had much puzzled the writer, namely how a slide could change to a turbulent flow.

The above reasoning concerning the launching leads one to suppose that the volume and thickness of the turbidity current increased to their maximum between 1000 and 1900 fathoms.

The velocity then gradually sank to 55 knots as it reached a slighter slope and passed the first point, gradually slackening to 12 knots at Cable L.

TABLE 3

Depth range	Slope	C	d	Hydr. m. depth	Deduced Velocity Knots	Deduced Velocity Meters/sec
1000-2000 fath.	1:50	400	1.6	150	10.5	54
1000-2000 fath.	1:50	400	1.6	100	8.5	44
1000-2000 fath.	1:50	400	1.6	85	7.8	40
1000-2000 fath.	1:50	400	1.6	50	5.8	32

The velocity for various hydraulic mean depths, between 1000 and 2000 fathoms depth is shown in table 3. It is considered that the deduced decrease of thickness from Cable H to Cable L cannot have started much earlier. The preferred estimate for the average of m from the origin to Cable H is 85 meters (thickness 170 m). This would mean a thickness of 60 m at the origin at zero time, and 270 m when passing Cable H. The average velocity works out 40 m/sec or 78 knots.

Estimates as to the amount of sediment involved work out as follows: At its origin the flow was 60 meters thick and may be assumed to have had a length of at least 20 times as much, 1200 meters. For each meter of breadth the amount of sediment of a density of 1.6 was 72 x 10^3 m^3. The same amount was contained in the original slide imagined, which may have been 50 meters thick and 1500 meters long. Detailed knowledge of the bottom topography must be awaited before a more precise picture can be drawn of this initial phase of the current. Probably there were several slides, which may have merged into one or more turbidity currents.

By the time the turbidity current reached Cable H it must have been some 20 x 270 m long and would have contained 1400 x 10^3 m^3 of sediment per meter of breadth. This addition of 1328 x 10^3 m^3 came from bottom erosion over a distance of 122 kilometers and represents a layer 11 meters thick. The average length of the main body of the flow over this first part of the run was 3½ km and the current took 15 minutes to pass any fixed point. The erosion took place at 12 millimeters per second.

The amount of sediment required to give a velocity of 55 knots at Cable H is very large. If it had all come from a nearby slide, this slide would have to be 200 meters thick and 7 kilometers long. More probable is the supposed modest slide (or slides) and subsequent erosion on the steep slope above the first of the delayed cable breaks.

Naturally it is not supposed that the turbidity current showed an abrupt end. Behind the part considered above a tail of gradually diminishing density and velocity must have continued to flow for a long time. This tail may have deposited sediment in the wake of the eroding frontal portions.

The deduced thinning of the flow as it passed down the more gradual slope further along indicates that it was becoming longer and broader, possibly also less dense by the loss of coarse sediment. Erosion had probably ceased to exceed later deposition by the tail of the current by the time Cable J was reached, because this and the following cables were deeply buried.

A difficult point to evaluate is the influence on velocity due to thinning of the current. According to our estimates the center of gravity should have sunk with relation to the bottom by the following amounts: Cable H-I = 10 fathoms, I-J = 25 fathoms, J-L = 10 fathoms. The influence is negligible above Cable I, slight from I-J, but 25 per cent from J-L. In other words "internal slope" is adding to the effect of the bottom slope and the deduced thickness is too large. The best value lies around 100 meters.

The breadth of the current at Cable L was roughly 350 km. However, it is not probable that the front formed a smooth curve. On the slope the current will have shown concentration in density and in thickness along depressions. These fastest lobes will have caused the cable breaks. The intervening parts will have been thinner and less dense. Although these irregularities will have been gradually obliterated on the level ocean bed it is reasonable to suppose that this had not yet been fully attained at Cable L. Hence the total volume of wet sediment was less than is obtained by multiplying the lengthwise section by 350 km, let it be assumed one half or one fifth. This works out at 250 or 100 km^3.

A final point calling for attention is the distance to which the current may be expected to have spread. Assuming, to start with, that the ocean floor is horizontal beyond Cable L, the centre of gravity at Cable L is 50 m above the floor at the limit to which the flow reached.

Fine sand can be transported by a turbidity current with a velocity of the order of 50 cm/sec. This velocity would have been attained some 120 miles beyond Cable L. The graded bed deposited by the current will gradually merge with the normal pelagic deep-sea sediment. It might still show up at 200 miles from Cable L over an area of perhaps 100,000 square miles. The average thickness would be 40 to 100 cm. Needless to say these figures are merely a guess. Their only value is to indicate that in spite of the huge velocity and volume of the current at the bottom of the continental rise, it is highly unlikely that the deposit could be recognized as far away as, say, Bermuda or along the eastern edge of the basin. A graded bed at the generally somewhat disturbed upper end of a core might not show up if less than several centimeters thick. Otherwise it might be claimed that coring should already have revealed its existence.

As the ocean floor appears to slope slightly to the south with some topographic irregularity one may expect the deposit to reach out in this direction in irregular lobes to even greater distances than the above estimate. It is also obvious that if the deposit can be recognized and its volume established by bottom sampling, a much better understanding of the turbidity current mechanism will be attained. If the volume is found to be many times our estimate, the original slides and the erosion by the turbidity current must both have been much larger, the constant C in the formula smaller than suggested. If it is much smaller the most probable explanation would be that there were a few separate currents of limited breadth.

We are now in a position to review the estimated values and inquire whether there is reason for considering any of them excessive.

Velocity and size.—The average velocity before reaching Cable H is estimated at 78 knots. The maximum must have been even greater, say 85 knots or 44 meters per second. The discharge per meter of front at Cable H was 7500 m^3 per second, the velocity 28 m/sec, the thickness 270 meters, the length of the main body 5½ kilometers. These values may appear altogether fantastic to many. But it should be borne in mind that the available amount of water in the ocean is practically unlimited. Geologists and hydrologists are accustomed to think in terms of river dimensions. But to the oceanographer, who measures even surface currents with a discharge of 90 x 10^6 m^3 sec (1000 times that of the Amazon River), it may well appear reasonable to postulate a bottom flow with a discharge of 7 x 10^6 m^3/sec per kilometer of front. Likewise the velocity is not so excessive as may appear at first sight. Even a bore can travel up a river on a level surface at more than 13 knots, and velocities of 30 knots are claimed for the water in log chutes. The largest rivers carry but a trickle of water on an infinitesimal grade as compared to the deduced turbidity current. The grade above Cable L was 600 times that of the lower Mississippi River.

Magnitude of initial slide.—At the mouth of the Magdalene River deepening by a slide in 1935 amounted to 45 meters (Shepard, 1948, p. 196). In Sagami Bay at the time of the great Tokyo earthquake deepening reached no less than 180 meters. Our estimate of an initial slide of 50 meters thick is therefore quite reasoanble.

Thickness of the flow.—A number of submarine canyons show levees at their lower ends (Menard and Ludwick, 1951). These have evidently been built up by turbidity currents, which must have been able to lift sand to the level of the levee crests. Off California the bed of one canyon is at least 150 meters below the levee crests. In the Mediterranean values of more than 100 meters are indicated on a chart compiled by Bourcart. A thickness of 270 meters for the Grand Banks turbidity current is of the same order of magnitude (although the breadth was much greater).

Thickness and extent of the deposited bed.—Migliorini has found graded graywackes of more than 10 meters thick and extending for distances of at least many kilometers. The present estimate of an average thickness in the order of 1 meter is comparable. The failure to find the missing part of the last cable also tends to show that on a wide expanse of the ocean bed the deposit was more than a thin film. Ericson, Ewing and Heezen (1952) have discovered graded deep-sea sands which have travelled 1000 miles from the origin, almost twice the estimate for the present case.

In conclusion it appears that no inadmissibly large values for volume, thickness, or velocity either of the initial slide, the current itself, or the deposit need be assumed to build up a consistent picture of the postulated turbidity current. Hence these results tend to confirm the explanation Heezen and Ewing have offered for the delayed cable ruptures.

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