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TURBIDITY CURRENTS AND SUBMARINE SLUMPS, AND THE 1929 GRAND BANKS EARTHQUAKE*

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ABSTRACT. Following the 1929 Grand Banks earthquake which shook the continental slope south of Newfoundland, all the submarine telegraph cables lying downslope (south) of the epicentral area were broken in sequence from north to south. All previously published explanations of these breaks are considered and rejected because they do not adequately explain this sequence. A new explanation is offered according to which each successive cable was broken by a turbidity current originating as a slump on the continental slope in the epicentral area and traveling downward across the continental slope, continental rise, and ocean basin floor and continuing far out on the abyssal plain well over 450 miles from the continental shelf. We may consider these events as a full scale experiment in erosion, transportation and deposition of marine sediments by a turbidity current in which the submarine telegraph cables served to measure its progress, give evidence of its force, and by their subsequent burial indicate some of the areas of deposition. On the basis of widespread evidence for exposure of Tertiary and older sediments on steep submarine slopes, for numerous coarse graded deposits interbedded with deep sea clays in flat-bottomed ocean basins hundreds of miles from land, we conclude that large scale work by slump-generated turbidity currents is a fundamental process in submarine geology.

INTRODUCTION

STIMULATED by Daly's (1936) hypothesis that density (turbidity) currents carved the submarine canyons which dissect the continental margins, Stetson and Smith (1937), Kuenen (1937, 1947, 1948, 1950) and Bell (1942) conducted tank experiments from which they concluded that turbidity currents are not only possible in the modern sea but are important agents of transportation. Turbidity currents in Swiss lakes were early described by Forel (1885), and more recently Grover and Howard (1938) described similar currents in Lake Meade and Elephant Butte Reservoir. No matter how convinc-

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ing the experiments and the data from the lakes, they give no definite proof that turbidity currents occur in the modern oceans, although they make it extremely probable. The breakage of the submarine cables following the 1929 Grand Banks earthquake supplies not only an excellent example of a recent large-scale turbidity current but illustrates at least one way in which such currents can be generated. Under this interpretation, a relatively severe earthquake on the continental slope set in motion slides and slumps which, with the incorporation of water, were transformed into turbidity currents of high density. These currents converged to form a gigantic turbidity current which swept across the sea floor for well over 350 nautical miles, breaking each succeeding submarine cable. In this paper the phenomena following the 1929 Grand Banks earthquake are briefly described, explanations of the phenomenon given by previous authors outlined, a new explanation offered and several implications discussed.

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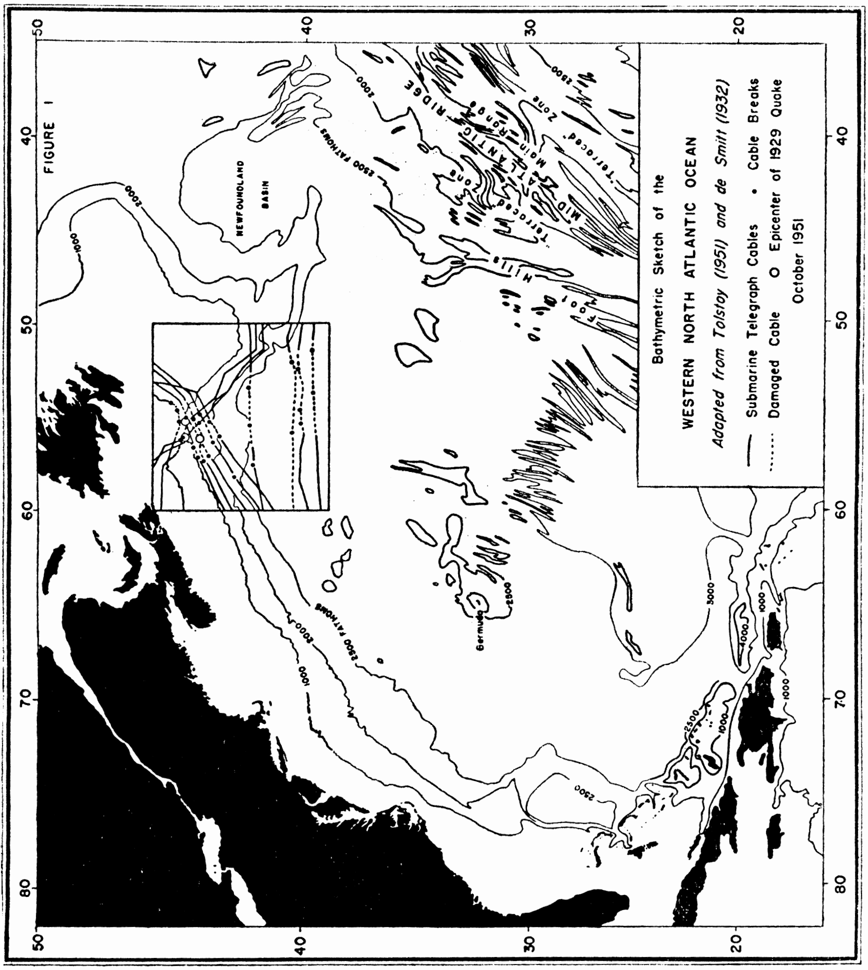
SYNOPSIS OF GRAND BANKS EARTHQUAKE

All the submarine telegraph cables from North America to Europe and their Atlantic Coast connections pass south of Newfoundland across either the continental shelf, the continental slope, or the floor of the adjacent deep sea basin. More submarine cables cross this area than any other area of similar size in the world. On November 18, 1929 at about 20 hours

32 minutes G.C.T.[1] a severe earthquake of magnitude 7.2 shook the continental shelf and continental slope south of Newfoundland. The epicenter lay between 1000 and 2000 fathoms on the continental slope southeast of Cabot Trench in the midst of this dense network of cables. The six cables lying between

FIGURE 1



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[1] Hodgson and Doxsee (1930) list the time and epicenter as 20h 31m 55s at Lat. 44.5° N, Long. 55° W. The International Seismological Summary lists 20h 31m 45s at Lat. 44.55°N, Long. 55.95°W and aftershocks with the same epicenter at 23h 01m 48s and November 19 at 02h 01m 18s. Gutenberg and Richter (1949) list the time as 20h 31m 58s at Lat. 44° N, Long. 56° W with a magnitude of 7.2.

150 and 1800 fathoms on the continental slope between Long. 54.5 W and 57.5 W were broken instantaneously by the initial ground motion or by the almost instantaneous slides and slumps. For 13 hours 17 minutes following the quake there occurred an orderly sequence (de Smitt, 1932) of breaks of each succeeding cable lying in increasingly deeper water for over 300 miles south of the epicentral area (fig. 1). Although all the cables on the continental slope and on the ocean floor to the south were broken, not one of the large number of cables laid on the continental shelf was disturbed. The instants of the cable interruptions were accurately recorded by automatic machines which record the telegraphic messages, and the locations of the breaks were determined by resistance measurements from the shore ends of the cables. Table 1, adapted from Doxsee (1948), lists the positions, times and depths for each break. The earthquake was felt along the eastern seaboard from Newfoundland to New York, and in Nova Scotia and Newfoundland (Johnstone, 1930) caused slight damage to unmortared chimneys and to unstable slopes near quarries and road embankments, and the spilling of mercury in lighthouses. A tsunami swept up towards Newfoundland, causing considerable loss of life and great damage to the fishing boats and fishing gear along the shores of Placentia Bay (Johnstone, 1930). A seaquake was observed by several vessels navigating over the area (Gregory, 1931).

The relationship between earthquakes and submarine telegraph cable breaks was pointed out by Milne (1897), and the hope of using seismological observations to avoid areas likely to produce numerous cable breaks was responsible for the establishment of many of the early seismograph stations. It was not until the earthquake of 18 November 1929 when 12 cables were broken in 28 places that any intensive study of the phenomenon was made. De Smitt's (1932) study of this earthquake "distinctly shows (1) that the direction of progression of destruction was to the seaward . . . to the south and southeast from the epicenter, that is from the continental slope towards the deeper parts of the ocean, (2) that the velocity of progression decreased with increase in distance from the epicenter, (3) that the area of broken or mutilated cables was restricted to the deepest part of the ocean—narrow in the northern part and broadening to the south, 355 nautical

TABLE 1
List of Cable Breaks after Doxsee (1948)

	Break No.	Lat. N.	Long. W.	Fathoms Depth	Time (GCT) 11/18/29	Interval between quake and break	Remarks
A	Commercial Cable Company, New York-St. Johns (N. Y. No. 1)						
	1	44°32′	55°04′	1450	2033	0	These breaks in epicentral area are probably due to landslides and slumps and initial ground movement.
	2	43°41′	57°07′	1890	?	?	
B	Commercial Cable Company, Canso-Fayal (Main No. 4)						
	3	44°23′	55°08′	1500	2033	0	
	4	44°43′	56°10′	220	2033	0	
C	Imperial Cable Company, Halifax-Harbor Grace						
	5	44°50′	55°09′	800	2032	0	
	6	44°55′	54°45′	700	2033	0	
D	Commercial Cable Company, New York-St. Johns (N. Y. No. 2)						
	8	44°12′	55°10′	1820	2033	0	
	9	43°47′	57°17′	1830	2033	0	
E	Commercial Cable Company, Canso-Fayal (Main No. 6)						
	10	44°07′	55°18′	1780	2033	0	
	11	44°45′	56°09′	310	2033	0	
F	Western Union Cable Company, New York (Hammel)-Bay Roberts (No. 1)						
	12	44°02′	55°02′	1800	2032½	0	
	13	43°25′	56°20′	2000	2033	0	
	14	42°42′	58°10′	2300	?	?	

TABLE 1 (*Cont.*)

List of Cable Breaks after Doxsee (1948)

	Break No.	Lat. N.	Long. W.	Fathoms Depth	Time (GCT) 11/18/29	Interval between quake and break	Remarks
G	French Cable Company, Cape Cod-Saint Pierre						This cable within the epicentral area held up for 13 minutes before being broken.
	15	44°20′	56°40′	1150	2046	0014	
	16	44°03′	57°12′	1000	?	?	
H	Imperial Cable Company, Halifax-Fayal						The following breaks downslope from the epicentral area are due to turbidity current.
	17	43°37′	55°15′	2000	2131	0059	
	18	43°15′	56°07′	2200	2131	0059	
I	French Cable Company, Cape Cod-Brest						
	19	42°05′	55°30′	2400	2335	0303	
	20	42°07′	53°30′	2600	?	?	
	21	42°00′	57°36′	2500	?	?	
J	French Cable Company, New York-Fayal						
	22	40°30′	55°55′	3000?	0533	0901	
	23	40°28′	52°06′	2800	0533	0901	
K	Western Union Cable Company, New York (Hammel)-Bay Roberts (No. 2)						
	24	40°00′	55°20′	3190?	0650	1018	
	25	40°02′	54°50′	2900	0650	1018	
	26	40°13′	52°30′	2800	0850?	1218?	
L	Western Union Cable Company, New York-Fayal (Horta) (No. 1)						
	27	39°29′	53°47′	2780	0949	1317	
	28	39°35′	51°41′	2800	0958	1821	

miles long and 210 nautical miles wide, with breaks radiating outward and with not a single break on the shallow continental shelf, and (4) that the ocean floor in the neighborhood of the breaks is rather even with an average angle of slope with the horizon of 1°50' and that about one half the breaks were on a slope of less than 1°."

SUMMARY OF PREVIOUS INTERPRETATIONS

Gregory (1929, 1931), Hodgson and Doxsee (1930), Keith (1930) and de Smitt (1932) attributed the cable breaks to movement along two southeast-trending faults extending along each side of Cabot Strait and subsequently across the continental slope and into the ocean basin. Gregory (1931) concluded that

> "The breakage of cables along both sides of the (Cabot) trench indicates that the movement was a renewed subsidence of the floor between parallel faults, and that the trench is a submarine rift valley . . . as the earthquake was sufficiently powerful to break cables over an area extending 360 (nautical) miles N and S and 150 (nautical) miles E and W, some displacement of the sea floor is probable . . . The clear evidence that Cabot Strait and Trench is a submarine rift valley indicates that the submarine canyons off the Congo and the Hudson and the Adour are probably also tectonic and due to subsidence of the ocean floor along faults."

He assumed that Cabot Strait was a down-faulted block and that the apparent coincidence of cable breaks with projections of these walls proved the extension of the assumed faults. The sequence of the breaks was dismissed with the following statement:

> "These more distant cables either yielded . . . to a stress that had been acting for about thirteen to fourteen hours or they were broken by a subsequent earth movement or slip of the sea floor."

McIntosh (1930) believed that the Cabot Trough was cut by an "old Laurentian river" which carried a "tremendous amount of rock waste from its bed and basin" and deposited it on the continental margin "seaward from its mouth." He attributed the Grand Banks earthquake to "settling and fracturing of the thick mass of sediment concealed beneath the waters of the embayment." However, he made no attempt at explaining the sequence of breaks.

Johnstone (1930) gave an account of the effects of the quake in Newfoundland and Nova Scotia and mentioned the cable breaks, attributing their breakage to "very great vibratory and oscillatory forces." Neither McIntosh nor Johnstone seems to have been aware of the orderly sequence of the breaks, for neither author mentions it.

Hodgson and Doxsee (1930) concurred with Gregory that the cable breaks were due to the down-faulting of a portion of the sea floor, "the northern end being the more seriously displaced." On the orderly sequence of the breaks they wrote:

> "To account for the breaks occurring at times successively later as one moves south, we may suppose all the cables loaded more or less with silt and ooze, which serves to weigh them and, in a measure, to hold them in place. A drop of the bottom of, say 25 feet, at 44.5° N and considerably less at 39° N left the cables unsupported at two points at least, which caused them to break due to the weight of the silt lying on them. The reason advanced for the southern cables yielding so much later is that the drop in the ocean floor may have been less there."

Keith (1930) concluded that

> "All the evidence is in harmony with the theory that parallel faults produced the Cabot Trench in the past and the Grand Banks earthquake in the present."

He continued:

> "There still remain to be explained the cable breaks far to the southwest off the extensions of the trench margins. By the same line of reasoning other and parallel faults must be appealed to for explanation of these breaks. Direct evidence of this arrangement appears to be given by the difference in time between some of the breaks."

Apparently Keith believed that the difference in the time of the different breaks was due to the difference in the time of the supposed faulting along "secondary" faults.

De Smitt (1932) concurred with Gregory, Hodgson and Doxsee, and Keith in attributing the breaks in the cables to parallel faults. In his opinion "the severely shaken area doubtless extends beyond the southernmost broken cable."

After a study of the Cabot Strait, Shepard (1931) concluded that

> "the trough has been shaped principally by glacial erosion . . . (and that) the Grand Banks earthquake was associated with the irregular topography of the continental slopes and deep ocean basin rather than with the St. Lawrence submarine trough, suggesting that the proximity of the trough may be only coincidental."

Kindle (1931), although accepting faulting as the cause of the breaks in the vicinity of the epicenter, pointed out that faulting explains neither the multiple breaks in the cables near the epicenter nor "the north to south progression of cable breaks, with an interval of 13 hours between the first and last breaks." To explain the burial of some of the cables, Kindle drew an analogy between the Grand Banks earthquake and the New Madrid earthquake of 1811 in which the "soft" ground of the Mississippi bottom land was severely disrupted and quantities of sand were expelled through fissures. He quoted statements by Murray and Hjort and Milne concerning "tidal currents" at great depths in the ocean, and concluded that "we must . . . assume . . . the existence of sea-bottom currents in depths as great as 2,000 fathoms or more." He considered the currents to be due to the combined action of tides and storm winds. The shock of the earthquake was considered to have left the bottom sediments in an unstable condition so that these currents, while normally incapable, could under these special conditions erode the bottom. He concluded that

> "The progressive north-to-south order of the breaks appears to square well with the hypothesis that most of the breaks were caused by submarine landslides developed through the agency of bottom currents which in turn were produced chiefly by the gale blowing at the time of the earthquake."

Shepard (1932, 1934) states that "there is reason to believe that Corsair Gorge was opened (by a landslide) at the time of the Grand Banks earthquake in 1929." Johnson (1939) pointed out the weakness of this statement and the improbability that the supporting evidence is significant. To his objections can be added the fact that the records of the Western Union Company show no breaks in several cables passing through and near the Corsair Gorge at the time of the Grand Banks earthquake.

Stetson and Smith (1937), in discussing suspension currents and mudslides, have concluded that about 10 grams per liter of typical continental shelf sediment would be required to increase the density of water of the continental shelf in summertime sufficiently to enable it to sink to the foot of the continental slope, whereas about 3 grams per liter would be required in winter. These writers have emphasized that such currents will leave the continental slope and spread out horizontally when they reach a depth at which the density of normal ocean water exceeds that of the suspension. In the paper of Stetson and Smith there is a section on slumping in which the possibility that slumps could be induced by the frictional drag of suspension currents (turbidity currents) is discussed and considered negligible. There is no mention in their paper of the possibility that slumps on the continental slope may be transformed into turbidity currents, thereby enabling the sediment to be carried far out into the ocean over very gentle bottom slopes. It seems clear that they were considering the slumps only from the viewpoint of agents in canyon erosion. Their statement that "Submarine landslides on a major scale are known to occur, as for instance the one which broke the Western Union Company's cables off the Grand Banks of Newfoundland following the earthquake of 1929," referring as it does to the cables of only one company without reference to the literature and without statements about the slopes and distances involved, indicates that no detailed examination of the cable break data was made.

Bucher (1940) offered an explanation which has some points in common with that of Kindle, stating that

> "The picture becomes intelligible when the breaks are interpreted as the result of erosion along the sides and bottoms of submarine valleys brought about by the tsunamic waves set up by the earthquake . . . (The tsunami) were probably created by submarine slides set off by the earthquake and some of the cables were undoubtedly broken and buried by such slides, especially along the faults that bound the graben of Cabot Strait."

He supposed that the cables broke "of their own weight" when the canyons were scoured sufficiently to "leave portions of the cables unsupported." Since the velocity of the tsunami was several times that of the propagation of the breaks, he assumed that

> "With increased distance from the origin, however, more and more of the energy of the tsunamic waves spreading into still water was lost, and the orbital velocity of the water particles reduced proportionately. The resulting weaker current required more time to produce the same amount of erosion."

Shepard (1948) in part followed Kindle and Bucher, stating:

> "Since the breaks did not follow any line suggesting faulting, it may be assumed that they were due to mass movements of the loose sediment leaving sections of the cable unsupported."

Doxsee (1948) stated:

> "The fact that the breaks range themselves into two groups whose east and west separation becomes greater as the progression extends southeast from the epicentral zone to about 39° north latitude suggests a subsidence of the ocean floor between two fault planes each roughly parallel to the axis of the Cabot trench and extending from about 45° N to approximately 39° N."

The fact that the cables to the south broke later "would indicate that the greatest displacement was in the northern section of the disturbed zone." Doxsee's paper, probably written in 1932 but not published until 1948, expresses the same opinion as Hodgson and Doxsee (1930).

Kuenen (1950) in discussing cable breaks states:

> "In many cases the ruptures are not due to direct faulting of the sea floor but to sliding . . . (1) the surface over which ruptures occur is often very extensive . . . (2) the cables are frequently found buried . . . (3) many breaks may occur several hours after the shock and successively later at greater distances from the epicenter. This indicates a secondary cause, probably tsunamis."

DISCUSSION OF THE PREVIOUS THEORIES

Although most of the previous authors were aware of the orderly succession of breaks from north to south into successively deeper water, none of the above explanations satisfactorily explains the sequence. Gregory's statement that the later breaks may have been due to stresses acting for several hours or to later land slips offers no explanation for the orderly succession. Hodgson and Doxsee's explanation is equally unsatisfying. The explanation of Keith, attributing the later breaks to a complex system of later faults, seems excessively complicated and offers no explanation for the later succession. The later faults should be expected to cause later earthquakes. Only two aftershocks were recorded although there were six later cable breaks; further, the times of the aftershocks do not correspond to the times of the later breaks, and the epicenters were approximately identical with those of the original quake and the magnitudes much smaller. Gregory's and de Smitt's impression that the whole area from 45° N to 39° N was severely shaken by the quake resulted from their assumption that all the breaks were directly caused by seismic action. The determinations of the epicenter showed no such trend. The explanation given by Kindle that hydraulic currents set up by a gale were primarily responsible for the breakage and that the only role of the quake was to render unstable the bottom sediments is unsatisfying even if one considered such action by that type of currents to be possible. That a quake would bring sediments to a critical stability over a 350-mile area but that no movement would occur until a hydraulic current passed over the area is almost incredible.

Bucher's idea was that the tsunami which was set up by the earthquake caused erosion in the submarine canyons which the cables passed across, and that when erosion proceeded far enough to leave the cables unsupported over a certain unspecified distance they broke. Further, since he supposed that in the deeper water farther from the quake the erosive action of the tsunami was less, it would take longer for this unspecified amount of undermining to take place. The velocity curve (fig. 3) shows the time of the breaks *versus* distance from the epicentral area. In every case each succeeding point falls near the curve formed by the other points. The cables were of widely different ages, different types of construction and consequently different breaking strengths. Only a close adjustment of degree of undermining and breaking strength would produce so smooth a curve, an adjustment which is highly unlikely. Since the breaking strength of a new cable such as the farthest cable is about 10½ English tons (Higgins in Hodgson and Doxsee,

1930) and its weight per mile about 1.1-1.3 English tons in water, the canyons would have to be widened by several miles. The topography is not very accurately known in the region of the deeper breaks, but it can be said that no canyons of the size required by Bucher's hypothesis occur in those depths. Further, this hypothesis does not explain the concurrent burial of hundreds of miles of the deeper cables.

This criticism applies also to Shepard's idea that the cables broke because mass movements left sections of the cables unsupported. The previous published hypotheses are unsatisfactory for various reasons, but they have in common one major failing—none of them satisfactorily explains the orderly succession of breaks from shallow to deeper water.

CABLE BREAKS IN GENERAL

Soon after the laying of the first successful Atlantic submarine cable in 1866, it became obvious that there was much more activity beneath the sea than had been anticipated. Benest (1899), in the introduction to a very informative paper, states that "accidents to cables have already been valuable . . . in directing attention to hitherto unsuspected forces constantly in action and altering the features of the sea bottom." Milne (1897) and Benest (1899) presented much valuable evidence concerning the breakage of cables. Although we may not agree with their interpretation of the facts, it will be valuable to cite a few examples given by these early workers. Milne mentions one case which may have been similar to the occurrence after the Grand Banks earthquake. Speaking of the October 4, 1884 breakage of three cables running parallel to the contours on the southeast side of the Grand Banks in about 1500 fathoms depth, he states:

> "A very significant fact is the case when three cables running in parallel lines 10 miles apart broke at points nearly opposite to each other, on the same straight line."

The records are not clear but there appears to have been some delay in breaking from cable to cable, indicating that the cause of the breaks could have been a slump or turbidity current. Milne mentions numerous examples of cable breaks in submarine canyons, and repeatedly in his notes on the cause of the breaks the statement "landslides or earthquakes" appears.

Benest (1899) discusses repeated breaks of two different cables in a submarine canyon north of Cape Verde, West Africa. The breakage was finally avoided by laying the cables on the continental shelf. He also gives an account of the repeated breakage of the Central and South America Cable Company's cable off Talara, Peru in April 1891, March 1892 and April 1892. He states on the authority of the captain of the cable ship that

> "It was noticed in every or nearly every case that the specimen of bottom brought up from the deep part of the gully was coarse grey sand and small stones: that of the sides, a very tenacious clay; and from the comparatively level part farther away, soft green mud."

This description squares well with the condition found to prevail in the Hudson Canyon (Ericson, Ewing and Heezen, 1951) in which turbidity current transportation of the coarse sediment is unquestioned. It may also mean that the walls of this South American canyon, like the Hudson, are composed of Tertiary sediment. To avoid breakage Benest states that on several other occasions the cables have been relaid inshore at a higher level,

> "notably off the Rovuma River, in the cable between Zanzibar and Mozambique . . . (which) broke down eight years in succession. Since it has been relaid inshore, some twelve years ago, it has never broken down . . . (After) the São Thomé Landa cable . . . had broken down twice in fifteen months, it was relaid nearer the shore, and it then lasted five or six years."

Here again is an instance when those cables which passed along the slope through the canyons were repeatedly broken, but when relaid inshore they were not disturbed, just as the many cables on the Grand Banks were not disturbed after the Grand Banks earthquake. De Smitt (1932) made a study of the correlation of cable breaks and earthquakes for all the pre-1930 breaks. This report contains much valuable information on cable breaks.

It can be concluded from a study of the published reports that cable breaks are very frequent on the continental slopes, especially in canyons. It is true, however, that the greatest number of breaks occur on the continental shelf, but most of these can be explained by abrasion to shallow water near shore or by snagging by trawlers, whereas the slope breaks have up to now been harder to explain.

PRESENT KNOWLEDGE OF TURBIDITY CURRENTS

The present authors, together with Tolstoy, conducted a survey of the seaward extension of the Hudson Canyon in 1949 (Tolstoy, 1951; Ericson, Ewing and Heezen, 1951; Heezen, Ewing and Ericson, 1951; Heezen, Ewing and Tolstoy, in preparation). The striking streamlike characteristics of the canyon, which were so well described in the works of Veatch and Smith (1939) for the portion of the canyon which dissects the continental slope, were found to persist in the previously unknown portions which extend for another 200 miles from the foot of the continental slope across the continental rise to the floor of the abyssal plain at 2650 fathoms. The sediments strongly indicated that turbidity currents had been active in the canyons but not in the intercanyon areas of the continental rise. Sands were found over a wide area near the end of the canyon on the abyssal plain and the base of the continental rise. Gravels and sands were found in the bottom of the canyon overlying Tertiary sediments, and outcrops of Tertiary sediment were revealed on the canyon walls, while the intercanyon divides of the continental rise were covered by "normal blue silty mud." In a discussion of Tolstoy's paper Heezen, Ewing and Ericson (1951) suggested that the abyssal plains of the ocean basins were formed by the ponding of sediments brought in by turbidity currents. Ericson, Ewing and Heezen (1952) offered criteria for recognition of sediments transported to great distances by turbidity currents, and evidence of transport to distances of the order of 1000 miles.

A number of other canyons between Cape Hatteras and Flemish Cap that have recently been sounded and sampled for sediments in rapid reconnaissance fashion appear to have the same characteristics as the Hudson Canyon. A large canyon a few miles north of Great Abaco Island of the Bahamas, and also the Northeast and Northwest Providence Channels and the Tongue of the Ocean Canyon in the Bahama Islands, have been surveyed and sampled in a reconnaissance fashion. Here also are found streamlike topography, coarse clastics on the canyon floor, older sediments exposed on the walls and a great delta composed of numerous graded beds of calcareous sediment. The authors, together with Hersey, have conducted reconnaissance seismic, topographic and sediment surveys in the Puerto Rico Trench north of Puerto Rico. The deepest part of the trench was found to be flat at about 4700 fathoms (corrected to true depth) and this flat floor was found by coring to be underlain by a succession of graded beds of calcareous sediment and thin layers of the red clay "normal" for that depth. The flat floor and the graded "shallow water" sediment are undoubtedly the result of turbidity current deposition.

Studies of topography, sediment cores, and seismic refractions within about 60 miles of Bermuda have demonstrated that surrounding the volcanic core of the island there is a great fan of calcareous sediment containing numerous graded beds of shallow-water material. In moving down the slope to deep water, the turbidity currents which undoubtedly deposited these graded beds eroded the flanks of the Bermuda pedestal and exposed Tertiary sediments (Ericson, Ewing and Heezen, 1952).

The outcrops of Tertiary sediment reported from the continental slopes of the world are compelling evidence for present-day erosion of the sea bottom by turbidity currents (Northrop and Heezen, 1951; Stetson, 1949; Shepard, 1948). The graded beds prove that the erosive agent acts intermittently and the gravel found in the canyons (Ericson, Ewing and Heezen, 1951, 1952) proves that its transporting capacity must be great, therefore its velocity must be great. Thus there is strong evidence that turbidity currents are a major factor in submarine geology. Additional support for the concept that turbidity currents are a fundamental submarine process is given in a recently published symposium on turbidity currents (Symposium, 1951).

EXPLANATION OF THE CABLE BREAKS BY TURBIDITY CURRENTS

The mounting evidence for the vast importance of turbidity currents and slumps in the sea and the inadequacy of all the published hypotheses to account for the regular sequence of the cable breaks led the authors to consider the following explanation. A severe shock jarred the continental slope and shelf, setting landslides and slumps in motion. These virtually instantaneous movements affected an area 80 by 150 miles along the continental slope. These mass movements, starting on the relatively steep continental slope, raced downward, and by the incorporation of water the moving sediment was transformed from sliding masses into turbidity currents. Undoubtedly the pattern of canyons and tributaries caused initial concentrations of the flow, but as the canyons joined the currents grew larger, quickly becoming so large that they were not restricted by the submarine canyons and eventually covered the bottom of the 200-mile-wide bight which lies between the southern Grand Banks and the continental slope off Sable Island. The currents had many times the force necessary to break the cables, and snapped each cable shortly after reaching it. In all cases, at least two breaks occurred 100 miles or more apart, and the intervening section of cable was either buried or carried seaward so far that it was never found. As the current began to slow down, because of decreasing slope, finer and finer sediments were deposited in a manner which produced graded bedding. Since the flow passed the last cable in the area at a distance of about 400 miles from its origin with a velocity of 12 knots and sufficient force to destroy 200 miles of the cable, it is probable that the area of deposition extended hundreds of miles farther.

Mr. C. S. Lawton and Mr. V. P. de Smitt, after hearing the writers' interpretation, brought from the files of the Western Union Company a letter written by A. C. Veatch to G. H. Ridge, then Ocean Cable Engineer of the Western Union Company. In this unpublished letter of December 13, 1934, Veatch emphasized the significance of several facts in de Smitt's unpublished report (1932). He noted as significant the sequence of breaks, the fact that none of the cables on the continental shelf were disturbed, that the cables on the steep continental slope were not buried in the least while the deeper cables were buried extensively. He stated that

> "All these facts, together with the detailed data that have been collected on some earthquakes, notably the great San Francisco earthquake, point to the conclusion that the breakage of the cables was due, not to the relatively minor displacement which caused the earthquake, but to one or more landslips produced by the earthquake."

He concluded that the orderly sequence of cable breaks proved that the principal agent responsible for the cable breaks was a single major landslide affecting an area whose dimensions are measured in hundreds of miles and that this extensive landslide originated near the epicenter on the steep continental slope and came to rest near the last cable. This view is similar to that of the present authors, the main difference being that Veatch did not suggest any mixing of the sediment and the sea water; therefore he was led to the view that the disturbance was a landslide rather than a turbidity current such as the present authors have described.

The transformation of the landslide into a turbidity current explains two major points. The first of these is the graded nature of the sediments deposited—a fact unknown to Veatch. The second is that a landslide could hardly carry on to so great a distance over so slight a gradient. Veatch attempted to make this plausible by appeal to the lubricating action of the deep-sea clays, but in the opinion of the present authors this point alone is a fatal objection to the simple "landslide" theory. Veatch believed that this landslide could not possibly have gone much farther seaward than the southernmost cable and therefore suggested that future cables be laid farther to the south to avoid damage, a conclusion with which, as will be seen later, the present authors do not fully agree. Shepard also suggested that landslides were responsible for the breakage of the cables; however, he suggested that segments of the cable were broken when undermined by local slides, while Veatch suggested that the breaks were due to the force exerted on the cables by sliding masses of sediment.

The topographic profile with superimposed velocity graph (fig. 2) clearly shows the positive relation between velocity and slope. The velocities shown on figure 2 were determined by drawing tangents to the time-distance curve (fig. 3), and are subject to the inaccuracies inherent in this method. The horizontal scale for the profile is the measured distance along the axis of the bight extending south from Cabot Strait. A better knowledge of the topography of the area may alter the distances and change the velocities to some extent. It can be seen that on the upper portion of the continental rise where the slope is about 0.5 per cent the velocity is about 50 knots, while on the very gently-sloping oceanic floor to the south

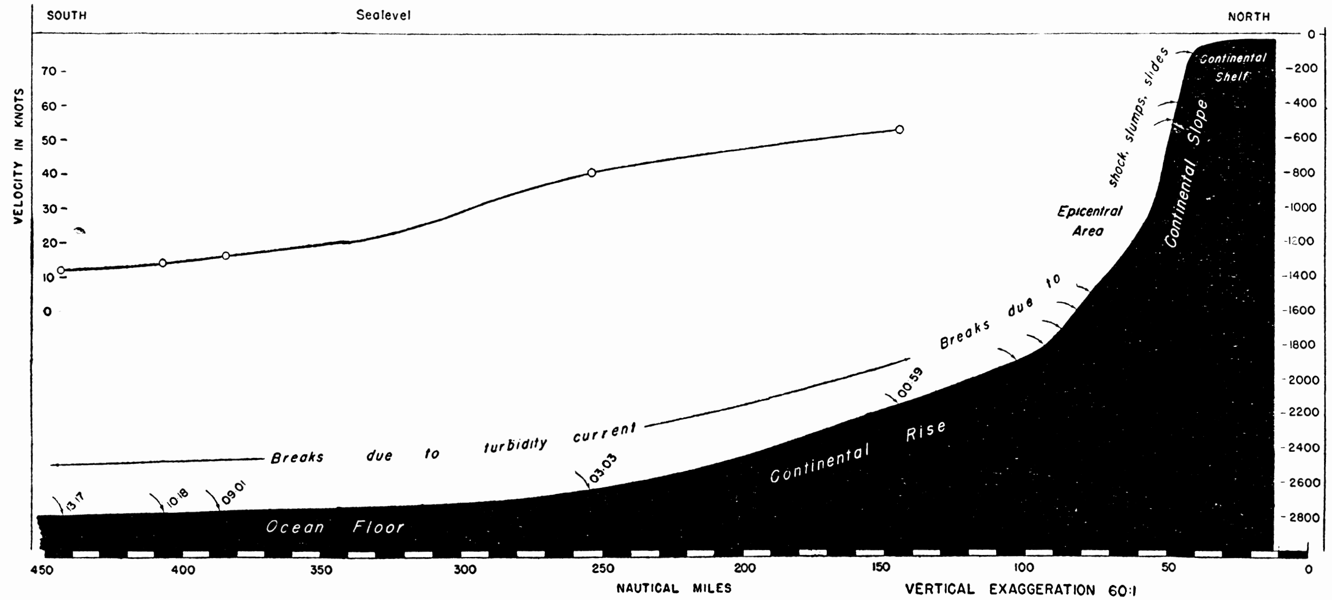

Fig. 2. Topographic profile south of Cabot Strait with superimposed graph of the velocity of the turbidity current as determined by the successive cable breaks.

where the slope is about 0.05 per cent the velocity has dropped to about 12 knots. With this decrease in velocity a great amount of material must have been deposited, as indicated by the extensive burial of the deeper cables.

On the theory that a turbidity current should produce a prolonged disturbance at the ocean surface, the tide records

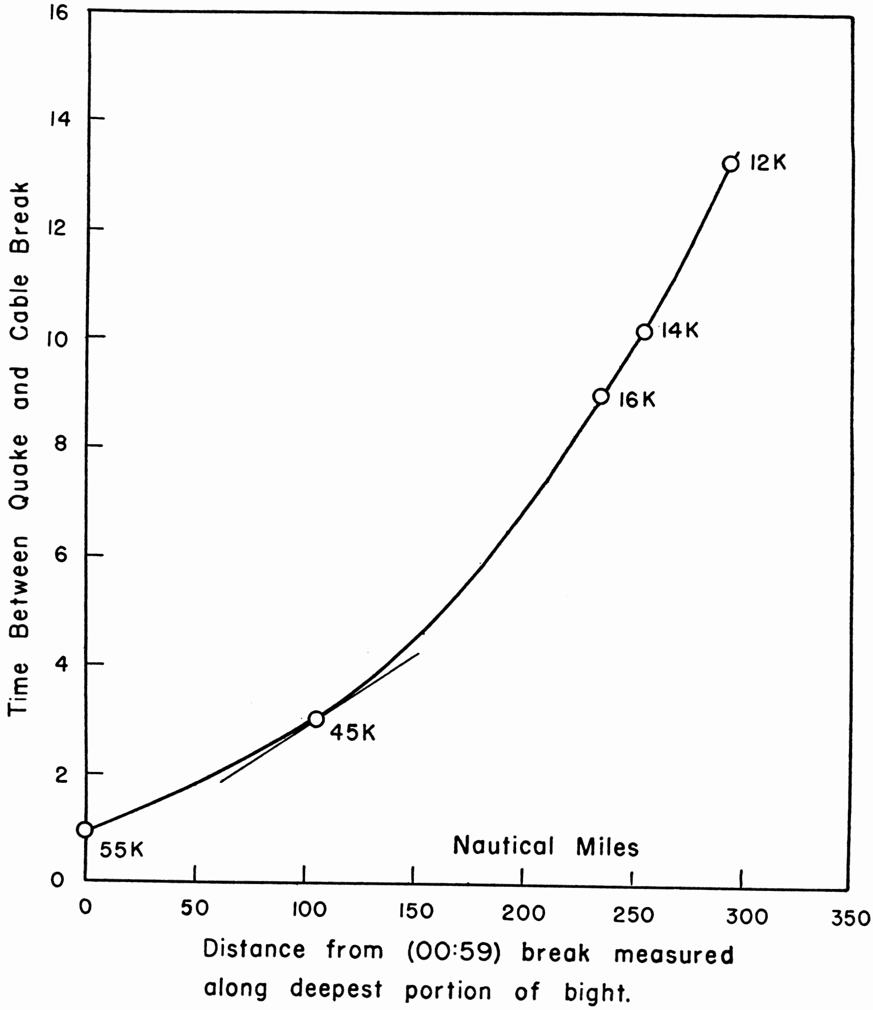

Fig. 3. Distance along the deepest portion of "bight" south of Newfoundland vs. interval between instant of earthquake and instant of cable break. Time in hours, distance in nautical miles, velocity in knots (K).

obtained at Halifax, Nova Scotia, and Atlantic City, New Jersey, following the Grand Banks earthquake, were examined. Each showed a train of waves associated with the tsunami which may be related to the passage of the turbidity current. The waves had periods of one to two hours and heights of about one foot, and they continued until about 1500 G.C.T. 19 November 1929, about 20 hours after the seismic shock and about 5 hours after the last cable break. The possibility that this tidal disturbance was due to the heavy gale blowing south of Newfoundland at the time has not been entirely removed, but strong tidal surges at Bermuda and the Azores (Doxsee, 1948) following this earthquake indicate that the disturbance of the Halifax and Atlantic City tide gauges was probably not due to the strong gale. A study of tide-gauge records from all parts of the Atlantic for this and for other cable breaks is being undertaken, and it is hoped that through this study criteria may be developed to identify the passage of turbidity currents in the past and in the future by the study of mareograms.

Evidence of numerous large turbidity currents, probably starting as submarine slumps, is found in the study of deep-sea sediments (Ericson, Ewing and Heezen, 1952). Such evidence, together with that presented in the present paper, offers strong support for the view held by many seismologists (see, for instance, Gutenberg, 1939) that the principal cause of large tsunamis is submarine slumping. In this view the correlation between T phase production and tsunami production (Ewing, Tolstoy, Press, 1950, and Ewing, Press, Worzel, 1952) simply means that the situation which is favorable for efficient transmission of horizontally traveling compressional waves from the solid earth into the water is equally favorable for generation of large submarine landslides. Both phenomena depend upon strong earthquake waves impinging on a steeply sloping ocean bottom. The two principal factors are availability of material in an unstable position and the earthquake which triggers it into a large scale landslide. If the unstable material is sediment slowly accumulated, the frequency of large earthquakes in the area may determine the size of the tsunami, but if the unstable topography is due to present orogeny there may be no relation of tsunami size to earthquake frequency.

The type of turbidity current which affected the area south of the Grand Banks was obviously in some way different from the turbidity currents which have carried sediment down the Hudson Canyon. In the case of the Hudson the evidence is strong that the current was largely restricted to the canyon until at a depth of about 2400 fathoms the sands were deposited by distributaries. In the case of the Grand Banks the current flowed over a segment of the sea floor 150 miles wide. The difference is interpreted as largely one of scale. Probably none of the deposits which we now see associated with the Hudson Canyon were deposited by as extensive a current as that following the Grand Banks earthquake, as shown principally by the presence of undisturbed sediments between canyons.

Daly supposed that turbidity currents were generated by the turbulent action of storm waves on the continental shelf. Here we suggest that the Grand Banks earthquake triggered off a very large turbidity current. Although convinced of the great importance of the earthquake triggering effect, the authors do not wish to imply that it is an exclusive process. Turbidity currents probably are generated in a number of ways. Storm waves, tsunamis, and internal waves may cause mixing of sediment with the sea water as suggested by Daly (1936), or these processes, plus earthquakes, may cause slumps and slides which may with the incorporation of quantities of sea water be transformed into turbidity currents. It seems likely that the most powerful (high density) turbidity currents are more frequently formed by the transformation of slides and slumps.

Whether one considers the phenomenon which followed the Grand Banks earthquake a landslide, a mud flow, a turbidity current, or a combination of the three, its importance as an agent of suboceanic transportation is great. The suggestion was made by Heezen, Ewing and Ericson (1951) that the flat floors of the ocean basins and oceanic trenches are due to the ponding of sediment derived from turbidity currents or similar bottom-seeking movements. The large scale movement after the Grand Banks earthquake serves as overwhelming proof that currents do occur which will transport large amounts of sediment far out into the oceanic basin. The southernmost cable was on the floor of one of the great oceanic plains described by Tolstoy (1951) and Tolstoy and Ewing (1949). It will be remembered that the velocity of the current as it passed the last cable was of the order of 12 knots, and that the sediment dredged up by the cable ships making the repairs contained "sharp sand and small pebbles." A formidable quantity of sediment must have been carried for hundreds of miles to the south across the gently sloping deep sea plain as the current lost velocity and deposited the rest of its load, which undoubtedly contained vast quantities of mud and silt. Successive turbidity currents should create a deep sea sediment which contains many alternations in lithology from sand to mud. Each such current would travel a slightly different path as the flows originated at different points along the continental slope and spread overlapping blankets of sediment over the deep sea floor.

Although it is impossible to draw a line separating an area of erosion from one of deposition in the present case, the fact that several submarine canyons have been shown to continue to comparable distances from shallow water with sands and gravels concentrated in their beds leads to the conclusion that the events associated with the Grand Banks earthquake of 18 November 1929 may be considered as a full-scale experiment in erosion, transportation, and deposition of marine sediments by a turbidity current in which the submarine telegraph cables served to measure its progress and to give tangible evidence of its force.

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