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ORIGIN OF SUBMARINE "CANYONS."

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ABSTRACT

Echo-sounding has increased to nearly one hundred the number of great valley-like trenches now known to fret the edges of the submerged continental slopes. No published explanation of these "canyons" by subaerial river-cutting seems adequate or permissible. A new working hypothesis is offered for discussion. During the Glacial stages of the Pleistocene Period the sealevel was lowered all over the world, in maximum from 200 to 300 feet. Then wind waves and tidal waves were everywhere breaking on the loose muds and sands of the continental shelves, and for long intervals of time not far from the upper limits of the continental slopes. The water so agitated was specially loaded with suspended sediment and therefore had effective density exceeding that of cleaner sea water elsewhere. The loaded water tended to slide down the continental slopes, along the bottom. The question arises as to whether the velocities of the density currents sufficed to have eroded the actual trenches. A definite answer cannot now be given, but the general hypothesis should be tested by appropriate observations. The possibility that in pre-Glacial time some "canyons" were cut by bottom currents is also considered.

The Problem.

Recent discoveries of many valley-like trenches that interrupt the outer, steeper slopes ("continental slopes") of continental shelves are truly startling. Echo-sounding is responsible for the rapid increase of known examples. Thirty trenches have been located along Georges Bank off the New England coast. Several occur along the continental shelf between the latitudes of Cape Cod and Cape Hatteras, a stretch including the classic case off New York City. More than thirty trenches have been sounded between the northern end of Vancouver Island and southern California. Others have been discovered in the northern and western parts of the Gulf of Mexico; off the western coast of Mexico; the coasts of Brazil and Ecuador; the eastern coast of Korea; the western and eastern coasts of Japan; the eastern and southern coasts of Formosa; off the mouths of the Ganges and Indus rivers; off the coast of Ceylon; off the eastern coast of Africa south of Zanzibar; off the coast of South Africa; opposite the mouths of the Congo, Ogowe, and Niger rivers of westcentral Africa; off the Gold Coast and Cape Verde; and off the coasts of Portugal, France, and the British Isles. Shepard reports examples around the Hawaiian Islands.[1] The total number already charted approaches one hundred, with a distribution that may be fairly called world-wide. The distribution is planetary, not merely regional.

The recorded facts permit some generalizations bearing on the origin of the huge "canyons," a question as baffling as it is weighty for earth science.

(1) Most of the grander trenches lie along seaward prolongations of the axial lines of great rivers. Some of these rivers, including the Mississippi, Fraser, Indus, Ganges, and Niger, are now building deltas of the first rank. On the other hand, no important delta accompanies the submerged "canyon" off New York City.

(2) Many trenches have no direct topographical relation to existing rivers. This is obviously the case at the isolated Georges Bank, which, moreover, could not supply any large river if the bank were to emerge from the ocean. Lack of genetic connection with old rivers of size is again shown by the close spacing of the trenches along Georges Bank, a feature appearing also in other regions.

(3) Some continental shelves, inside the 100-meter isobath, are interrupted by valley-like furrows, graded oceanward and reaching maximum depths not greater than 100 meters. These comparatively shallow furrows seem clearly due to erosion by rivers when extended out over the shelves during the Glacial stages (hereafter called "epochs") of the Pleistocene period. Then glaciation of the lands lowered sealevel everywhere, at maximum probably 75 to 100 meters, so that river mouths were a long time far out toward the continental slopes or fall-offs.

(4) With floors 500 to 1200 or more meters, in individual maxima, below the adjacent surfaces of the continental slopes, many trenches have been traced to depths ranging from 1000 meters to nearly 3000 meters below sealevel. These deeper parts are hardly to be explained in the same way as the shallower incisions traversing the broad flats of the shelves inside the 100-meter isobath.

(5) Each trench is comparatively straight, with axis directed

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[1] Shepard, F. P.: Geog. Review, vol. 22, p. 79, 1933; Trans. Amer. Geophys. Union, 16th Ann. Meeting, p. 246, 1935; Zeit. für Geomorphologie, vol. 9, p. 99, 1935.

in the sense of the general continental slope, as if it had been cut by a stream "consequent" on that slope. Some trenches branch at their upper ends, suggesting analogy in a poorly developed dendritic pattern of river drainage. According to the mapped isobaths some trenches widen, flare, at their outer ends, toward the deep ocean.

(6) As a rule the longitudinal gradients of the deeper parts of the trenches range between 1:100 and 1:10, and are continuously oceanward. In a few cases the bottom is somewhat irregular, hummocky, as if recently laden with the debris of slides from the trench walls.

(7) Toward their tops the walls may be remarkably steep, with slopes between 20° and 45°.

(8) At Georges Bank Stetson's dredge tore from the trench walls lithified blocks of Upper Cretaceous sediment, and also late-Tertiary clays, tenacious enough to form blocks and yet decidedly plastic and weak. He has evidence that most of the material of the walls is not hardened into rock in the ordinary sense of that term. Shepard reports late-Tertiary "rock," dredged from the walls of trenches off California.[2] As Stetson has pointed out in personal discussion, the steepness of the walls at Georges Bank need imply rigidity of the material in general no greater than that illustrated in the visible clay of the Island of Marthas Vineyard, where the clay, like typical loess, is tenacious enough to stand in nearly vertical cliffs and yet offers little resistance to attack by running water.

(9) So far as examined, the floors of the trenches are covered with mud of specially fine grain, indicating deposition there, rather than active erosion, for some time past. If so, the trenches must have been formed during a geologically recent period when the oceanic régime differed from that at present.

(10) The general resemblance of the trenches all over the world is most simply understood if their development was nearly or quite simultaneous.

Published Suggestions of Origin.

Although the problem has confronted geologists for half a century, no acceptable general explanation of the "canyons" has been produced.

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[2] Stetson, H. C.: Trans. Amer. Geophys. Union, 16th Ann. Meeting, p. 226, 1935. Shepard, F. P.: ibid., p. 246.

Buchanan accounted for the great Congo trench by postulating a marine bottom current running landward along the axis of the trench, a current which compensates for the seaward flow of Congo River water as it forges its way out over the continental shelf. He supposed this current of reaction to defer deposition on the path of the lower current, while deposition of river silt was compelled to right and left, so that the bank with the normal profile of the delta advanced into the Atlantic along these lateral belts without interference. It was an early announcement of the idea of differential deposition, working long enough to give deep transverse furrows in growing continental shelves or deltas. In the particular case of the Congo Buchanan's hypothesis is not adequately sustained by either theory or observation. It cannot apply to the majority of the known trenches, where there is no relation to large, delta-making rivers.[3]

That a few of them are of tectonic origin, each belonging to a specialized kind of fault-trough or rift, is conceivable, but has not been proved for a single case and is inadmissible as a general explanation.

Ever since Lindenkohl and Dana ascribed the "submerged Hudson River canyon" to river erosion during a temporary high stand of the continental shelf, many writers have adopted the same idea for submarine trenches the world over. Yet as a general explanation it is ill supported by the facts of geology and geophysics. The development and grading of the broad continental shelves were slow processes, involving many millions of years. The grading implies that for a large fraction of that time there was a nearly constant hypsometric relation between continent and ocean bottom. The prevailing conception of origin for the trenches demands that toward the end of the development the shelves in the three oceans were hoisted nearly 3000 meters, then for a geologically brief period kept stable, and finally forced to sink nearly 3000 meters, so as to restore with extreme nicety the hypsometric relation described. The improbability of such an oscillation, affecting five continents and the corresponding sea floors, is at once manifest.

The rivers assumed, according to the uplift hypothesis, to have cut many trenches along the eastern and western shelves of North America were necessarily short and of small power.

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[3] Buchanan, J. Y.: Scot. Geog. Mag., vol. 3, p. 217, 1887.

If they excavated these trenches, then the master rivers of the continent must have simultaneously induced physiographic changes (either cutting broad valleys with floors now far below sealevel or else making local, voluminous deposits of sediment) on a much larger scale and visible in the existing morphology and structure of the continental land. No drastic effects of the kind have been found. The implied colossal deformation of the ocean basins would entail world-wide displacement of marine strands, the traces of which should still, on account of the youth of the trenches, be registered on the lands. Geology knows of no strand-marks that are referable to this cause.

In the effort to lessen the difficulties encountered by the uplift hypothesis, Shepard suggested that the trenches may have been cut by rivers at long intervals of time, especially during epochs of mountain-building; and that some of the more ancient trenches were more or less completely filled with shelf sediments and afterwards, recently, emptied by the oceanward downsliding of the soft material of the fills.[4] This modification of the old hypothesis is based upon precarious assumptions as to the relative weakness of trench wall and trench fill, and as to the thoroughness with which the sliding would clean out the trenches. That the actual, open trenches cannot date far back in geological time is shown by their interrupting the general slopes of the outermost and therefore youngest parts of the continental shelves. A further proof is the discovery of late-Tertiary sediments in the walls of trenches both at Georges Bank and off California. Considering how similar in form and depth the trenches are, in all three of the principal oceans, it seems not unreasonable to believe in the essentially contemporaneous and recent development of most of the furrows.

Nevertheless it seems quite possible that a few trenches, including perhaps more than one off the coast of California, were actually river-cut far back in geological time, then drowned, afterwards more or less completely filled with sediment, and finally, recently, re-excavated by the same process which has caused the majority of the open furrows now being discovered by soundings. See also footnote "21" below.

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[4] Shepard, F. P.: Trans. Amer. Geophys. Union, 13th Ann. Meeting, p. 226, 1932; This Journal, vol. 27, p. 24, 1934. Having recognized its difficulties, Shepard seems to have abandoned the hypothesis described and now (Science, vol. 82, p. 615, 1935) prefers to assume an enormous eustatic oscillation of sealevel.

Were the trenches cut by rivers that sought their baselevel after a temporary, world-wide or eustatic lowering of the surface of the ocean by nearly 3000 meters had taken place? As already noted, the formation of Pleistocene ice-caps did lower the sealevel eustatically, but at maximum no more than about 100 meters. On the other hand, no one has ever suggested how the capacity of the ocean basins could, since the Miocene period, have been temporarily increased so as to draw sealevel down nearly 3000 meters along the continental borders; and how the capacity of the basins could have been diminished again by almost exactly the full amount of the former increase.

A New Conception of Origin.

However, the more moderate eustatic oscillations of sealevel due to the fourfold Pleistocene glaciation and deglaciation of the lands represent a set of facts on which may be based a rational hypothesis concerning the development of the submarine trenches. Each of the four sets of ice-caps grew slowly and melted slowly, each process taking at least 25,000 years. Hence for more than 200,000 years, out of the million years or so that have elapsed since the Ice Age dawned, wind waves and tidal waves were beating on the mud and sand of the continental shelves—a condition utterly unlike that now ruling. These more or less mobile sediments had been built into embankments with widths measuring scores of kilometers and with depths averaging at least tens of meters. The volume of fine sediments was therefore enormous and sufficient to keep the tidal currents and storm waves of the lowered ocean well charged with solid particles for a large fraction of the 200,000 years. The waves were especially muddy because the depth of water on the outer, still submerged parts of the shelves was small. Then, too, the average storminess of the world was doubtless more pronounced during the Glacial epochs than at present.[5] Storms no more intense than those now affecting the shelves must have made the water overlying the continental slope (the fall-off of each shelf) much richer in suspended sediment than the water of similar location in pre-Glacial, Interglacial, or post-Glacial times. The tidal currents and gales of the twentieth century disturb the bottom of the North Sea so powerfully that sand

[5] cf. Bryan, K.: This Journal, vol. 27, p. 251, 1934.

is thrown up from depths of 40 to 50 meters to the decks of laboring ships. So long as sediment was "suspended" in the water on the Pleistocene shelves, that water was effectively denser than the clean water farther out to sea or the water below the zone of rapid stirring. There must have been a tendency for the weighted water to dive under the cleaner water, to slide along the gently inclined bottom of the shelf, and to flow still faster down the steeper continental slope. Since the solid particles kept settling out, the horizontal distance through which any such density current operated was limited. It is therefore important to remember throughout the discussion of the general hypothesis, that the belt of strong agitation by waves was, at the times of lowered sealevel, much nearer to the continental slope than now. In principle the imagined bottom current would be similar to the flow of ink or muddy water placed at the appropriate point in a tilted, partly filled glass of clear water. Each of those denser fluids slides down along the inclined "floor" of containing glass.

We thus picture a special kind of density current or convectional movement. Were these bottom currents strong enough to have excavated the submarine trenches now under discussion? The question is much too hard to answer offhand, but some facts suggest that an affirmative answer may not prove to be entirely wild.

If a thick, uniform sheet of mercury were kept continuously pouring out from the whole shore of a continent, it is easy to see what would happen in a general way. The mercury would quickly seek and flow down any slight, initial, transverse depression in the continental shelf and erode the depression deeper. With this progressive deepening, more and more mercury would be drawn into the new trough from both sides, thus increasing the thickness, velocity, and eroding power of the stream of mercury that occupies the trough. To him "that hath shall be given."[6] Reaching the much steeper continental slope, the mercury flood, so concentrated, would slide down

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[6] It is worth noting also that, with each Glacial lowering of sealevel and emergence of the continental shelves, old rivers were extended over the new lands, where, in addition, many consequent streams were born. Each stream must have quickly trenched the soft materials of the shelves to some depth less than 100 meters. Until such new valleys became filled with wave-swept and tidally swept detritus during the next eustatic rise of sealevel, those furrows could hardly fail to guide and concentrate the flow of loaded water. Since each eustatic rise of sealevel probably lasted through at least 25,000 years, this control over the direction of the bottom currents of loaded water and over the rate of trenching would have long existed.

yet faster and dig a deeper trough in the soft sediments beneath the slope. Continued long enough, a submarine "canyon" would there be produced. This fanciful analogy may help to clarify the hypothesis now to be elaborated.

Discussion would be easier if we knew what amount of sediment can become suspended in strongly agitated water adjacent to the continental slope; and, again, what proportion of the maximum amount remains in suspension for say ten hours after the loaded water has sunk below the level where wind waves and tidal currents cease to keep sediment and water mixed together. Some idea of the maximum amount may be gained from measurements of the sediment in torrential rivers. According to A. Geikie's Textbook of Geology the lower Rhone River, even when only two-thirds of the way up to highest water, carries sediment to the extent of 2.2 per cent by weight. Corresponding figures for the Vistula and Durance rivers at high water are about five per cent and three per cent (at rare intervals as much as ten per cent) respectively. If the maximum for the agitated Pleistocene sea-water was normally only one or two per cent, the added density could hardly fail to produce a powerful current at the bottom, down the continental slope.

At the surface of the Severn estuary, hyperbolically described as a "sea of more or less diluted mud," the ratio of mud to water by weight has been measured and reported to reach the value 1:972. Thus the suspended sediment increases the effective density by about 0.0006. For the bottom layer the increase is probably at least twice as great, if we may trust the analogy of rivers and lakes, where the amounts of sediment suspended at surface and bottom have been actually measured.[7]

But during great storms the shelf waters of the Glacial epochs must have been charged with proportionately much more sediment than that found in the Severn estuary, where the ratio of solid to liquid was measured during relatively calm weather. Inshore, at the times of the Glacially lowered sealevel, an effective density 1.01 times that of clean water at the same salinity and temperature seems quite possible. Tidal

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[7] See Sollas, W. J.: Quart. Jour. Geol. Soc. London, vol. 39, p. 611, 1883; Thoulet, M. J.: Comptes Rendus Acad. Sci. Paris, vol. 109, p. 831, 1889; Collet, L. W.: Les Lacs, Paris, p. 204, 1925; Humphreys, A. A., and Abbot, H. L.: Report upon the Physics and Hydraulics of the Mississippi River, Washington, p. 134, 1876.

and wind-made, superficial currents with offshore components of motion transferred the loaded water out over the continental slope, then so much nearer the zone of breakers than at the present time. Into the water deepening outward over the continental slope the grains of sediment settled to the bottom at rates of fall that can be estimated.

Many geologists hold, without specific qualification, that sedimentary material settles in sea water many times faster than in fresh water. As Sidell showed long ago, this is true when the solid particles are clayey and exceedingly small. The law does not hold for particles as large as those prevailing in river silts or of larger diameters. Thus Vernon-Harcourt found the silts of the Hugli (Ganges), Rhone, Dnieper, and Mississippi rivers to settle in sea water only about ten per cent faster than in Thames River water and about twice as fast as in distilled water. The observed average rate of settling in sea water was small, namely 72 centimeters per hour. The experimental results of Wheeler were similar in principle. For solid particles of similar size Rubey showed that the relevant Stokes law is obeyed with considerable exactness, the observed velocities of settling in fresh water being nearly the same as those recorded by Vernon-Harcourt in the case of sea water.[8] Hence, while ionic coagulation of minute clay particles hastens the clearing of merely "turbid" sea water, it does little to speed the fall of the larger particles that make up most of the sediment in strongly agitated seas.

Since the rate of settling was low in absolute measure, it seems credible that a thick layer of bottom water on the continental slopes in Glacial times may have had its effective density temporarily increased 0.005, if not 0.01 by suspended sediment.[9]

Similarly the silt carried out over the continental slope by the larger extended rivers of the Glacial epochs would slowly settle into and through the underlying sea water, and, for the many hours occupied by the settling, increase any relative

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[8] Sidell, W. H.: in Appendix A of the Report on the Physics and Hydraulics of the Mississippi River, by Humphreys, A. A., and Abbot, H. L., Washington, p. 500, 1876; Vernon-Harcourt, L. F.: Minutes of Proc. Inst. Civil Engineers, London, vol. 142, p. 272, 1900; Wheeler, W. H.: Nature, vol. 64, p. 181, 1901; Rubey, W. W.: This Journal, vol. 25, p. 325, 1933.

[9] For evidence that the effective density is a direct function of the weight ratio of suspended sediment to water, consult F. A. Forel (Bull. soc. Vaudoise des sci. nat., vol. 23, separate, p. 5, 1887).

excess of density of the deeper water. It can hardly be doubted that this denser layer of bottom water would slide down the continental slope. The crucial question is as to the rate of flow.

The problem seems to defy direct mathematical treatment, and, on account of the difficulty of scale, convincing experiments with laboratory models are not to be readily performed. Until a better method of attack is developed, the writer guides his own thinking by again using an analogy. In principle it is based upon the engineer's formulas connecting the velocity of a stream with the controlling factors.

Arbitrarily assuming uniform motion in all parts of the stream's cross-section, and also assuming the motion to have reached the steady state, the equation relating the velocity (v) with the density of the liquid (d), axial slope (s) taken to be the same for both surface and bottom, and the hydraulic mean depth (m, equal to the area of the cross-section divided by the wetted perimeter) is

$$v = c\sqrt{m.s.d},$$

where c is a quantity depending on the roughness of the stream bed and the slope of the channel.[10] Experiments show that for large rivers moving on smooth bottoms and along low slopes, c varies little when m varies from two to infinity, and is of the order of 150 in the foot-second system of units.

The equation does not apply to actual rivers, whose flow is not linear but is more or less turbulent. From a table compiled by Humphreys and Abbot (page 316 of their Report on the Mississippi River) it appears that the mean velocity of large rivers varies rather closely with the fourth root of the surface slope. At Carrollton on the lower Mississippi the surface slope at high water is about 1:50,000; the hydraulic mean depth, about 65 feet; and the mean velocity about 5.9 feet per second or four miles per hour. If the same body of fluid had a density of only 0.004 but had a surface slope of 1: 10, its ultimate velocity would approximate two miles per hour. If both surface slope and bottom slope were 1:10, the velocity would exceed two miles per hour. Further,

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[10] A statement regarding the derivation of this equation is conveniently found in the Encyclopædia Britannica, 11th edition, 1910, art. "Hydraulics," by W. C. Unwin, p. 69.

according to the formula the velocity would be nearly doubled if the mean hydraulic depth were quadrupled.[11]

Of course the conditions affecting the flow of the Mississippi River differ from those controlling the speed of any density current which is supposed to run down the continental slope during a Glacial epoch. While rivers flow against the resistance of overlying air, the assumed marine currents had to overcome greater resistance because overlain by water. Probably the work of overcoming the extra resistance would diminish the speed of the density current in the steady state by no more than 50 per cent.[12]

On the other hand, the excess density of the sea water muddied by the storms of the Pleistocene may well have attained values from two to three times the 0.004 hypothetically considered in the discussion of the Mississippi. If our equation involving the square root of the density here applies, the importance of the density to stream velocity is at once apparent.

Again, allowance must be made for the probability that the concentration of loaded water in a submarine trench would give to this layer a hydraulic mean depth greater than the 65 feet of the Mississippi case, with another positive effect on velocity of flow.

Finally, the effort to use the observations on the Mississippi and other rivers should be judged in the light of the relation between a stream's erosive power and its velocity. At two miles per hour it will sweep along pebbles as large as an egg; at one mile per hour it will erode fine gravel; and at 0.5 mile per hour it will lift fairly coarse sand.

Comparison with rivers is troubled with uncertain factors. Yet the analogy does encourage one to ask seriously whether the loading of sea water with sediment by tidal currents

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[11] At the velocities considered, the increase of viscosity by increase of sedimentary load is unimportant.

[12] The effect of pressure on viscosity is here negligible. A bottom current loses some velocity because it has to give differential velocities to the layers of overlying water, at values which slowly diminish with increasing height above the primary stream. When the steady state is reached, the shearing resistance is an integral along a low velocity-gradient. The total shearing resistance at and close to the solid floor of the lower current, where turbulence is more pronounced, is probably greater; it is an integral along an enormously steep velocity-gradient. As noted later, the lower current at the Strait of Gibraltar, though due to a difference of water densities of the same order as that assumed in the explanation of submarine trenches, and though working against a strong reverse current overhead, keeps running at approximately four kilometers or 2.5 miles per hour.

coöperating with major storms along the Pleistocene shores, which were relatively near the continental slopes, produced bottom currents flowing down those slopes and strong enough to erode loose sand and mud.

A point of much importance may now be made. "When a stream passes from the régime of Poiseulle (rectilinear filaments) to the régime of turbulence, the grains of sand are lifted above the bottom to a certain height. Accordingly . . . . . there is formed at the bottom a layer of water charged with more or less sand."[13] Collet actually found four times as much sediment in the bottom layer of a Swiss river as at the surface. If a prolonged tempest increased a trench current so that mud, that had been temporarily deposited on the bottom of the trench during quieter weather, was stirred up and incorporated, the density, velocity, and eroding power of the current were increased.

There is a related, possibly even more significant, question. Let us assume that the mud immediately underlying a continental slope at the beginning of the first Glacial epoch was mobile because water-soaked; that the surface of the sediment was at or near the angle of rest; and that a moderate density current generated during that Glacial epoch was started down the slope. The current's drag on the bottom would tend to initiate bodily sliding of the sediment, to mix the now agitated sediment with the current, and so increase the drag, as well as cutting power, of the original current. Thus, a given trench would be the joint product of down-cutting and of similarly localized sliding of sediment that was much diluted with sea water. Does one go too far in assuming that directed sliding of sediment was even the dominant process in the development of the trenches? Did the density currents make trenches, principally because they triggered off the potential energy of sediments that stood high above the floor of the deep ocean and were ready to slide, if urged by a comparatively small force?

Still another relation should be examined. Strong onshore winds pile sea water on the coastal flats, where, with or without the aid of the tide, the mean surface of the water may be raised one meter or more. The water thus super-elevated on the continental shelf has potential energy. The "banking" produces at the surface longshore currents which attain off-

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[13] Quoted in free translation from L. W. Collet (Les Lacs, Paris, p. 202, 1925).

shore components at distance, with some diminution of the potential energy. However, we may suspect that, under the conditions of a Glacial epoch when the banked water was loaded with sediment, a part of this potential energy should have been used to accelerate any localized bottom current running oceanward, as assumed by the proposed explanation of the submarine trenches. The banking should have added to the differential pressure along the upper part of the density current. Reflux, correcting for the super-elevation, would thus be in part directed oceanward, this part of the flow lacking any significant longshore component.

In review, it appears that the problem of horse-power for the imagined density currents during the major storms and tidal flowings of the Glacial epochs is decidedly complicated. The potential energy is conceived to have originated in: (1) the contrast of density between clean sea water and sea water loaded with sediment (whether incorporated by marine turbulence or by settling from overlying, silty river water); (2) the difference of level between continental shelf and deep ocean bottom; (3) banking of coastal waters by violent onshore winds. It is suggested that an initial density current of the Pleistocene may have triggered off the potential energies listed under headings (2) and (3), and so considerably increased the velocity of that initial current, in spite of the braking action of new turbulence and new frictional resistance that must have been developed by such increase of velocity.

Each of these speculative mechanisms involves the principle of self-acceleration, a principle already seen to apply for quite a different reason, namely, the deepening of the current by inflow of loaded water from the two sides of a trench.

In any case we should expect trenching to have progressed at variable rates. Most of it may well have taken place during exceptional storms of the Glacial epochs, averaging perhaps one such paroxysmal event in a decade of years. On the other hand, wherever the topography of the continental shelves, then covered by shallow water, caused strong tidal currents, the density currents due primarily to the agitation by these turbulent flowings may have been eroding more or less constantly.

Density Currents Now at Work.

After the writer had developed the idea of the Pleistocene age of the trenches and their excavation by muddy bottom currents, a practical test of one of the basal assumptions came to mind. If the hypothesis is well founded, the water of rivers that are building deltas into fresh-water lakes of nearly the same temperature should plunge under the water of the respective lakes. Years ago, from the heights above Montreux, the writer had seen the muddy water of the Rhone spread in labile equilibrium on the surface of Lake Geneva, and noted the exceeding sharpness of contact between the turbid water and the clear water of the lake. Only recently has he grasped Forel's explanation. By a convincing experimental method Forel showed that the muddy water plunges *en masse* almost vertically ("wie ein Wasserfall," as Heim puts it); continues to fall; and, when the Rhone is in flood, actually slides along the gently inclined bottom toward the deepest part of Lake Geneva.[14] Further, an accurate survey showed the sublacustrine part of the Rhone delta to be strongly trenched. The trench is seven kilometers long, is 500 to 800 meters wide, has a maximum depth of 60 meters below its rim, and can be followed down to a depth of 230 meters below the lake level. The size is impressive.

In his first paper on the subject Forel supported the conclusion of de Salis, that the trench was cut (creusé) by the bottom current, flowing because of the load of silt and consequent excess of density. Two years later Forel had changed his opinion and attributed the trench to differential or deferred deposition (German "Aussparen"), the bottom current serving merely to carry the delta silt far out to deep water, while the water nearer the surface, moving much more slowly, keeps depositing its load along the sides of the trench.[15] In his Handbuch der Seenkunde (Stuttgart, p. 84, 1901), Forel uses the word "gleitet" to describe the motion, and remarks that similar streaming, though with more pronounced effects, takes place in the ocean. He did not discuss the question whether such submarine currents can have surpassed the critical velocity at which erosion of the bottom begins, though naturally accompanied by deferred deposition. In spite of the lowness of the

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[14] Forel, F. A.: Bull. soc. Vaudoise des sci. nat., vol. 23, p. 18, 1887; Heim, A.: Geologie der Schweiz, Leipzig, vol. 1, p. 431, 1919.

[15] Forel, F. A.: Comptes Rendus Acad. Sci. Paris, vol. 101, p. 725, 1885; Bull. soc. Vaudoise des sci. nat., vol. 23, p. 23, 1887; Le Léman, Lausanne, vol. 1, pp. 65 and 385, 1892; cf. Wey, J.: Schweiz. Bauzeitung, p. 36, 1887.

Romieux, J.: (Les carbonates dans les sédiments du Lac de Genève, Thesis published by the University of Geneva, p. 12, 1930) believes that the current is actually eroding its bed. Its velocity under the varying conditions of the seasons should be determined by a specially designed meter.

velocity of the bottom current in the Rhone delta, Forel thought it sufficient to have caused eddies along the rims of the sublacustrine trench, the turbulence being great enough to leach out the finer silt and leave local lenses of sand.[16]

A similar trench has been developed in the Rhine delta at Lake Constance. This trench is 11 kilometers long, has a maximum depth of 70 meters below its rim, and can be traced to the depth of 205 meters below the surface of the lake.[17]

The whole assemblage of facts won by the able, careful experts, Forel, Heim, Collet, and the hydrographers of the Swiss Government, seems strongly to favor the general conception of the genesis of the submarine trenches now being presented.

A second analogy, from a different point of view but offering additional support, is found in the double current at the Strait of Gibraltar. The top of the rock sill between the Mediterranean and Atlantic is about 400 meters below sea level. Down to nearly half that depth Atlantic water, under ordinary conditions of wind and tide, keeps pouring into the Mediterranean basin at an average speed of four to five kilometers per hour. The lower current, running even more steadily into the deep Atlantic basin, has a velocity of the same order, but, when increased by a combination of wind and tide, reaches a maximum velocity of at least seven kilometers per hour. Yet the essential cause of each four-kilometer current is a difference of density between Mediterranean and Atlantic water that is only about 2/1000 of either.[18] Here, then, we have a case of a bottom current powerful enough to move even gravel and yet caused by an excess of density of the same order as that of sea water which is temporarily loaded with sediment.[19]

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[16] Forel, F. A.: Le Léman, vol. 1, p. 65, 1892.

[17] Forel, F. A.: Le Léman, vol. 1, p. 63, 1892. See also Collet, L. W.: Les Lacs, p. 188, 1925.

The writer has been informed that the muddy water of the Colorado River dives to the bottom of the long Boulder Dam lake, and, while preserving its individuality as a couche of water with effective density greater than that of the great, overlying body of the lake, flows down the inclined floor of the artificial lake all the way to the dam.

[18] Murray, J., and Hjort, J.: The Depths of the Ocean, London, pp. 290-293, 1912; Krümmel, O.: Handbuch der Ozeanographie, Stuttgart, vol. 2, p. 484, 1911.

[19] According to G. Schott, the difference of level between the Atlantic Ocean and Mediterranean Sea, at points 66.6 kilometers apart, is only about 13 centimeters. Jessen, O.: Die Strasse von Gibraltar, Berlin, p. 82, 1927.

Are true homologues of the Pleistocene mud-controlled currents to be found in the ocean of the twentieth century. Such density currents might well be looked for along the trenches sunk in great deltas, the search being made during the flood stages when the silt of the corresponding rivers is carried in large volume out to sea and ultimately precipitated into the salt water beneath. Perhaps bottom currents of some strength are generated where the hurricanes of the present epoch continue to deepen trenches that are located along exceptionally narrow shelves. If the width of the shelf is only a few kilometers, the horizontal distance between the belt of agitated and therefore muddy, weighted, water alongshore and the relatively steep, outer slope of the shelf is small. Hence the loaded water, carried out by offshore surface currents, does not lose its potential energy before it is forced to slide down the steeper slope with accelerated velocity. Actual demonstration of such currents, by current-meters or otherwise, would be difficult.

Conclusion.

If the revised conclusion of Forel is correct, deferred or differential deposition of silt in the growing deltas of the Rhone and Rhine rivers accounts for the strong radial furrowing of each delta to the depth of 200 meters below the lake surface. Because this mechanism demands relatively low velocities for the more localized bottom currents, it might appear easier to explain the submarine trenches in the same way. Yet there are serious objections. The Indus, Congo, and other trenches, including some along Georges Bank, are much too long to be credited to differential prograding of the corresponding banks during Pleistocene time.[20] Another difficulty is the steepness of the trench walls, too great to represent angles of rest for mud in actual deposition. Moreover, the process described does not well account for the pronounced

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[20] The great Congo trough has special features which are not easily understood on any theory of origin for trenches in general. In this particular case the trench, with floor considerably more than 100 meters deep, extends well into an estuary, flanked with dry land. If the giant furrow was excavated by down-sliding bottom currents, it would seem necessary to assume extraordinary headward growth; yet there is no obvious reason why the Congo trench should have been so remarkably lengthened by recession of its upper limit. Again, the chart shows that the longitudinal profile is not continuously oceanward, the slope being reversed in at least one locus.

flaring at the mouths of some trenches. This feature, like the steepness of the walls, is explicable if the imagined bottom current erodes its bed, and in the very act takes up additional sediment and thus attains higher density and additional power to erode and transport.

An origin by erosion under the peculiar conditions of the Glacial epochs has been pictured in the light of certain facts and their logical consequences. Some of these need not be restated. Others, perhaps more liable to be lost to sight in an attempt to value the hypothesis, are: (1) The relatively small depth of water on the continental shelves during the four Glacial epochs;[21] (2) The absolute slowness with which muds sink in sea water; (3) The close proximity of the belt of shore breakers to each continental slope when the ice-caps were voluminous;[22] (4) The paroxysmal effects of major storms and of spring tides at the time, including extraordinary increase of suspended sediment and corresponding increase of potential energy in the mixture of water and sediment; (5) The probability that the "fore-set" sediments under the continental slope were close to the angle of rest, and hence in danger of sliding where dragged by a localized bottom current; (6) The increase of density of sea water by receipt of the silt that settles out of overlying river water as this, by its own momentum,

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[21] Although the conditions of the Glacial epochs are emphasized in this paper, the possibility of some trenching of the continental slopes in pre-Glacial time is not thereby excluded from a full discussion of the general problem. According to both theory and observation, the continental shelves were truncated by wave erosion during each Glacial epoch. Hence, just before the first major glaciation began, the average depth of water on stable shelves may have been something like 25 meters smaller than at present. In other words, at that earlier time the shelves may have been more closely adjusted to wave-base, as defined for ordinary storms, than the shelves are now. If so, the sediments of the shelves may have been stirred up by exceptional, quasi-hurricane storms operating in pre-Glacial time. The question arises as to whether density (muddy-water) currents of prolonged, pre-Glacial time actually began the development of the trenches. The answer must be difficult and not to be satisfactorily made until the depths of wave-base for both ordinary and extraordinary storms and the relation of those depths to shelf profiles have been more accurately defined than has yet been done. The narrower the detrital shelf of pre-Glacial time, the greater would have been the likelihood of such earlier trenching.

[22] Shepard, F. P., explains the absence of trenches along the northern edge of Georges Bank (see Figure 1 of his paper, Bull. Geol. Soc. America, vol. 45, p. 281, 1934) by assuming glacial erosion there, sufficiently intense to have removed "all signs of stream erosion." However, is it not possible that the thick ice, responsible for the morainal material found on the northern part of the bank, prevented the trenching by bottom currents while the trenches along the ice-free, southern edge of the bank were developed?

forces its way out over the open ocean; (7) The self-acceleration of the density currents by lateral addition of loaded water on each shelf and within each deepening trench, and by increase of the density where turbulent erosion of the bottom added to the sediment in suspension; (8) The smallness of the excess of density (probably no more than 0.004) required in a bottom layer of water 60 to 100 meters thick, in order to cause that layer to flow down a continental slope at the rate of two to three kilometers per hour—an eroding rate; (9) The expectation that the erosional effects of the assumed bottom currents would rather closely resemble those due to rivers on the land, even to the point of making systems of branching trenches that recall the dentritic ground-plans of visible rivers.

On the other hand, the offered explanation of the trenches is based on assumptions which are far from being certainties. Perhaps the most vital of all is that the materials underlying the continental slopes are weak enough to have permitted the cutting of the trenches within a time interval no greater than about 200,000 years. If Shepard's evidence that slumping of, "landsliding" from, the trench walls is substantiated by future charting, we should have direct proof of weakness.[23] It is to be hoped that with ship and appropriate apparatus several questions can be answered. What proportion of unconsolidated sediment, like Stetson's late-Tertiary clay, is characteristic of the trench walls? When was the lithification at Georges Bank accomplished? Is the lithified material concretionary and local, or does it constitute extensive layers parallel to the bedding of the shelves? However, while awaiting the results of future investigations, geologists should value the experience of Stetson, the pioneer among those who have actually dredged samples from the trench walls. According to his opinion, expressed verbally, much less than half of the wall of any Georges Bank trench is endowed with the strength of hard rock, the lithified material occurring in individual layers separated by soft layers.

A second assumption calling for test by experiment or otherwise is that the imagined bottom currents retained sufficient velocity in spite of the resistance offered by the overlying water as well as by the sedimentary bottom. That the former kind of resistance should not be over-emphasized in the problem is suggested by the analogy at the Strait of Gibraltar.

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[23] Shepard, F. P.: Geog. Review, vol. 23, p. 86, 1933.

A third principal question calling for future investigation relates to the apparent lack of submarine trenches along several long stretches of the continental slopes. According to Shepard this is the case off the Pacific coast of North America from Cape Mendocino almost to the mouth of the Columbia River, a distance of 550 kilometers. So far no trench has been reported off the Atlantic coast between Cape Hatteras and the Straits of Florida.[24] For the one instance it is natural to suspect the influence of the Gulf Stream. If in Glacial times this mighty current hugged the continental slope, it would have interfered with any transverse density currents that might otherwise have developed trenches. Or, if trenches were there actually excavated, the Gulf Stream of late-Glacial and post-Glacial time with its abnormal erosive power may have rubbed them out of the submarine topography. The absence of trenches off Washington State can hardly be attributed to a current sweeping the coast at the present time, and as yet there is no evidence of such a current during the Glacial epochs. In general, too, we need to know more about the conditions under which lithification of shelf sediments takes place. If local stretches of the shelves had already been lithified, the density currents of the Pleistocene could not have cut deep trenches there.

In view of the many uncertainties the idea of mud-control must now be rated as merely a working hypothesis. Yet its troubles seem incomparably less serious than those of the older explanations of submarine "canyons." On the other hand, it would be manifestly wrong to suppose all furrows crossing the continental shelves to have been excavated by marine density-currents. Here and there canyons and other types of valleys, cut by ordinary rivers in pre-Glacial time, have been drowned by strong, local subsidence of continental borders. Such old, rock-hewn valleys, if they had not been quite filled with fine-grained detritus, would naturally have attracted the water loaded with sediment during the Glacial epochs. The resulting, localized currents would have been likely to remove some of the filling of each of the old trenches, and thus have revived the open-valley form more or less completely. Illustrations of this speculative process might be looked for particularly along the coasts of California, Japan, and other uneasy parts of the continental borders.

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[24] Shepard, F. P.: Zeit. für Geomorphologie, vol. 9, p. 99, 1935.

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