SUBMARINE CANYONS

by

PH. H. KUENEN.

(Reproduced from the *Tijdschrift van het Koninklijk Nederlandsch Aardrijkskundig Genootschap, Leiden,* Nov. 1938, p. 861.)

(Translated from the Dutch).

I. INTRODUCTION

As early as last century, deep gullies which cut into the continental slope and are located in front of the mouths of several large rivers, were known to exist. For instance such submarine canyons have been discovered off the mouths of the Hudson and Congo Rivers. As long as they were considered merely as exceptional formations, geologists displayed but little interest in their existence and were satisfied with the assumption that they were submerged river valleys.

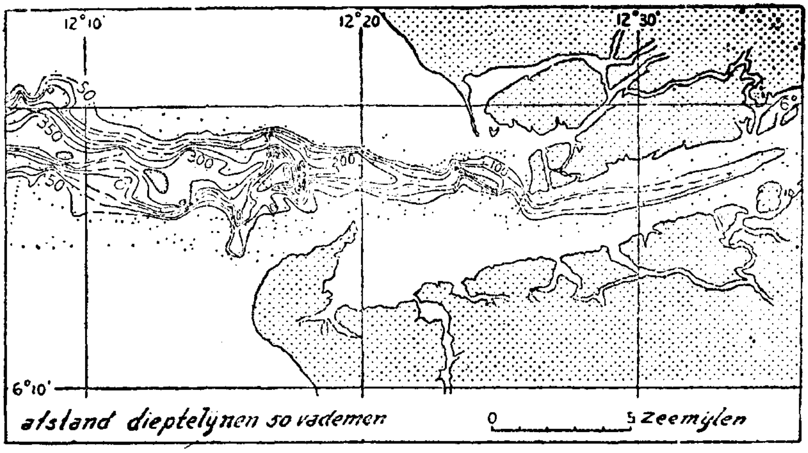


Fig. 1. — Inner portion of the Congo Canyon.

Little by little, however, it was found that such canyons exist also where no connection with a river is possible, and that they are so numerous that most of the continental slopes are notched by several, even by innumerable gullies. A debt of gratitude is particularly owed to the American **SHEPARD** (1) for having directed attention to these most remarkable formations. This investigator arranged that the vast echo-souding material collected in recent years by the U. S. Coast and Geodetic Survey be put at his disposal. Besides, by studying in detail surveys of other regions and, finally, by taking soundings and dredging canyons himself, he collated considerable data of the utmost importance. Of the articles published by him on this subject, only the most important can be reviewed here.

The American **STETSON** has not only taken soundings and made researches with the drag, but has also carried out current measurements in canyons off the East coast of the United States. Lastly, one of his countrymen, **DALY**, has built up an hypothesis by means of which the origin of the canyons might well be explained.

---

(1) See Hydrographic Review, vol. XV, n° 2, page 125.

II. DESCRIPTION OF THE SUBMARINE CANYONS

A. *Topographical Features and Lie:* Although dozens of canyons have already been discovered below sea level, the number of those for which an accurate bathymetric chart could be drawn up is still comparatively small. It would therefore be premature to attempt to give a subdivision into groups. We shall therefore restrict ourselves to the description of a few examples which show the diversification of the forms and sizes and which at the same time give an idea of the enormous dimensions reached by many of them.

The accuracy of modern echo-sounding and position finding may be considered fully sufficient to make the general features of the seabed stand out clearly. Further, the amount of information derived from American surveys is large enough to preclude any gross error in the drawing of the depth contours. However, where the sides of the canyons are very steep, the gradients indicated should be somewhat guardedly accepted. Local errors of 10° are certainly to be expected. Unfortunately the surveys have not yet been extended to the outermost extremity, so that nothing is as yet known of the depth reached by the canyons and how they merge with the sea-bottom.

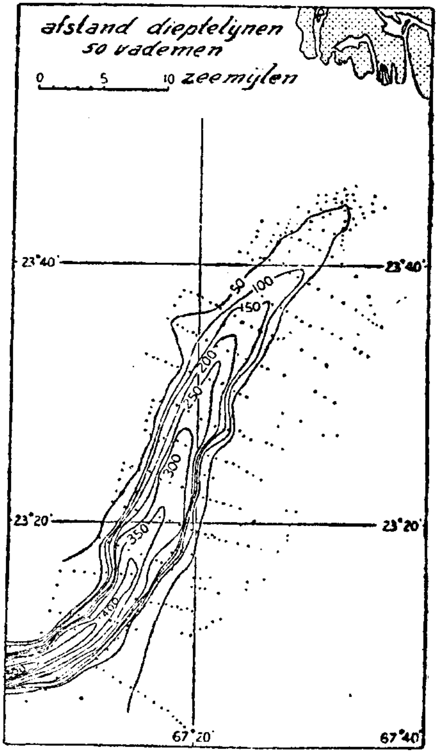


Fig. 2. — The inner portion of the Indus canyon : depths in fathoms.

As first example let us take the classic gully at the mouth of the Congo River, sounded out by means of the lead line only (Fig. 1). This gully is irregular in shape and reaches, to landward, a few kilometres beyond the coastline. The canyon off the Indus delta (Fig. 2) is on the contrary regular in shape, and begins barely 20 km. from the coast, cuts, however, through the wide plateau and on the edge of it is already 1000 m. deep.

Along the western slope of the North American continent, about twenty-four large canyons have been discovered. Fig. 3 shows the dendritic ramification of two examples, while Fig. 4 shows the details of the features. Not only the ramification but also their sinuosity strongly recall the current-system of a river. It is also a striking fact that the steepest sides are encountered on their outer windings and that the secondary valleys without exception disembogue at bottom-level of the main valley and thus are neither shallower nor deeper than the main valley itself. The very regular seaward slope of the bottom also closely resembles that of a normal

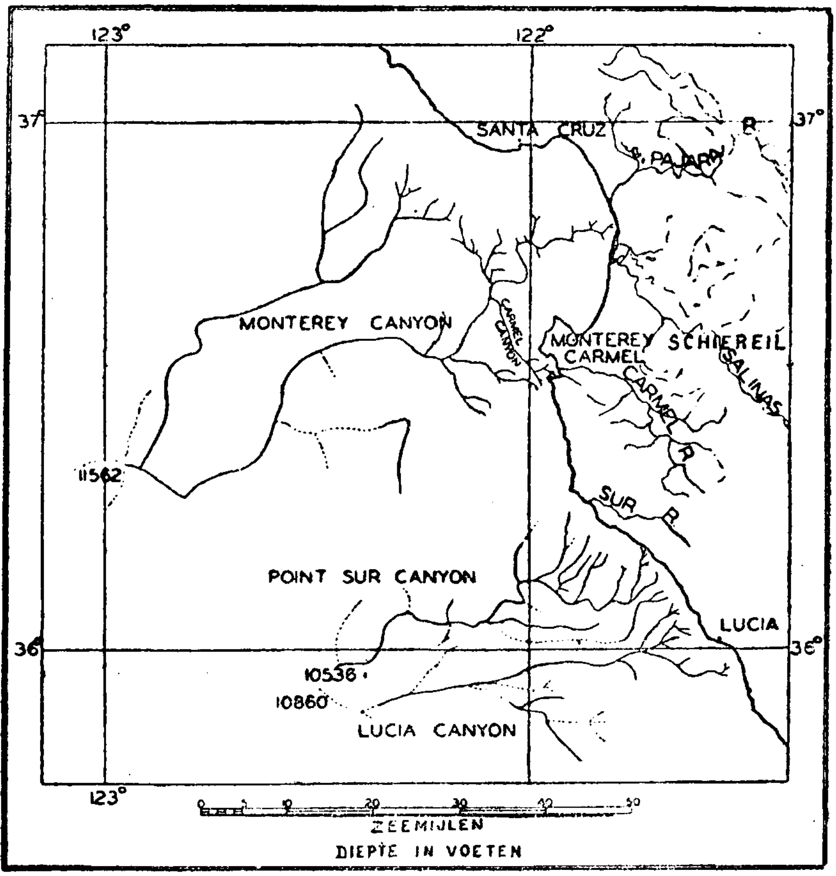


Fig. 3. — Dendritic ramification of the Monterey and Lucia canyons : depths in feet

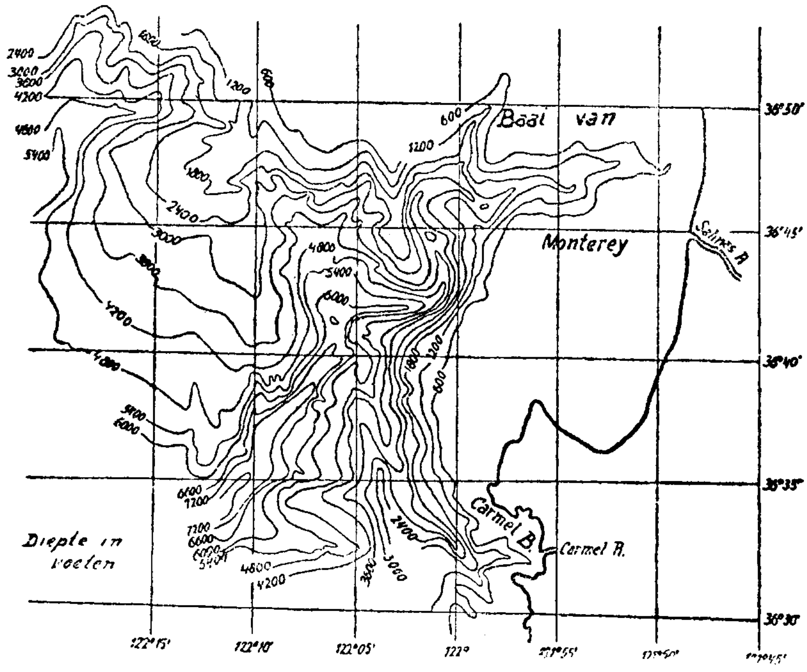


Fig. 4. — Monterey canyon on the west coast of California : depths in feet

erosion-valley. The Monterey-Bay canyon is cut down to 1500 m. and depths of over 3000 m. are ascertainable 100 km. from the coast. The remarkable point about these canyons is that some of them have their origin just under the coast.

Figure 5 gives an idea of the enormous steepness of the walls of certain gullies, whereas Figure 6, by its exaggerated vertical scale, gives a more spectacular image of the slopes ; but despite this exaggeration it is seen that the submarine canyons, as concerns magnitude need by no means yield to the greatest known canyons on the mainland.

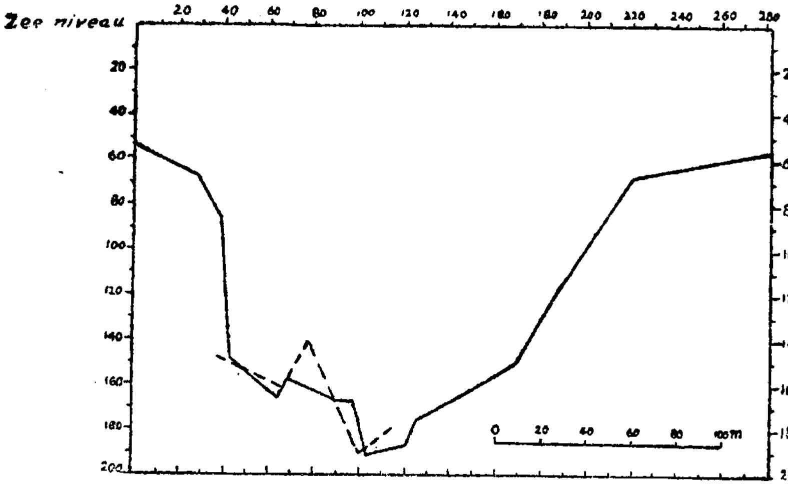


Fig. 5. — Two profiles through the canyon off La Jolla, California (vertical scale not exaggerated).

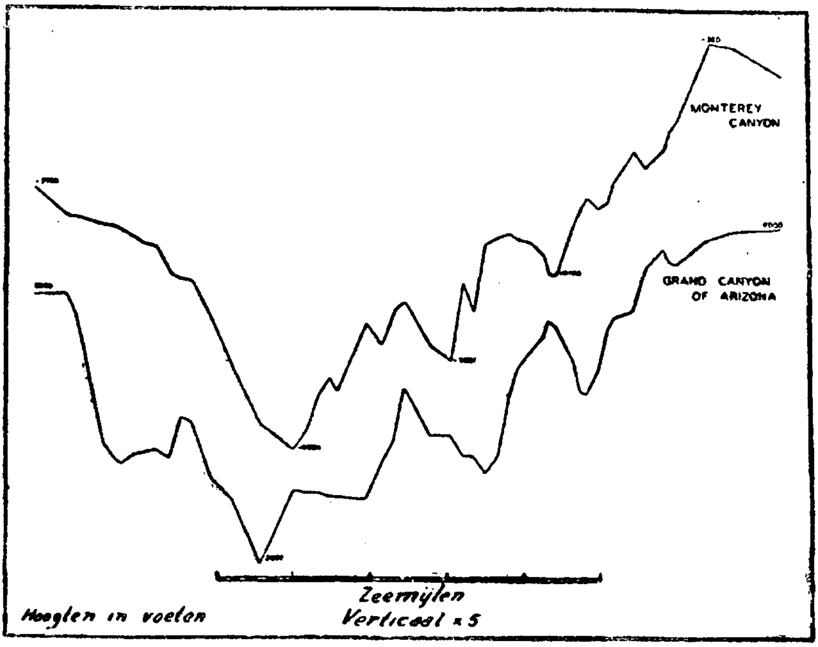


Fig. 6. — Two profiles through the Monterey submarine canyon and the Grand Canyon of the Colorado River in Arizona. Vertical scale in both cases exaggerated 5-fold.

The great value of the extreme accuracy of the surveys carried out by the U. S. Coast and Geodetic Survey is illustrated by the results of the sounding of the so-called Hudson Gorge. On Figure 7 the gully in the plateau which was formed by the Hudson River during

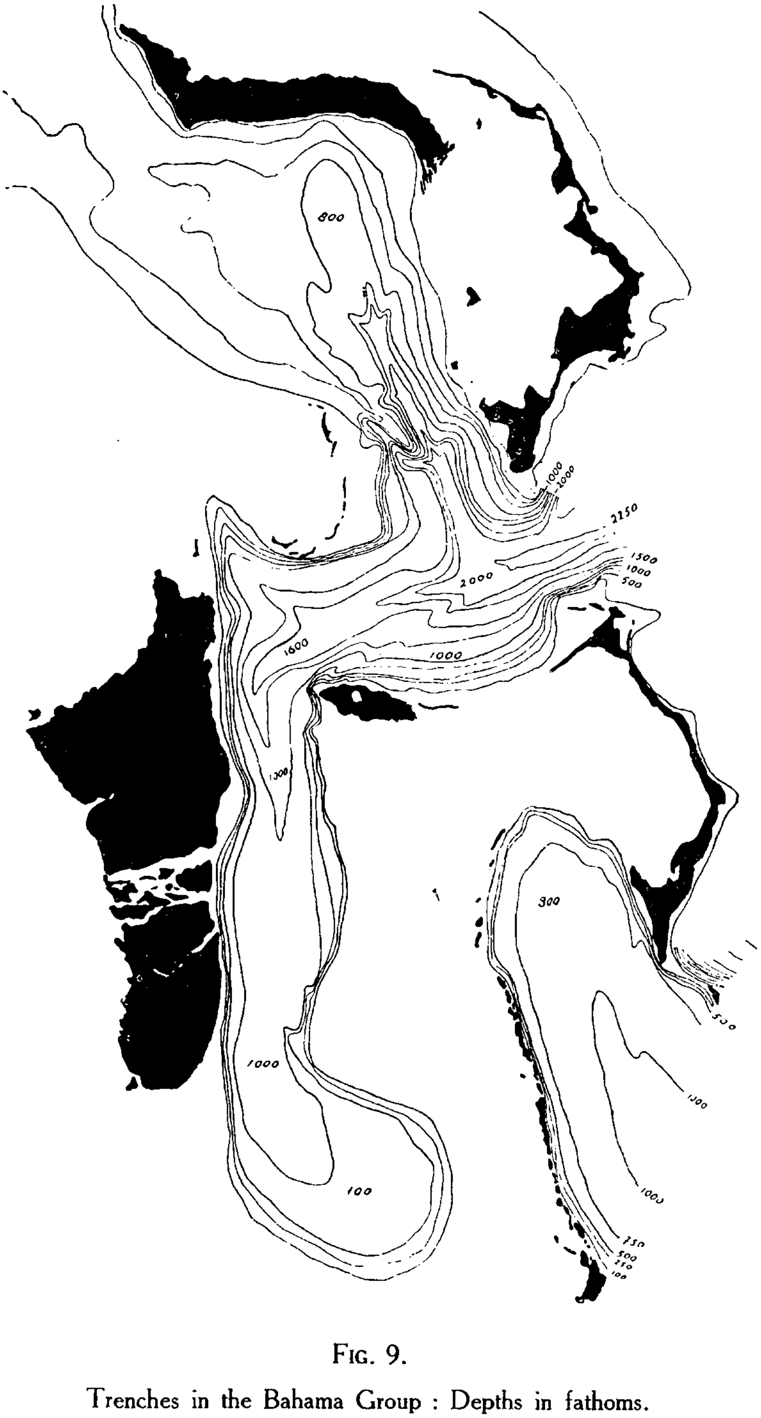
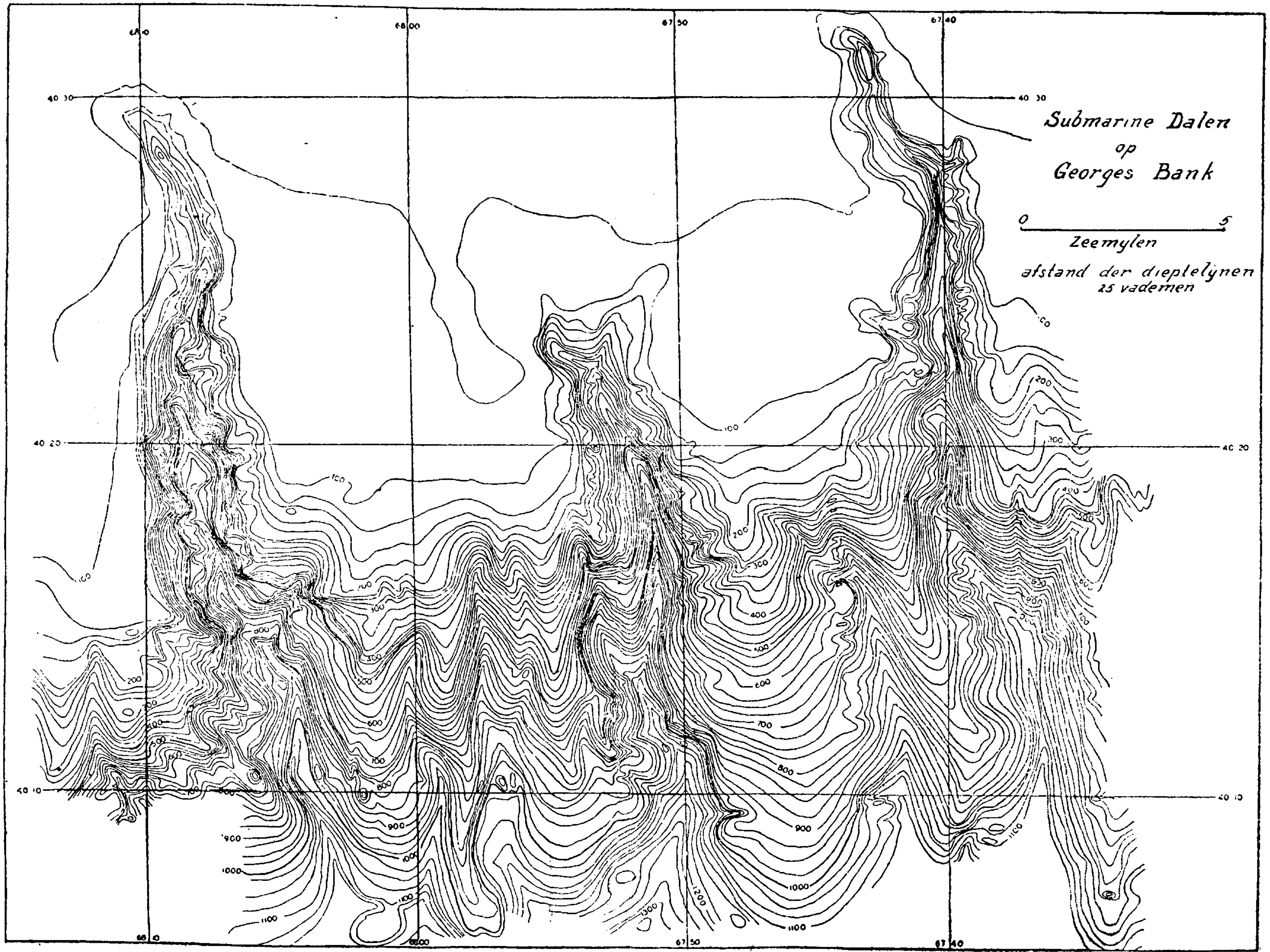


FIG. 9.

Trenches in the Bahama Group : Depths in fathoms.

Fossés de l'Archipel des Bahama : Profondeurs en brasses.


Submarine Dalen
op
Georges Bank
0
5
Zeemylen
afstand der dieptelynen
25 vademen
40 30
40 20
40 10
68 10
68 00
67 50
67 40
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300

the glacial epoch, when for some time the mouth lay near the 40-fathom curve, is clearly seen. The submarine canyon which was formerly considered as the direct communication of this gully, seems to have its origin towards one side of the mouth of the river.

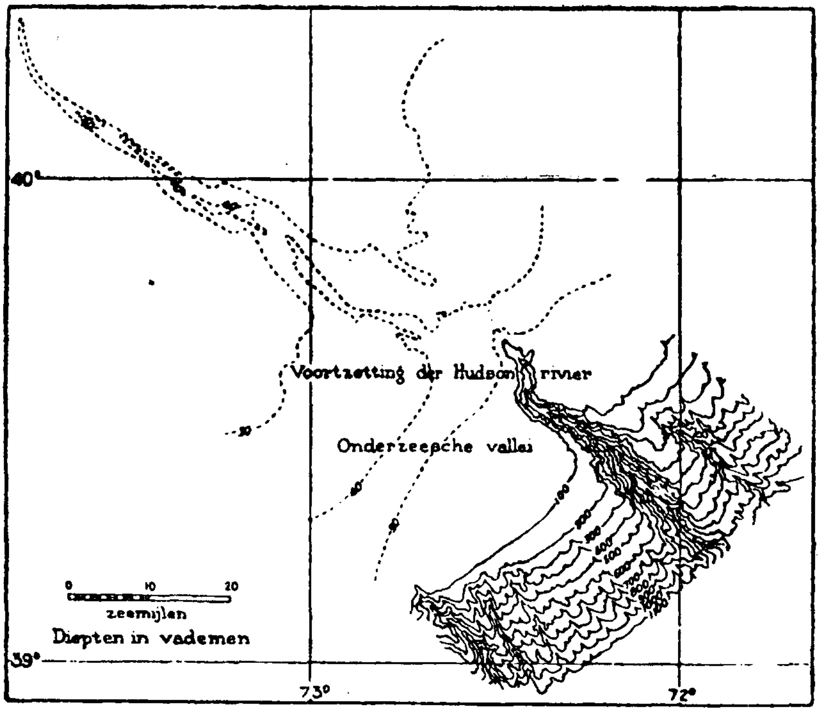


Fig. 7. — The gully over the plateau with submarine canyons off the mouth of the Hudson River.

The most remarkable examples are undoubtedly the group of over a dozen trenches which plow through the continental slope of Georges Bank. The three largest are reproduced on Chart N° XVI.

As far as is known they are 50 km. in length and sunk 1000 m. deep, while having been traced down to 2000 m. below sea level. They are very regular in shape and have only a few lateral ramifications which are most frequently limited to the portion which indents the continental shelf. The intervening space is taken up by a few smaller gullies which do not reach further than the shelf's margin.

It must not be forgotten that the Georges Bank is separated from the mainland by a deep bay, the Gulf of Maine, and that therefore the canyons have no extensive hinterland.

Of quite a different shape is the shallow but very wide, flat-bottomed trench which, to southward of the Mississippi delta, intersects the plateau and continues down the slope (Fig. 8). This trench is, in places, 20 km. wide while peculiar protusions give the relief of the slopes an interesting aspect.

As a final example let us consider Figure 9 showing the gigantic bowl-shaped gullies in the vicinity of the Bahama Islands. Though these also slope to seaward regularly throughout their length, it is felt that they cannot be counted with the normal forms ; in fact, they are sea basins with a narrow more deeply-cut gully along their bottom.

If we wish to get an insight into the distribution of the canyons the world over, we are obliged to limit ourselves mainly to the United States, since it is there only that comprehensive data are available. An examination of Fig. 10 shows that long stretches of coast exist on which submarine canyons are totally lacking, whereas in other localities they are closely spaced.

Outside the United States, in spite of the dearth of information, a great many examples are already known. They are situated off the coasts of Mexico, Brazil, Ecuador, Japan,

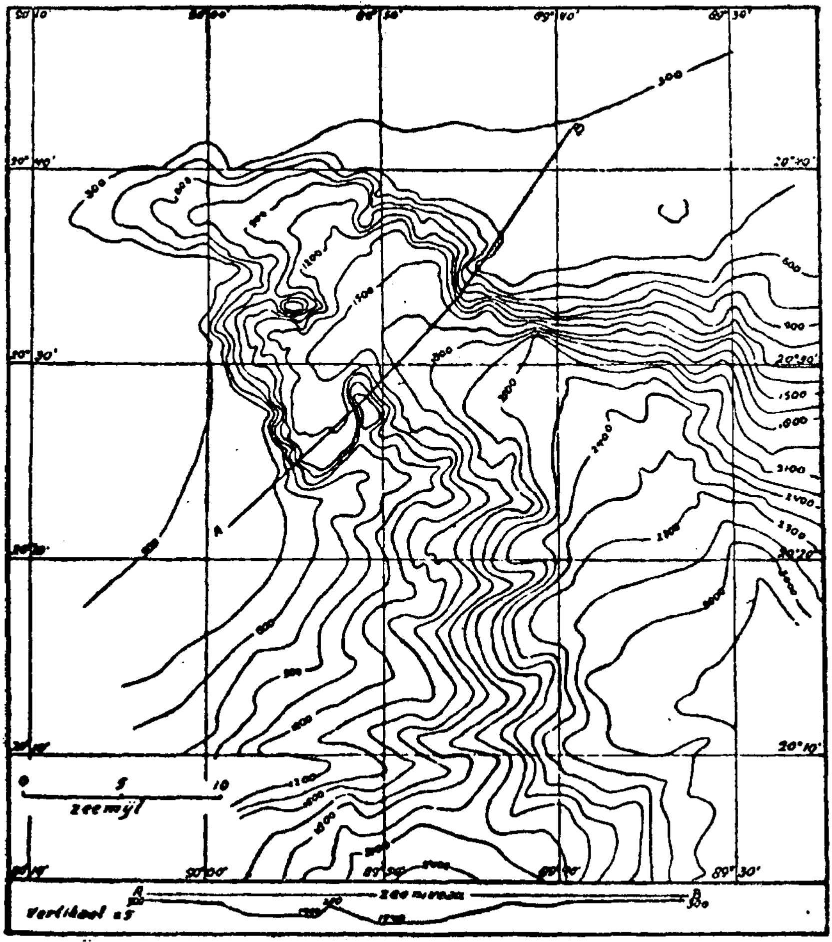


Fig. 8. — Submarine trench off the Mississippi Delta : depth-contour interval 150 feet.

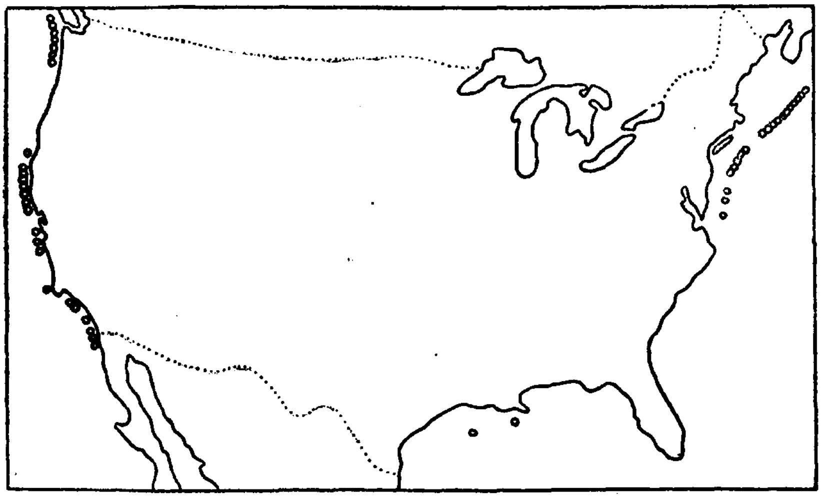


Fig. 10. — Distribution of the canyons along the coasts of the United States.

Korea, British India, Africa, Portugal, France and the Hawaii Islands, i. e. in all latitudes and on very divergent types of coasts. The distribution may thus well be considered universal.

B. *The Material of the Sides:* In investigating the possible mode of formation of submarine canyons, it is apparent that the nature of the material of which they are modelled is of the utmost importance. It is not so simple a matter, however, to carry out satisfactorily an investigation of the kind, although STETSON and SHEPARD have managed to dredge along the canyon walls by means of heavy dredges, and to detach fragments from the solid rock. With the aid of the ordinary sounding apparatus, samples of the softer filling material have been brought to the surface. However, the results obtained by these methods are so divergent that it has not yet been possible to form any opinion regarding the general composition of these walls.

SHEPARD (Bibliogr. Note 10), referring to the West-American canyons, is of opinion that one has to deal generally with hard rock. Even granite seems to have been encountered in the sides.

STETSON (Bibliogr. Note 16) has found in canyons off the east coast of America subrecent deposits which may well be ancient "filling-in" deposited in the canyons during the interglacial age. On the Georges Bank, however, (Bibliogr. Note 15), the original massive wall which seems to be built up of tertiary sediments and slopes down gently seaward, has been encountered, while early-to-recent glacial mud coats the gentler slopes and the bottom. Although thin hard layers are not lacking, according to STETSON the nature of the rock is as a rule friable sand and soft clay.

Besides by direct observations, it is also possible to form a theory concerning the nature of the sides along speculative lines. Whenever a river cuts into a valley, two different processes come mainly into play (apart from any possible complications). The flowing water hollows out the bed and this process, left to itself, may lead to a very steep-walled cleft. Next comes the crumbling to pieces, washing, rifting and fall of the sides, whereby the latter are continually worn away; the cleft widens and becomes less steep. The material thus brought down must be carried away by the watercourse. The steepness of the valley depends on the relative velocity with which the process takes place; with a slow direct action of the watercourse, a wide valley with gentle slopes ensues.

For the submarine canyons also it must be assumed that the direct wearing-away action is limited to the undermost portion of the cross-section, and this manner of formation is moreover admissible because the cross-section is of such enormous size (several kilometres wide). If the sides of the submarine canyon had been built up of very resistant rock, a lengthy denudation-period in the air would in itself be capable of explaining this formation. In truth, in the case of rapid cutting, no place is left for the very slow process of widening by washing-away, etc. Generally speaking, no wide *submarine* valley can be formed, because the factors likely to bring about such a process in hard rock are undoubtedly altogether lacking below sea level.

For some of the canyons it has been proved that the rock in which they are cut is of comparatively recent origin, so that there has not yet been the material time necessary for the formation of a wide valley in such a compact mass. There remains alone, therefore, the assumption that the sides were composed of plastic or loose material which, by recession or crumbling, collapsed under its own weight, each time that erosion below the valley created overhanging masses. Collapsing thus went hand in hand with cutting, and the rapidity with which it occurred was dependent solely on the rate with which the vertical incurvation took place.

When harder material presents itself here and there in the sides, escarpments or even protrusions are formed, and it is precisely from these that the dredge breaks off pieces and brings them to the surface, so that a false idea may be formed of the average toughness of the slopes.

In this connection a recent observation, likewise made by SHEPARD, is very significant. (1) When investigating the head of the La Jolla (California) canyon in the summer of 1937, a recession was ascertained by soundings; a portion of the side had loosened and sunk as a whole in the canyon, so that within a week depth increases of 9 metres were noted. In this case the friable composition of the side is proven.

As long as satisfactory direct observations are lacking, the thesis that the sides are as a rule built up of rather loose material in which harder rock is embedded here and there, should consequently be somewhat cautiously accepted.

---

(1) Communicated by letter (See also Bibliogr. Note 13).

III. EXPLANATION OF THE FORMATION OF THE CANYONS

The explanation of the submarine canyons which most naturally comes to the mind is that they are submerged river valleys. It has become evident, however, that in most cases they reach down to a few thousand metres below sea surface and are distributed the world over: hence this concept is no longer tenable. Such general and far-reaching subsidence of the continental shelves is in conflict with the stable distribution of the great earth masses; with the geological structure and history of the adjacent coasts; with the compensated profile of the river-beds between sea level and source; with the necessarily constant content of ocean basins; in short, with all available data having any relation to the lie of the continental slopes. **Shepard** formerly defended *also* an opinion according to which the canyons exhibit the greatest variety of age and from the time of their submersion are kept open by the sliding out of the loose sedimentary filling which tends continually to obstruct them anew. Though the above-mentioned criteria may be applicable in a lesser degree against this concept, which allows more time for the process of submergence, it has been abandoned by the author himself. It is not excluded, however, that some canyons — especially the rocky ones — have been formed in this manner.

In his latest publication **Shepard** wonders whether a temporary subsidence of sea level is not responsible for the cutting of the valleys. It may be that during the maximum spreading of the glaciers in the ice age the surface had subsided farther down than has been so far generally admitted; yet, in pursuit of his inquiry, **Shepard** is unable to go further than to a 1000-metre subsidence. Without going further into the improbability of such extreme glaciation of the earth, it should be noted that most of the gullies are traceable at least down to 2000 or 3000 metres; so that the problem is not satisfactorily explained even if the subsidence of 1000 metres be assumed. However, and this is a major point, no indications whatever are to be found around the 1000-metre depth that the sea surface ever lowered to this level; and just as little do the canyons exhibit breaks in their run indicative of a former emptying of rivers at these places. This attempted explanation also fails.

One is therefore compelled to assume that the canyons originated under water, because neither the continental slopes nor the sea surface could have undergone variations in level which might afford a satisfactory explanation. Formation by fracture would yield another type, and the collapse of a mountain teaches us that a landslip of such a nature results in a broad spoon-shaped excavation. This does not of course mean that landslides may not have co-operated locally, as has, in fact, been indicated above. Especially for canyons of such type as those lying off the Mississippi delta a large place may be assigned to this mechanism.

Possibilities are in reality therefore, reduced to "flow" of one kind or another. An important contribution towards the solution of the problem was made by **Stetson** when he carried out current surveys on the beds of canyons. These surveys made it evident that tidal streams attain velocities up to + 15 cm. per second, but they do not always follow the direction of the canyon ; further, the velocity is much too small to have been capable of dredging the canyon. At the utmost they may have retarded the filling up by sedimentation, by carrying away the finest particles.

The formation of canyons would still be an absolutely puzzling phenomenon if **Daly** had not put forward an hypothesis as ingenious as original (Bibliogr. Note 1). Briefly formulated, **Daly's** hypothesis is as follows :—

During the ice epoch, sea level gradually subsided some 70 to 80 metres below present mean level as a result of the stagnation of water in land ice-caps. While the continental plateaus previously formed wide bands of such depth that only a little of the sand and clay could be stirred up by storms, an enormous quantity of ooze lay at the time of the subsidences within the area of the glacial storm waves. The stirred-up sediment increased the specific weight of the muddy water. This thick liquid must have spilled over the edges of the plateaus down the continental slopes towards deep-sea bottom, being heavier — heavier even than the cold deep-sea water. The overwhelming mass of these currents excavated gullies in the slopes till finally there remained deep-sea canyons which, in their turn, received deposits of fine sediment. In this way the plateaus were worn down several dozens of metres while a covering of coarser thoroughly rinsed material remained.

Daly's reasoning enables us to explain most of the features of canyons. Their origin is still young although the scouring has now come to a standstill. They all originated at relatively shallow depths, chiefly off the edges of the continental shelf. This hypothesis would explain their distribution over the whole of the globe and the great depths to which they reach. The features reminiscent of river valleys (branching off in upstream direction, the debouchment level of lateral valleys, erosion at the outer sinuosities, regular longitudinal profile) are formed as a consequence of the flowing water though below sea level. On the other hand the presence of sites where a hinterland (with great rivers) is lacking, occasions astonishment. That they frequently lie off river mouths is due to the rich transportation of fine particles and to the cutting of the valleys during the ice-age, even in dried-up plateaus. Automatically there must have existed a declivity to graft these gullies onto submarine valleys in the vicinity. The Hudson Gorge (Figure 7) illustrates a case where grafting has not completely come to an end.

It is seen how the hypothesis of the glacial density-currents is capable of resolving those problems without restriction. A few weak points remain however, where more certainty is urgently needed. Obviously, scouring of the gullies may be imagined to have taken place in a comparatively short space of time where the continental slopes comprise non-resistant material. Only a few per cent of the remainder may, by undermining and landslides, have been transported in a crumbled condition to bottom there to be comparatively easily picked up and carried away by the first current which occurred. However, the samples brought up by SHEPARD and the local inclination of the slopes warn us against accepting in its entirety the theory of a non-consolidated structure of the sides.

A second point of interrogation must be placed against the question of the California canyons, which originate where the continental plateau is very narrow. It may be that the contribution of heavy matter at these places was not sufficient to engender lively streams.

The last point, into the details of which it is necessary to go somewhat more thoroughly, is whether the velocity of flow and the mass of the glacial currents were great enough to produce a noticeable erosion. DALY has naturally given this question special attention and attempted, by analogy with rivers, to reach an estimate of the current velocity. Where rivers flow into seas, deltas are formed, and it has long been known that in some deltas gullies of a few metres depth and traceable far into the open sea, occur. Surely in this case water weighted with sediment seems to have sunken and eroded the deltas or, at least, to have slowed down the rate of sedimentation. An investigation of these questions is at present in progress in the weir-pools of the United States, and it is hoped that ere long comprehensive data will be available.

DALY has moreover made an estimate of the increase in density of sea water by stirred-up silt. Assuming a probable value for the current and applying a formula for current velocity (allowing for friction, slope, dimension and density) he comes to the conclusion that a velocity of 2 to 3 km. per hour, or 70 cm. per second, is certainly possible: a velocity whereby even coarse sand may be set in motion.

An illustration of the principle and, at the same time, a check on the applicability of the above-mentioned formula was given by the author of this article by means of the following experiment. (Bibliogr. Note 3). The glass-paned gutter of the laboratory for experimental geology at Leiden was kindly loaned by Prof. ESCHER. A sand model was erected representing a stretch of the continental shelf and the slope, perpendicular to the coast.

The gutter was filled with water to about a few centimetres above the level of the shelf. The slope of the continental talus was only slightly exaggerated in the model. By spreading a suspension of clay on the plateau directly under the coast, a state of things is created such as must have existed in a storm during the ice-age, viz. a heavy suspension on the plateau. It was fascinating to see how the thick suspension progressed at first slowly seawards over the plateau and then, as a whirling avalanche, rushed down the slope, to spread uniformly over the deep-sea bottom and to come finally to a standstill. Even an extremely shallow gully in the slope seemed actually to swallow up all the muddy water and to lead it down in a narrow track. Mixing of the suspension with the clean water occurred but rarely.

Now, other conditions being equal, the velocity of flow increases with the dimensions of the experiment. While in the test velocities of a few centimetres per second only were attained, by enlarging to natural size strong currents are produced. The smaller velocities in the test may therefore result in the deposition of the clay which cannot result when it is a question of the whirling current of Nature. By taking a coloured salt solution, it was possible to reduce this possibility still further and to obtain series of comparable tests. The specific weight of the solution was varied and afterwards the quantity. In this way it was possible to lay down a formula for the calculation of the velocity in nature, and to determine its constants. It is true that so great an extrapolation must be applied that the result is necessarily to some degree unreliable; but one is nevertheless in a position to ascertain its order of magnitude. The above-mentioned investigations in weir-lakes allow a conjecture that the calculation of the velocity made from the tests on the shallow edge cannot be accepted as of any great value.

The case of Lake Mead, the weir-pool in Colorado which was formed by the erection of the Boulder Dam (Bibliogr. Note 4) may be quoted as an example. When, after heavy rains, the river carries abnormal quantities of mud, the water in the river has a notably higher specific weight than that of the lake. The inflowing water plunges under the clearer water of the reservoir and flows for a week with a velocity of 30 cm. per second along the bottom, to arrive, finally, at the foot of the weir. Over the 150 kilometres' route along the submerged bed of the former river, the muddy water is carried away without mingling appreciably with the clearer water. If the slope and the dimensions of the phenomenon had been greater, a higher velocity would have been attained. As a matter of fact the submarine canyons differ in this sense and mathematical reduction, even with a much lower mud content than assumed by DALY, gives a greater velocity than it has been possible to admit on the basis of the tests alone.

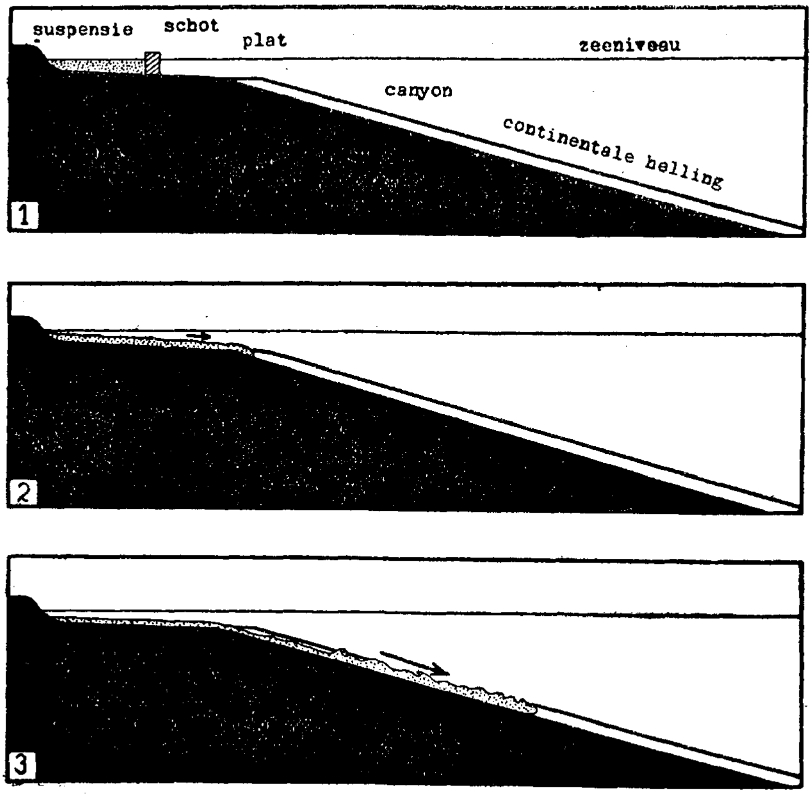
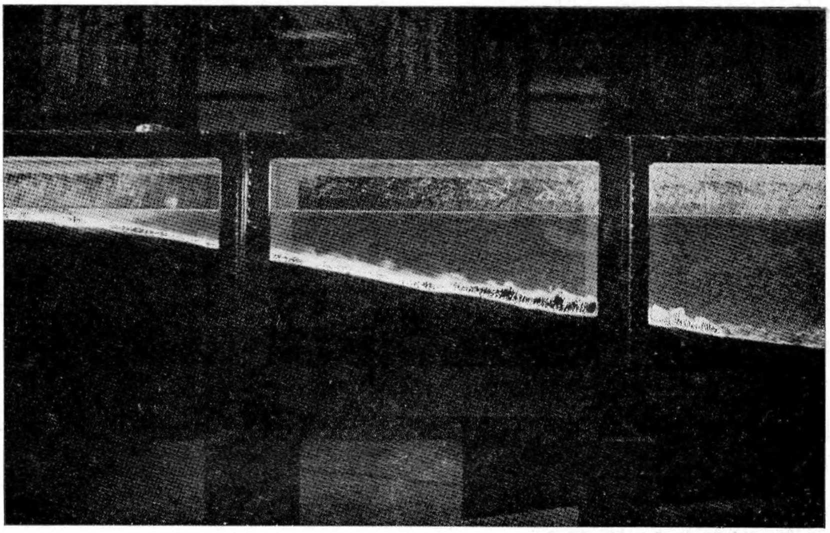


Fig. 11. — Diagram of the test: 1. The heavy suspension is distributed on the plateau behind a partition; 2. The suspension creeps towards the edge of the plateau; 3. The current rushes down the gutter.

To go further into the matter here would lead us too far. It suffices to indicate that in each case a greater velocity is arrived at than that assumed by DALY. Also, it seems that the mud stirred up was of subordinate significance only. The material picked up under way by the whirling motion of the current had far more influence. The dimensions and velocity of a current thus increased notably downwards.

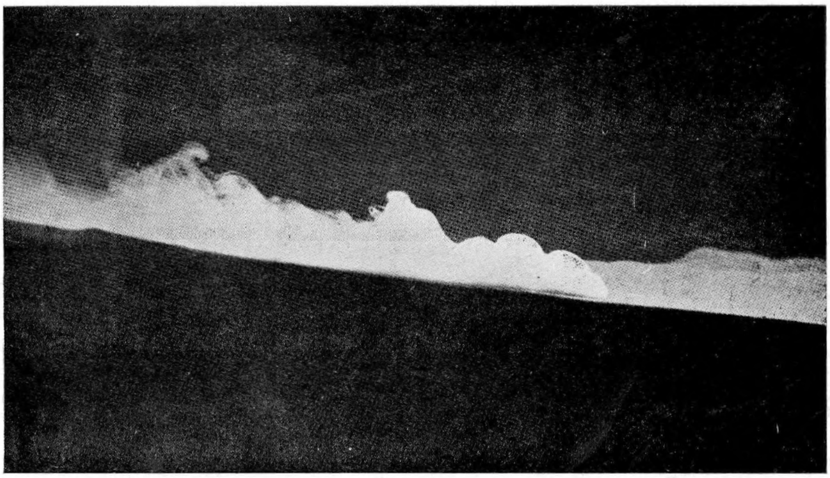
We are thus induced to attach greater importance to DALY's hypothesis. Though it is by no means irrefutably proved, it may be considered well-founded, and the uneasy feeling that the submarine canyons are to remain an insoluble puzzle is thus done away with. Formerly a geologist told us of the soaring eagles over the Hudson where dolphins now disport themselves. Austere science has ousted such vagaries, but does it not actually give a much richer picture



PHOTOGRAPH I.

The gutter in the Leiden Laboratory seen sideways.
A clay suspension flows down without mixing with the clean water.

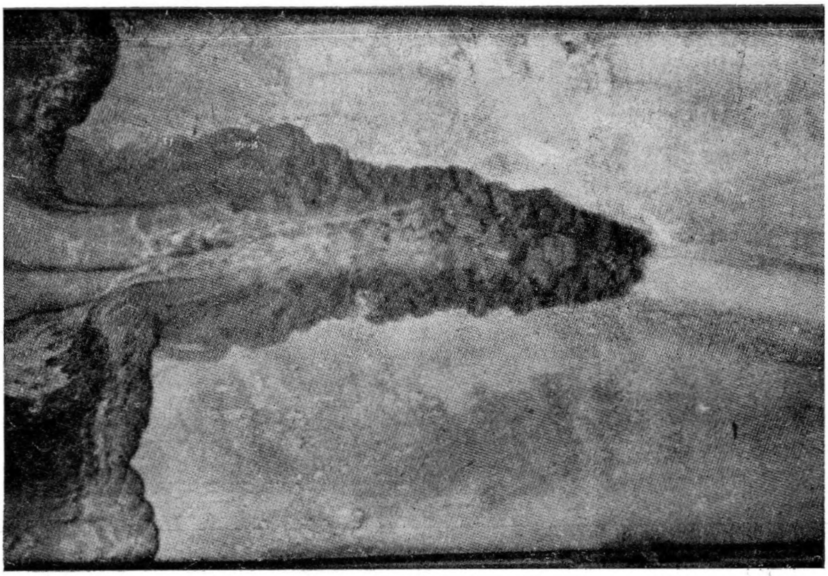
Gouttière du Laboratoire de Leide, vue de côté.
Les flocons en suspension s'écoulent sans se mêler à l'eau pure.



PHOTOGRAPH II.

A suspension rushing down in gulley along the glass panes.

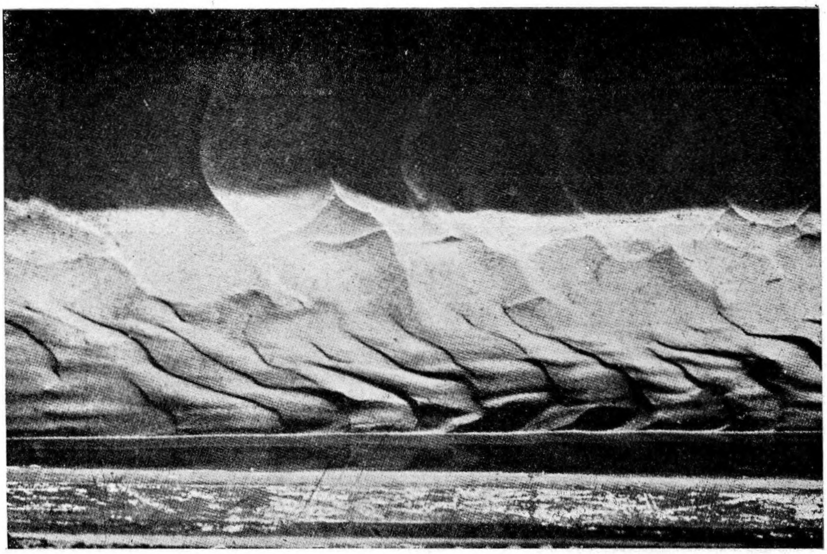
Les flocons en suspension descendent le long des panneaux en verre de la gouttière.



PHOTOGRAPH III.

A suspension in a salt solution rushing downwards to the right in a gulley.
Seen from above.

Flocons en suspension dans une solution salée s'écoulant vers la droite en forme d'épi.
Vue d'en dessus.



PHOTOGRAPH IV.

Ripples in the sand on the gulley caused by flowing to the right.
Seen from above.

llen

Ridius formés sur le sable, par suite de l'écoulement vers la droite.
Vue d'en dessus.

in their place ? The mighty tide of the sea-surface oscillations during the ice-age ; the raging storms which tore up the mud ; the formidable currents which dashed down the continental slopes excavating gigantic gullies and depositing the mud over the deep-sea bottom far away from the coast ! We are allowed at the same time a glance into the remote past and into the pitch-dark depths of the oceans. No, geological science can assuredly not be accused of an arid reality which kills all phantasy !

BIBLIOGRAPHY

1. DALY R. A., *Origin of Submarine « Canyons »*. Am. Journ. Sc., 1936, p. 401-420.

2. HESS H.H., *The Navy-Princeton gravity expedition to the West Indies in* 1932. U. S. Hydrogr. Office, 1933.

3. KUENEN Ph. H., *Experiments in connection with DALY's hypothesis on the formation of submarine canyons.* Leidsche Geol. Med., 1937, p. 327-351.

4. KUENEN Ph. H., *Density Currents in connection with the problem of submarine canyons.* Geol. Mag., 75, 1938, p. 241-249.

5. SHEPARD F. P., *Submarine Valleys.* The Georg. Review, 1933, p. 77-89.

6. SHEPARD F. P., *American Submarine Canyons.* Scottish Geogr. Mag. 1934, p. 212-218.

7. SHEPARD F. P., *Canyons off the New England Coast.* Am. Journ. Sc., 1934, p. 24-36.

8. SHEPARD F. P., *Submarine Canyons off the American Coasts. Zeitschr. f. Geomorphologie,* 1935, p. 99-105.

9. SHEPARD F. P., *The underlying causes of submarine canyons.* Proc. Nat. Acad. Sc., 1936, p. 496-502.

10. SHEPARD F. P., *Continued Exploration of California submarine canyons.* Trans. Am. Geoph. Union, 1936, p. 221-223.

11. SHEPARD F. P., *Daly's Submarine canyon hypothesis.* Am. Journ. Sc., 1937, p. 369-379.

12. SHEPARD F. P., *« Salt » domes related to Mississippi submarine trough.* Bull. Geol. Soc. Am., 1937, p. 1.349-1.362.

13. SHEPARD F. P., *Shifting bottom in submarine canyon heads.* Science, Vol. 86, 1937, p. 522-523.

14. SMITH P. A., *Marine surveys of the United States Coast and Geodetic Survey and their relation to geology and geophysics*. C. R. Congr. Int. Géographie, Amsterdam, 1938, T. 2, p. 141-149.

15. STETSON H. C., *Geology and Palaeontology of the Georges Bank canyons:* Part 1, Geology. Bull. Geol. Soc. Am., 1936, p. 339-366.

16. STETSON H. C., *Dredge-samples from the submarine canyons between the Hudson Gorge and Chesapeake Bay*. Trans. Am. Geoph. Union, 1936, p. 223-225.

17. STETSON H. C., *Current-measurements in the Georges Bank canyons*. Trans. Am. Geoph. Union, 1937, p. 216-219.

⁂