THEORIES OF THE ORIGINS OF THE CANYONS.

Extract from an article entitled "CONTINENTAL SLOPES AND SHELVES"

LECTURE

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THEORIES OF THE ORIGINS OF THE CANYONS. — The discovery of the canyons on Georges Bank, based on accurate soundings and positions, stimulated a large crop of theories in explanation. At a very early stage one particular theory was advocated by SHEPARD and others who were particularly concerned in these earlier investigations on the Atlantic coast of the United States. On this theory the canyons were developed by subaerial dissection by stream-erosion during a period when the shelf and the Continental Slope had been laid bare and a subsequent return of the sea submerged the topography produced by subaerial erosion. This theory has found favour also with the authors responsible for the contouring of the charts published with Special Paper N° 7. The contouring of these charts is mainly the work of the late A.C. VEATCH and the system of contours is based on the idea that he had to deal with a topography developed under subaerial conditions.

Douglas JOHNSON, in "The origin of submarine canyons" (New York: Columbia University Press, 1939), has recently published a critical review of the hypotheses put forward within the last half-century. They are classified into groups involving tectonic, subaerial, and subterranean origin. Many of these are of academic interest or were evolved to explain special cases.

Discussion has until recently centred mainly around two opposed methods, subaerial stream erosion and subsequent submergence, and Daly's hypothesis of erosion by turbid streams of mud washed off the Continental Shelf while it was uncovered during the glacial period. Both involve the supposition that sea-level was lower than at present, but whereas DALY demands only a withdrawal of the sea to some 100 fathoms, the other theory requires a withdrawal to at least 1500 fathoms.

A.C. VEATCH, from a study of the lower Congo basin and the Congo submarine canyon which presents many resemblances to the American canyons, conclude that in Mousterian time "there was a recession of the Atlantic waters to a shore-line located 10,000 feet or more below the present sea-level, and the return of these waters to the present level less than 10,000 years ago".

Later it is stated more categorically that the "data on both sides of the ocean indicate that during the last erosion period the sea reached a point approximately 12,000 feet below its present level. Any explanation of these facts must account for a change of 12,000 feet, down and then up again, along a strip between our north-eastern Atlantic coast and the Congo, and in the very short period between the time — 20,000 to 25,000 years ago — when the Wisconsin ice cleared the Mohawk outlet and the return of the sea to its present level about 5000 years ago".

One would have thought that the necessity of making this extravagant assumption about sea-level would have administered the *coup de grâce* to the theory of subaerial erosion. But, in one form or another the theory, in spite of its forbidding basic assumption, still has adherents.

(*) See also : *The Geographical Journal for March* 1941 *and Special Paper N° 7 issued by the United States Coast and Geodetic Survey.*

Daly's theory was put forward in an attempt to supply some explanation less incredible than that of subaerial erosion and the enormous changes of sea-level which it demands.

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More recently Douglas JOHNSON, having reviewed both Daly's and the subaerial theory, concluded that as there was so little support for either except as a remote working hypothesis, some other explanation was obviously called for. His new hypothesis assumes that water issues in powerful springs from the sediments which build up the coastal shelf and that the solvent effect of the spring water is so great that in time the rocks are dissolved or sapped and the spring migrates towards the land, leaving in its retreat the canyon.

We will now review the arguments for and against these three hypotheses; it is convenient to discuss them in the reverse order.

Johnson's hypothesis. — Others had already attributed certain canyons to discharge of rivers which had flowed through subterranean channels from the adjoining land to the Continental Slope, but the chief novelty claimed by JOHNSON for his hypothesis is that it attributes the formation of the canyon to solution and sapping of the canyon head by artesian waters emerging on the slope, not by the ordinary process of stream erosion, operating on the sea floor.

Stated summarily the hypothesis rests upon the proved experience that the deposits of the coastal plain of the U.S.A. from New Jersey to Florida contain water-bearing horizons which if tapped by boring yield artesian water; numerous reported instances in this area and other parts of the world of fresh-water springs breaking out under the sea at varying distances from the coast; the known capacity of water, particularly when charged with certain gases, of dissolving to some extent all rock-forming minerals; and the fact that certain box-canyons in the basalts of the Western United States and shallow through-like valleys in Florida called "square heads" have been explained by the solvent and sapping action of powerful springs which issue at their heads.

Assuming that water-bearing horizons similar to those that underlie the coastal plain occur in the seaward continuation of those deposits under the continental Shelf, then it becomes highly probable that water may escape at various points of the slope as springs large or small. Since the majority of the known water-bearing horizons of the coastal plain are Cretaceous or Tertiary, whereas the superficial deposits of both the coastal plain and the shelf, as well as of parts of the slope, are pleistocene or Recent, it is improbable that these water-bearing sediments outcrop directly on the slope. Springs fed from them may however reach the bottom of the sea by breaking through the overlying deposits, or the latter may in places slide off the face of the slope, thus laying bare one or more of these horizons. In order that springs may continue to flow it is necessary that there is sufficient head inland to overcome the greater density of sea water (about 1°025) and the frictional resistance of flow through the water-bearing sediments. There is no difficulty about securing on the present coastal plain the head necessary to overcome the sea-water density, but it requires a considerably greater head to force the inland fresh water over 100 miles to the slope.

If a spring breaks out on the Continental Slope, then according to the hypothesis a canyon will begin to develop. Material is removed in solution by the spring water, thus weakening the rocks and causing them to crumble and fall into the depression created at the spring.

The succeeding stages of canyon development are passed over rather lightly by JOHNSON. If however it be imagined that the spring has migrated some distance inward from the face of the slope, then the original partially consolidated sediments emerging on the slope have been replaced by a deposit which has crumbled down and fallen in from the sides. This material may well occupy in its disintegrated condition a larger volume than the original sediments which it replaces, and it is obviously important to find some means of removing some or all of it, as otherwise canyon development may cease. The water of the spring may be comparatively fresh and thus lighter than sea-water, when it will rise to the surface of the sea against the head wall of the incipient canyon; or it may be so impregnated with mineral matter removed in solution during its passage towards the shelf as to be denser than sea water, when it will flow down the slope. In the latter case only it may have power to transport brokendown material which cumbers the floor of the canyon. In

the former case the only material that can be removed is by solution. It is unlikely that either of these processes will prove effective in keeping the canyon clear, and JOHNSON assumes that the weakened material which falls into the canyon will slide out at the canyon mouth. If spring water can sap the canyon head, and submarine sliding is effective in removing the material that falls in from the head and sides as the sapping proceeds, then there is practically no limit to the length of canyon that can be developed in time by these operations. Again, given sufficient time the hardness or insolubility of the rocks do not prevent extension of the canyon; they only slow down its rate of formation.

This hypothesis has several obvious merits; it accounts for canyons of various sizes along a given strip of Continental Slope; it also affords a possible explanation of the different levels at which they head on the slope, and it meets the possibility that some canyons on the coast of California may have been developed in granitic rocks, although the claim that this is so has not been definitely confirmed. It also overcomes the objection that canyons are absent from parts of the coastal plain where underlying deposits are probably similar to those farther north, where many examples occur. If for any reason the springs were not able to break through the deposits on the face of the Continental Slope no canyons could be produced.

It is however faced by several obvious difficulties, some of which have been foreseen by its author. First, the present coastal plain which received the rainfall to feed the springs is of such low relief that it is doubtful if there is sufficient head to overcome frictional flow through the water-bearing formations to the face of the slope. It is possible however that water percolating into the more elevated surface of the Piedmont region may find its way into the lower part of the coastal plain deposits and thus provide the necessary head. It is not safe to argue as the author does that because water flows continuously from a well bored near the coast there was a constant flow of water seaward at that point before the well was made. Secondly, there is no coastal plain north of the Georges Bank, and it is difficult to see how the hypothesis under existing conditions can account for the canyons of that area unless the springs are assumed to be feld from the crystalline rocks of Massachusetts some 250-300 miles away.

Thirdly, on any probable view of the structure of the coastal plain any water-bearing horizon slopes gently seaward, and its outcrop may be 10,000 feet or more below the surface of the sea. As the canyon head retreated the level of a spring at that horizon would presumably rise inland in conformity with the rise of the water-bearing stratum. Since the intake ends of these formations lie some distance inland from the shore it is difficult to see why in the first place the larger canyons all head at so nearly the same level on the coastal shelf, and in the second place why the canyons have a gradient which is many times greater than the probable slope of the water-bearing stratum which guided their headward migration. This difficulty is not touched on by JOHNSON. It is not however insuperable and a way out of it can be suggested. Since continued canyon development depends on the removal of the material which falls on to the floor it is not improbable that the gradient of the floor of the canyon is just that which is necessary for submarine sliding. Below the floor there may be a fill of weakened material which has not slid out because of insufficient slope. In these conditions weakening of the rocks about the outlet of the spring below the fill can occur only between the canyon head and the fill, but above the level of the floor collapse of the head and side walls of the canyon may take place.

This is a serious difficulty which requires some further explanation. Alternatively headward erosion beginning at a lower level may tap other springs at a higher level, which may continue the process after a spring at a lower level has become ineffective. This alternative would appear to leave a good deal to chance.

Fourthly, it may be asked whether fresh water which had been in contact with the minerals of a water-bearing formation during its long passage from the surface to the Continental Slope would not be already saturated and incapable of dissolving anything more when it emerged on the sea floor; and whether the contact of water of high mineral saturation with sea water would be more likely to promote further solution or to lead to precipitation. The effectiveness of springs action would appear to depend upon the answer to these questions.

JOHNSON points out that the difficulty of providing a gathering ground at a sufficiently high level would be less in past times, such as the late Cretaceous and Tertiary, when the

deposits of the coastal plain extended widely beyond their present margin at the fall-line on to the higher regions of the Piedmont and the Appalachians. There would then be an ample hydraulic gradient for the water to reach the Continental Slope, wherever it may have been. Canyon development might therefore have been most active in earlier geological periods and may now be in a waning phase, and the present canyons mainly or wholly an inheritance from earlier conditions.

The appeal to former conditions only partly meets the difficulty of the Georges Bank group. Since however there are remnants of Cretaceous and Tertiary rocks on Long Island and Miocene deposits occur on Martha's Vineyard, it is possible that an extensive coastal plain once existed off the Massachusetts coast, which reproduced at that time conditions similar to those that now prevail from Long Island southwards. If so, the Georges Bank canyons ceased to develop a long time ago and have remained more or less in their present condition since some part of the Tertiary period. Gradual collapse of their sides and head should have reduced these slopes more than in canyons farther south, whose development may have continued to more recent times, perhaps even to the present. The soundings do not appear to support such a conclusion, though a distinction has been drawn between the Georges Bank Canyon and those off Maryland, from differences in the rock samples obtained by dredging across the canyon.

Daly's hypothesis rests on two main postulates : that during the glacial period a large volume of water was locked up in ice and snow at the expense of the volume of water in the sea, so that the coastal shelves of the world were laid bare for a considerable distance from the former shores; and, that sea water rendered very turbid by waves on the exposed coastal shelves sank through the clearer sea water over the Continental Slope and eroded the surface of the slope.

The evidence for the first postulate is discussed at length in connection with Daly's glaciai control theory. The lowering generally considered possible is round about 300 feet, which would lay bare rather more than half the existing shelf; but much larger estimates have been put forward. The formation of the canyons depends however much more upon the validity of the second postulate.

That water of greater density from matter in solution or suspension will sink in water of less density may be accepted, but this does not necessarily involve belief that a current set up in this way can cause erosion, either general or local, of the surface over which it flows.

JOHNSON, in the discussion of Daly's views, finds that much confusion has been caused by the analogy drawn by DALY between the canyons and sublacustrine ravines that occur near the mouth of the Rhine in Lake Constance and that of the Rhone in the Lake of Geneva. In both these lakes the silt-laden waters sink suddenly and violently out of sight below the clear warmer surface waters of the lakes. The inference drawn by DALY was that if these silt-laden waters could excavate sublacustrine trenches some 50-70 metres deep such as occur in these lakes, it was not unreasonable to suppose that turbid currents under favourable, conditions might erode deeper and longer trenches comparable with the submarine canyons. JOHNSON shows however that FOREL and others who had investigated the sublacustrine ravines had come to the conclusion that they owed little if anything to erosion but were due in the main to the deposition of levées of silt in the quieter waters along-side the strong silt-laden current flowing near or on the bottom, and that the floor of the ravines was at approximately the same level in the Lake of Geneva as the floor of the lake beyond the foot of the levées and little, if any, lower in the Lake of Constance. JOHNSON further points out that in other lakes silt-laden waters sink violently below the surface, yet no sublacustrine ravines have been produced in them. The theory is faced by other difficulties. It is not obvious why the muddy waters gathered into narrow threads at certain points on the shelf; nor how a continuous supply of muddy water was maintained after the waves had done their worst in stirring up material when the self became exposed. Furthermore it is unlikely that there ever was much mud on the shelf in pre-glacial times, any more than at present. But the main difficulty is the absence of evidence that such currents if they could be produced would have the necessary eroding power.

There remains the hypothesis of subaerial erosion during the emergence of the Continental Slope : commonly associated with the name of F.P. SHEPARD, though it is accepted by others. It rests on three assumptions : that there is no alternative; that the winding

character, branching forms, tributaries, cross sections, and longitudinal gradients of the canyons are similar to stream-eroded valleys on land; and that the features of the dissected Continental Slope are similar to certain gullied areas in the Western United States. Each is open to criticism; but the main difficulty in this hypothesis is its basic requirement that a change in the relative levels of land and sea has taken place of some 12,000 feet in both directions in comparatively recent geological time.

It has been suggested that the canyons are much older features than their association with the sediments of the coastal shelf would suggest and have been kept open in various ways (also by Shepard); or that the exposure did not involve a general lowering of all the ocean, but was due to warping of the coastal regions (advocated by A.C. VEATCH and more recently by A.L. DU TOIT); or that the sea was much lower during the glacial period than is contemplated by DALY (this also by Shepard). There is nothing to choose in point of extravagance between the second and third suggestions.

It is more important to examine the claim that the submarine topography of the Continental Slope simulates stream erosion so closely that no other origin can be considered possible.

The soundings reveal clearly very considerable elevations and depressions along numerous traverses, especially those run nearly parallel to the edge of the shelf. Each of a large number of parallel traverses shows very similar features. In the best traverses of the Coast and Geodetic Survey the soundings are shown about five to a statute mile; on others they may be about twice this distance apart. The traverse lines are however spaced, in general, at intervals varying from something under 1 to 3 miles and occasionally 5 to 6 miles. One way of showing the soundings along a traverse is by drawing a vertical section along the line, joining individual points by straight lines or by smoothed curves which take account of neighbouring soundings. While the smoothed curves may not be accurate in detail this method probably gives a truer idea of the form of the surface than if the points are joined by straight lines.

The method most commonly employed on land is that of contouring; if any doubt exists about the run of a given contour-line it can be checked by inspection of the ground. When the method is employed for representing soundings, visual control is impossible; the only check is by running fresh traverse, which is difficult, as even with the most painstaking care there would be some uncertainty in the relative horizontal position of a fresh line run later.

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In some respects it is unfortunate that the recent charts have been contoured in the belief that the topography is the result of stream erosion, instead of drawing the simplest form of contour lines that conformed with the data, regardless whether the lines appeared consistent or not. The result of Veatch's contouring is a pretty picture, but it is quite certain that the data will not support more than a fraction of the smaller details shown on these charts. In particular the majority of the short "tributaries" which abound on the charts would disappear.

Still more unfortunately another series of charts (Series B) has been issued showing in blue the contours and in brown the courses of streams which are supposed to have flowed down these valleys. So long as these stream-lines are looked upon merely as a convenient means of picking out "valleys" from "ridges" on the A Series of charts no great harm will result. It is very difficult however to retain an open mind regarding the significance of a mass of sounding data if they are overlaid by a pictorial representation based on some idea which may have been wrongly conceived. It should be emphasized that the contour lines on these charts cannot be appealed to in support of the theory that the features were produced by subaerial erosion, since the contours have been constructed expressly on that hypothesis. But one may fear that many people have been fascinated by these contours into a belief in the subaerial theory.

The authors claim that there is no alternative explanation of the topography. Since then however JOHNSON has put forward one hypothesis of which an essential feature is the sliding of material out of the canyons; the same might occur at many places on the Continental Slope. DALY has propounded another which involves erosion by turbid currents sweeping down the slope. It is not clear also that ordinary slumping would not give rise

to a similar series of forms. In all these cases channels would be aligned approximately at right-angles to the trend of the slope. Unless therefore the channels exhibit some characteristic in which they differ from those produced by other means, and also agree closely with true stream-eroded channels, the statement that there is no alternative explanation of these forms cannot be accepted.

It is usually claimed that they agree with stream-cut valleys in their winding courses, their branching tributaries, their cross-sections, and their longitudinal gradients. There is no obvious reason why channels developed either on Johnson's or Daly's hypotheses or even by slumping should not possess the first three characteristics; the longitudinal profiles might however be expected to show differences characteristic of the particular mode of formation.

Now it is acknowledged that "the gradients of the submarine valleys between Georges Bank and Cape Hatteras are, without exception, remarkably steep; few features of the same magnitude are found in subaerial canyons". The relative figures show that the longitudinal profiles of the submarine channels are in general much higher than the most favourable cases of subaerial valleys. On the other hand they agree admirably with the sort of gradient to be expected if the material in them has been discharged by mud flowing or slumping. A mud flow like any other flowing body requires a higher gradient the smaller the mass in motion. If a mud flow began at or near the upper end of one these valleys its mass would increase as in its travel it picked up further mud from the floor and sides of the channel. The larger the mass became the lower the gradient that was necessary for continued motion, so that the floor of the valley would have a characteristic concave profile.

The fact that subaerial erosion as an explanation of the canyons has received any consideration at all is due to the too ready acceptance of statements that the characteristics of the canyons and of the Continental Slope are similar to those of valleys and gullies produced by subaerial erosion. This claim is not supported by an unprejudiced examination of the submarine forms revealed by the soundings and should not therefore be allowed to influence the judgment in considering other interpretations of the data.