THE STRENGTH OF THE EARTH'S CRUST

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PREFACE

PART I. GEOLOGIC TESTS OF THE LIMITS OF STRENGTH

PREFACE

The publication of a series of papers on "Diastrophism and the Formative Processes" by T. C. Chamberlin was begun in the *Journal of Geology* in October, 1913. The second part, on "Shelf-Seas and Certain Limitations of Diastrophism," is nearly identical in substance with a portion of a paper read by Professor Chamberlin on August 13, 1913, at the Twelfth International Geological Convention at Toronto, Canada. In this part particularly it is pointed out that the parallel surface and bottom of the shelf-seas, also their occasional extension as shallow water bodies over considerable portions of the continent at certain times, indicate a relation to sea-level and wave base rather than to a delicate isostatic adjustment. The implications of this and other lines of argument given by Chamberlin are toward crustal rigidity, not crustal mobility.

The first four parts of the present article on "The Strength of the Earth's Crust" had been completed before the writer read Professor Chamberlin's paper, or knew that he was at work upon the subject; but the conclusions are so closely in accord with his, though reached by other lines of attack, that this article may be regarded as a continuation of the same subject, an added contribution in the large field of diastrophism and the formative processes, following out certain of its ramifications.

A somewhat general survey is given here of the problem of the strength of the crust, beginning with the lines of evidence which bear upon it and following out to some degree the conclusions drawn from it. It has in this way been cast into the form of those articles published by the *Journal of Geology* from time to time, under the caption of "Studies for Students."

PART I. GEOLOGIC TESTS OF THE LIMITS OF STRENGTH

INTRODUCTION AND SUMMARY

The capacity of the outer crust to resist vertical stresses is an important field in the theory of dynamical and structural geology. On the one hand, it is known that the larger segments, those of continental and oceanic proportions, rest to a large degree in isostatic equilibrium, the subcrust of the continental areas being lighter than that of the oceanic areas in proportion to the regional elevation. On the other hand, the minor features, those which enter into the composition of the landscape, are known to have been sculptured by external forces and are to be explained therefore as sustained by reason of the rigidity of the crust.

Between these two extremes in magnitude of terrestrial relief lie mountain ranges, plateaus, and basins; made in part by tangential forces, modified by erosion and sedimentation. To what extent can these constructional and destructional forces work in opposition to those other forces which by producing vertical movement make for isostatic equilibrium? The method of attack is from two directions. The geologist examines the structures imposed by tangential forces, the mountains built by igneous extrusion, the surfaces made by erosion, the strata consequent upon sedimentation. From them he may determine the amount of strain which the crust can endure before periodic movements occur in the direction of relief from strain. The geodesist, by means of the plumb-line and pendulum, determines the subcrustal densities and notes the degree to which these are balanced against the relief, pointing therefore to a relation of flotational equilibrium within the solid earth.

Most geologists in former years have utilized but little the principles of isostasy, as may be seen by reference to the standard manuals. On the one hand, the weight of sediments may be spoken of as the *cause* of downsinking with such equal pace that the condition of a shallow sea prevails for a geologic period, though perhaps accompanied by the deposition of thousands of feet of sediment. On the other hand, and without argumentation to explain the apparent inconsistency, the same geologist may state that tangential forces have built folded mountains miles in height which may be subsequently largely removed by erosion before marked vertical warping of the crust occurs.

In contrast to the geologists, certain geodesists have argued in recent years for a high degree of isostatic adjustment; isostasy being regarded by Hayford, for example, as largely complete in areas probably between one square mile and one square degree in size, the mean departure of these unit areas from the level of complete compensation being stated by him as ranging from 250 to 570 ft. These figures he does not regard, however, as of a high order of accuracy, the latter being probably the more reliable of the two. He states that their significance is mainly in showing that isostatic compensation is nearly perfect. It has even been argued by Dutton, Willis, and Hayford, as an outflow of geodetic studies, that those vertical movements of the outer crust which tend to give isostatic equilibrium are the ultimate causes of the periodic great compressive movements.

There is here between geologists and geodesists a tendency to a fundamental difference of opinion, resulting from the emphasis upon one or the other of those opposing forces which work in the outer crust. The truth must lie within the broad zone between these two extremes of theory. To try to bring them together in harmony is the problem before us.

The first part of the paper, on the geologic tests of the limits of strength, opens with a brief review of the lines of geologic evidence which may be used as tests of the degree of resistance or response by the crust to vertical stresses, having regard to both area and intensity. Deltas built into deep seas seem best adapted to give quantitative measurements. Those of the Nile and the Niger therefore are subjected to detailed study. They indicate that the earth is competent over those regions to sustain stresses due to sedimentation which are measured by the weight of several thousand feet of rock, even where the load is continuous over tens of thousands of square miles. Whatever response there may be is so slow that the deposition is able to keep pace with subsidence and maintain the load as a permanent stress of this magnitude upon the crust. By analogy the conclusion may be applied to other parts of the earth, and to those negative loads created by the erosion to base-level of regions previously unwarped to an elevation presumably near to that which would give isostatic equilibrium. Consequently, also, the crust should be able to bear in considerable degree the folded and overthrusted structures piled up by the tangentially compressive forces which periodically operate to such large degree within its outer shell. Deeper changes, involving changes of density, are involved, however, in orogenic processes and express themselves in vertical warpings associated with, and following after, folding. This association of vertical and tangential forces complicates the problem of the crustal strength needed to support mountain ranges.

The measures derived from the study of deltas are more in accord with those larger estimates of the strength of the crust obtained by Putnam and Gilbert in 1895 from a transcontinental series of gravity measurements in which was developed and employed for the first time the conception of local rigidity but regional isostasy.[1] Their conclusions have been thought to be superseded and controverted, however, by much more elaborate and complete geodetic studies, first by Hayford, and later by Hayford and Bowie, which went to show that the crust was very much weaker and in much more perfect static equilibrium.

The calculations of Hoskins tended to show also that the crust within the zone of isostatic compensation could not bear permanently loads as great as those apparently imposed by these deltas. If, however, the great hydrostatic pressures within the deeper crust

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[1] *Bull. Phil. Soc. Wash.*, XIII (1895), 31–75; *Jour. Geol.*, III (1895), 331–34.

give to it an added resistance to stress differences as great as indicated by the experiments of Adams, then the strains imposed by the deltas may be permanently borne.

This confrontation of the conclusions drawn from various paths of approach raises the problems which are treated in the second part.

MOUNTAINS BUILT BY COMPRESSION OR IGNEOUS ACTIVITY

Mountain ranges made by folding or extravasation must be independent to some degree from vertical forces, but these are not suitable geologic tests of the rigidity of the crust, since it is known, as noted in the introduction, that they are secondarily connected with diminutions of density in the zone of isostatic compensation and in many cases are rejuvenated after partial erosion by later upwarping.

The individual mountains or plateau remnants left standing by circumdenudation, or piled up as volcanic cones are clearly burdens upon the earth. The volume which rises above the average level is a measure of the stress. Gilbert has so used them and obtained values ranging from 40 to 700 cubic miles.[1] These volumes, however, might be called minimum estimates, as may be seen upon examination of their nature.

If a certain broad upwarping reduces the vertical stresses to a minimum and erosion follows without further adjustment, it is the volume of the valleys rather than the mountains which soon comes to measure the larger possible departures from equilibrium. The remaining mountains by their weight produce local downward stresses, but the more regional stresses are upward and are due to the breadth of the field of erosion. These regional stresses will become larger ultimately than the local stresses due to the residual masses.

Volcanic cones do not continue to be built up until their base begins to sink into the crust as fast as the upward growth takes place. On the contrary, their growth ceases when the hydrostatic pressure of the high column of lava or a decadence of pressure in the reservoir below leads finally to a shifting of the vents.

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[1] "The Strength of the Earth's Crust," *Bull. Geol. Soc. Am.* (1889), I, 25.

Regional igneous activity has poured out lavas and breccias, burying previous mountainous topography and adding thousands of feet to the outer crust. Lack of simultaneous erosion, as in the Miocene flows of the Columbia plateau, shows that subsidence progressed, perhaps with approximately equal pace. The present altitude of the Columbia plateau is youthful, as shown by the steep canyon walls and undissected interfluvial areas. The initial subsidence accompanying igneous outpouring and the distinctly later upwarping without compression suggest that here isostasy has prevailed. But in such regions the geologic evidence points toward a minimum strength of the crust. The wide area of activity, the numerous vents, the general absence of localization, all are suggestive of widespread fluid rock beneath, magmas which are probably far above the level where the accompanying temperatures are normal. Such conditions would seem to imply the impossibility of the outer crust carrying over such regions the stresses which are possible in regions long free from igneous activity. More reliance as maximum measures of the strength of the crust should be placed therefore upon those external changes which are entirely independent in origin from the interior of the earth locally beneath them.

SHIFTINGS OF LOAD DUE TO CLIMATIC CHANGE

Some of the most striking examples of loading and unloading of the crust are those connected with the climatic fluctuations of the Pleistocene. The continental ice sheet formed, advanced, and retreated rather rapidly, as viewed from the geologic standpoint. As it retreated, the lacustrine and estuarine shores show that the land was rising with the melting of the ice. The upwarping accompanying deglaciation was limited to the approximate region of maximum glaciation and was greatest in the direction where the ice was thickest, in the St. Lawrence valley the maximum uplift being more than 600 ft. These relations suggest strongly an isostatic response to the relief of load. It is not known, however, to what degree the previous downwarp compensated for the burden of the continental ice sheet and what degree of regional stress the crust was able to bear. The lack of close response is seen in that the upwarp continued as a residual movement after the ice departed.

The movement of the crust could not keep pace with the climatic change but it shows by means of these fossil water planes its incompetency to bear without at least partial yielding a burden as broad and as heavy as the Pleistocene climates placed upon it.

Gilbert, in 1889, was led by reflection upon the changes of load imposed by the waters of extinct Lake Bonneville to use them as a measure of the strength of the earth's crust to resist isostatic adjustments,[1] and as previously stated, tested the conclusions drawn therefrom by comparisons with the volumes of mountains made by extravasation, or circumdenudation, or their combination, and of valleys of erosion. Of Lake Bonneville he states:

> Considering the main body of Lake Bonneville, it appears from a study of the shorelines that the removal of the water was accompanied, or accompanied and followed, by the uprising of the central part of the basin. The coincidence of the phenomena may have been fortuitous, or the unloading may have been the cause of the uprising. Postulating the causal relation, and assuming that isostatic equilibrium, disturbed by the removal of the water, was restored by viscous flow of crust matter, then it appears (from observational data) that the flow was not quantitatively sufficient to satisfy the stresses created by the unloading. A stress residium was left to be taken up by rigidity, and the measure of this residuum is equivalent to the weight of from 400 to 600 cubic miles of rock.
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> From these phenomena and theoretic considerations arises the working hypothesis that the measure of the strength of the crust is a prominence or a concavity about 600 cubic miles in volume.

THE EVIDENCE FROM EROSION CYCLES

Erosion base-levels folded and uplifted tracts, leaving for a time during the process mountains of circumdenudation whose local stresses have previously been discussed. The development of peneplains implies a rigidity of the crust sufficient to prevent responsive vertical movement until after the completion of the cycle of denudation. It may be difficult to determine the original average elevation and the degree of progressive uplift *pari passu* with erosion which preceded the peneplanation, but the fact that broad areas become flat and are controlled until the next deformative movement by the level of the sea suggests that they cannot

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[1] *Bull. Geol. Soc. Am.*, I (1889), 23–27.

lie after erosion in close isostatic equilibrium; that whatever stress this implies can be carried by the earth for long periods of time.

The ancient peneplains are now broadly warped and uplifted. The rivers, as a rule, are intrenched in youthful valleys; or their seaward courses are drowned and not yet reclaimed by delta building. These features testify to the recency of world-wide crustal unrest, marked chiefly by movements of a vertical nature; movements which presumably diminished the vertical stresses in the outer portions of the earth and has produced at the present time, as Willis has argued, a higher degree of isostatic compensation than has been customary through the long periods of quiet which separate the epochs of movement.

There are difficulties, however, in using ancient base-leveled surfaces now upwarped as measures of the previous stress. It is known that a region like the Colorado plateaus which now stand markedly high tended to lie near sea-level from the beginning of the Paleozoic to the end of the Mesozoic. Presumably a decrease of density within the zone of isostatic compensation has taken place here during the Cenozoic and the uplift has accompanied or followed the internal change.

Furthermore, if there are stages in the uplift, a considerable volume of rock is removed during each stage, so that at no one time has the average elevation of the region been as high as the residual masses might be thought to imply. Allowing for these qualifications, however, there seems no doubt that the study of erosion cycles will throw light upon the limits of stress due to unloading which the crust can resist, and also upon progressive changes in subcrustal densities through geologic times. This evidence of considerable crusted rigidity, shown by freedom from compensating movements during a cycle of erosion, or by warpings not in sympathy with isostatic stresses during cycles of crust movements, has been pointed out before. Hayford has sought to explain it away by invoking, first, the slight crustal cooling which would occur in regions of erosion because of removal of the upper rock, heating in regions of deposition. Second, he assumes as probable the existence of a high coefficient of compressibility sufficient to make eroded regions rise in appreciable ratio to the thickness of the load eroded. Third, he assumes a crustal undertow from heavy toward high areas which would not only fold the surface rocks and heat them in the region of undertow but restore the equilibrium of mass in the regions of erosion and deposition.[1] It may be said of all of these factors that when they are subjected to quantitative statement they appear so trifling as to fail wholly to explain the magnitude and breadth and periodicity of crust movements. The inadequacy of the temperature effects has been pointed out clearly by Harmon Lewis.[2] The assumption of the high coefficient of compressibility involves more instead of less difficulty for the high isostasist. The inadequacy of isostatic undertow to account for folding has been discussed briefly by the present writer elsewhere.[3] On the other hand, the control of the level of the earth's surface during epochs of quiet by the forces of planation and not by forces making for close isostatic adjustment has been discussed convincingly by Chamberlin in his present series of articles. It seems clear, then, that in the study of cycles of erosion and deposition much may be determined in regard to the limits of terrestrial rigidity. The subject could be developed further, but it is preferred to place the emphasis of this paper upon the more readily estimated loads produced by the building of deltas.

THE EVIDENCE FROM DEPOSITION

Preliminary statement.—The waters deposit sediment upon the depressed areas of the crust. To what extent may such areas be loaded before yielding of the base and resultant subsidence take place? The geologic record makes it clear that subsidence and deposition are necessarily related. It has been stated often that deposition was the cause and subsidence the effect, the two being regarded as in delicate isostatic adjustment. But this is in reality an assumption, for such a supposed relationship overlooks the extent to which subsidence might have gone forward without deposition and ignores the external load which may have been necessary to

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[1] "The Relations of Isostasy to Geodesy, Geophysics, and Geology," *Science*, N.S., XXXIII (1911), 199–208.

[2] "The Theory of Isostasy," *Jour. Geol.*, XIX (1911), 622, 623.

[3] Joseph Barrell, *Science*, N.S., XXIX (1909), 259, 260.

perpetuate and add to a crust movement initiated by internal causes. Sedimentation is dependent upon the rate and continuity of subsidence as well as upon the rate of deposition. Thus, although the sediments give the most complete record of crustal movements, for the distant past it is not easy to separate cause and effect and ascribe to each its part. Where the thickness of sediments, however, is small, as over much of the continental interior, the cause of submergence is presumably almost wholly independent of the local load. Where the sediments are thick and subsidence rapid, as within the geosynclines, the load imposed by sedimentation may on the contrary become the controlling force. It is a particular phase of deposition, however, which will be considered in this article, a study of the load imposed upon the crust by certain deltas. As long as the water plane lies at a constant level the delta builds out at its front. Upon subsidence of the supporting crust the shore retreats inland; less sediment reaches the now submerged front, and the delta in consequence grows chiefly by additions to the shoreward part of its upper surface. The two methods of growth not uncommonly alternate upon the same delta, showing the discontinuity of subsidence. In building outward a delta acquires a convex shoreline. This form is clearly related to aggradation, not to isostatic uplift, and its volume is a measure of a load inclined to further sinking, the larger rivers tending to drain toward and into the downwarps of a continent. To what degree, then, can a region of the crust which is possibly already resisting downward strain bear this added burden? A preliminary examination will be made of several classes of deltas in order to choose those best adapted to test this question.

Most of the deltas of Eurasia and South America are at present advancing rapidly into shallow embayments and the faunas of the continental islands show that the latter were recently a part of the land. The physical and organic evidence thus concur in showing that a very recent subsidence has taken place. It is to be concluded that a submergent phase in the Cenozoic crustal oscillations has marked the short interval since the last retreat of the Pleistocene ice. The great deltas constructed during the late Tertiary and in the Pleistocene are consequently now in great part drowned.

Their location, volume, and limits in most cases are not known. Their modern and smaller representatives, as they build out into shallow water, do not greatly increase the load upon the crust. Deltas recently drowned are therefore not well adapted to serve as tests of the strength of the crust.

Deltas which lie in re-entrant angles of the continents are also poorly adapted to be used as a test. Those of the Indus, the Ganges, and the Colorado are illustrations. As they fill up the heads of gulfs and are without the typical convex outline, it is not only difficult to compute their volume but their situation is such as to suggest that even without the construction of the delta the region might be far out of isostatic adjustment.

Certain rivers, which face the open ocean, such as the Columbia, do not build deltas because of the power of the waves and currents which sweep laterally the fine detritus.

Many rivers, however, build considerable submarine deltas even where the in-planing forces of the ocean prevent a terrestrial outward growth. Such submarine deltas, owing probably to the power of the waves rather than to recent submergence, are marked by convexities in the bathymetric contours opposite the river mouths. The Congo, the Orange, and the Zambesi are examples. These hidden deltas which are built out into deep waters cannot reach more than a certain distance from the shore and part of their detritus is carried laterally along shore by the waves, but nevertheless they possess a very considerable volume and the convexity which they make upon the ocean floor shows to that degree the rigidity of the crust.

The maximum test is found where great rivers have carried forward subaerial topset beds of their deltas over what was previously deep ocean. Fluviatile construction in such examples has dominated over marine destruction, giving a convex outline to the shore; but the subaqueous deposits may still make up the greater part of the volume. Even in these cases the question may be raised whether the deltas have attained the maximum possible size permitted by the strength of the crust. Their size may, on the contrary, be limited even here by the balance of the surface agencies and the limited time during which the river has dominated over the sea. It is a fair presumption, however, that the largest deltas have reached a size where subsidence keeps pace with added volume.

The deltas of the Nile and Niger.—Only the most powerful rivers, laden with abundant waste and protected by their situation from the heavier wave and current action, can build deltas of this last class directly into ocean basins. Perhaps the two best of the few good examples are those of the Nile and the Niger. Both have built out great deltas from regularly curving shores of the Atlantic type—the type where recent folded mountains do not mark the line between continent and ocean, the type where tangential forces cannot be supposed to have disturbed recently the isostatic balance of continent and ocean.

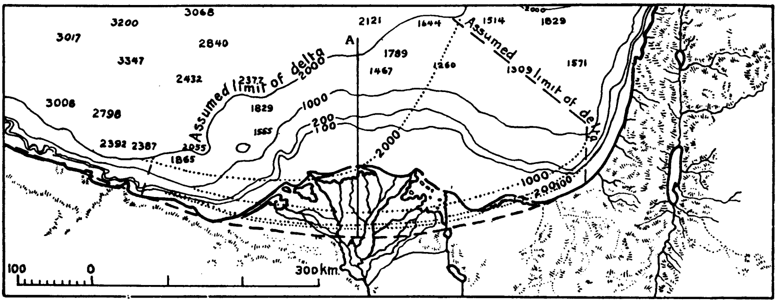

FIG. 1.—Delta of the Nile. Scale 1: 10,000,000. From Andree's *Allgemeiner Handatlas*, vierte Auflage.

To determine the areas, depths, and volumes of the deltas from the standpoint of isostasy, a smooth curve, as shown in Figs. 1 and 3, was continued through them from the shore beyond. The submarine contours were also projected in dotted lines, giving the form of the bottom as it presumably would now be if no rivers at these places had entered the sea. The volume of the deltas may then be determined by computing the volume included between these two sets of contour lines.

In both cases, in so far as the positions of the hypothetical bottom contours are open to doubt, they have been located somewhat above a most probable position, so as to tend to throw the error of computation in the direction of too small rather than too large a volume. For instance, the easterly drift of the water facing the Nile delta may have carried considerable mud in suspension to beyond the line assumed here as its limits. In consequence, the hypothetical 2,000-meter contour should be drawn perhaps much closer to the coast of Palestine than has been done. Beneath the Niger delta the contours lie close together on the west but have been drawn as spreading apart toward the east. It would perhaps be nearer the truth to project the steep character of the coastal slopes to the east of the Niger delta under it to where the contours meet the chain of volcanic island mountains extending from the Cameroons out to sea. This appears to be especially probable, since Buchanan has shown that the gentle slopes of the Guinea coast even beyond the limits of the deltas, and extending from long. 2°30′ E. to lat. 8° S., are mantled throughout by very soft, black, oozy mud, characteristic of river estuaries.

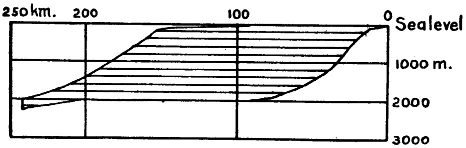

FIG. 2.—Vertical section of the delta of the Nile on *A-A*, Fig. 1. Horizontal scale 1: 5,000,000. Vertical scale 1:200,000. Area of section, 295 kilometers.

All the way down the coast as far as Loanda, lat. 8° S., the same gentle gradients and the same very soft river mud were found. It appears that the land dêbris brought down by the Niger and Congo, and by other less important rivers, is collected and concentrated in this district. The prevailing current past the mouth of the Congo is a northerly one, while all along the coast from Cape Palmas to the Niger an easterly current sets. These help to confine the drainage matter of both rivers to a comparatively small extent of littoral. If from the soundings west of Cape St. Paul we compute the mean continental slope, we find that the 500-fathom line is at a mean distance of 4.1 miles, the 1,000-fathom line at 11.7 miles, and the 1,500-fathom line at a distance of 17 miles from the 100-fathom line. If it is assumed that in the absence of the Niger and the Congo the continental slope would be much the same as the average found in the profiles west of Cape St. Paul, it may be concluded that the excess of mud forming the flatter talus along the coasts affected by these rivers is due to the mud brought down by them.[1]

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[1] J. Y. Buchanan, "On the Land Slopes Separating Continents and Ocean Basins, Especially Those on the West Coast of Africa," *Scottish Geographical Magazine*, May, 1887, pp. 7, 8.

Buchanan states that this gentle bottom slope extends for 1,100 miles along the coast, and computes the volume contained between the steep gradient presumably once existing and the flatter gradient of the present bottom. This represents a deposit of 66,000 cubic nautical miles of detritus due principally to the Niger and the Congo.[1] This great volume cannot be used safely, however, as the measure of a load upon the crust, since a believer in the theory of close isostatic compensation could claim with some degree of reason that the initial slope of the concave shores of the Gulf of Guinea need not have been as steep as the bold convexity of Africa to the west, or that the load may have depressed the bottom so as to have equalized the pressures. Furthermore, Buchanan does not include any of the land area of the Niger delta. The following estimates will give the volume only of the clearly constructional part of the Niger delta, including both the land and

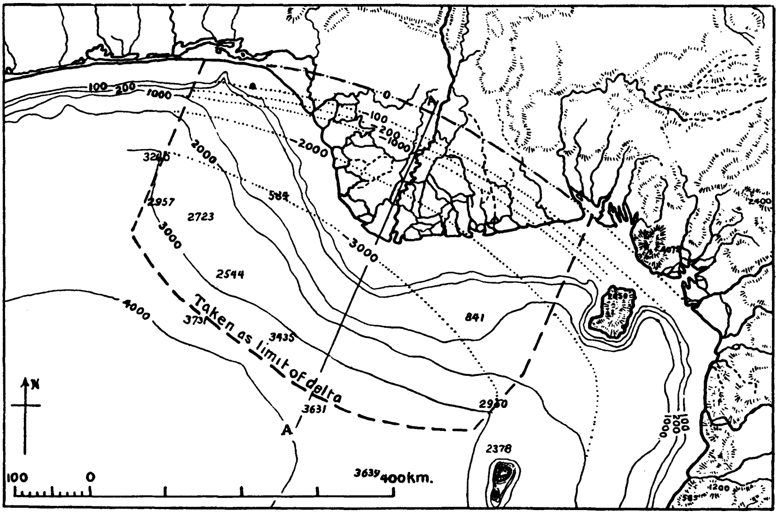

FIG. 3.—Delta of the Niger. Scale 1:10,000,000. From Andree's *Allgemeiner Handatlas*, vierte Auflage.

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[1] *Op. cit.*, p. 8 and Fig. 3. The volume stated by Buchanan appears to be correct if the two profiles have a common point taken upon the *shoreline*. In his figure, however, the common point A is shown as upon the 100-fathom contour. From this error in the diagram given by Buchanan the volume estimated from the diagram would be much less than 66,000 cubic nautical miles.

the sea portion. But it will be seen, from Buchanan's statements, that this is a minimum estimate of the areal load imposed by the rivers, for a more or less continuous burden on the crust would appear to stretch for a thousand miles along this African coast, reaching a maximum unit value, however, in the great delta of the Niger.

The outer limits of the deltas were taken where the convex slopes fade out into the general ocean bottom.

The results of computing the volumes shown between the two sets of contour lines are as follows:

TABLE I

DELTA OF THE NILE

Area within 1,000-m. contour	71,000 sq. km. (27,400 sq. mi.)
Area within 2,000-m. contour	106,000 sq. km. (38,800 sq. mi.)
Radius of equivalent circle	175 km. (110 mi.)
Equivalence in equatorial square degrees	8.6 sq. degr.
Average thickness within assumed limits	0.84 km. (2,800 ft.)
Equivalence in rock upon land	0.46 km. (1,540 ft.)
Ratio to 76 miles of crust	1 to 260=0.0038
Maximum thickness	2.0–2.3 km. (6,600–7,600 ft.)
Equivalence in rock upon land	1.1–1.3 km. (3,600–4,200 ft.)
Volume within assumed limits (extending on the east to somewhat below 2,000 m.)	89,000 cu. km. (21,300 cu. mi)
Equivalence in rock upon land	50,000 cu. km. (11,700 cu. mi.)

TABLE II

DELTA OF THE NIGER

Area within the assumed limits	195,000 sq. km. (75,300 sq. mi.)
Radius of equivalent circle	250 km. (155 mi.)
Equivalence in equatorial square degrees	15.8 sq. degr.
Average thickness within assumed limits	1.1 km. (3,600 ft.)
Equivalence in rock upon land	0.6 km. (1,980 ft.)
Ratio to 76 miles of crust	1 to 200=.005
Maximum thickness	3.0 km. (9,900 ft.)
Equivalence in rock upon land	1.65 km. (5,450 ft.)
Volume within assumed limits	217,000 cu. km. (52,000 cu. mi.)
Equivalence in rock upon land	120,000 cu. km. (27,000 cu. mi.)

The deltas in their growth had displaced their volume of water. The added loads which they throw upon the crust are measured by subtracting the weight of the water from that of the sediments. A specific gavity of 2.67 has been taken by geodesists as the average for the outer shell of the earth. The degree of consolidation of the deeper parts of the deltas is not known, but for present purposes the specific gravity of their sediments as a whole may be assumed as 2.50. This will be near the truth if the composition is that of the average shale, if 10 per cent of pore space be assumed and this is wholly filled with water. The specific gravity of sea water is 1.03, leaving an effective specific gravity for the sediments of 1.47. The ratio of 1.47 to 2.67 is 0.55. The thicknesses given for the deltas should therefore be multipled by this factor for estimating the equivalent burdens of rock of specific gravity of 2.67 above sea-level.

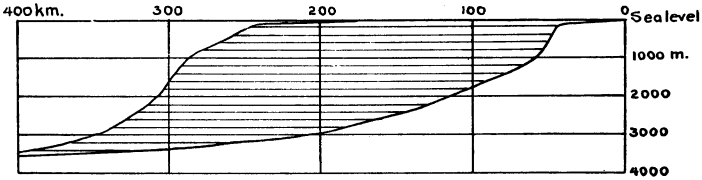

FIG. 4.—Vertical section of the delta of the Niger on *A–A*, Fig. 3. Horizontal scale 1:5,000,000. Vertical scale 1:200,000. Area of the section, 645 kilometers.

It is seen that the deltas are in the form of inclined double convex lenses. Thicknesses approaching the maximum are found over considerable areas in the middle. The load imposed by this thickness is equivalent in the Nile delta to 3,600–4,200 ft. of rock above sea-level; in the Niger delta to 5,000–5,500 ft.

Discussion of results.—The region of the southeastern Mediterranean is held by Suess to be geologically of very recent origin, downfaulted from the continent. The delta of the Nile, much smaller than that of the Niger, is therefore to be regarded as young and may be still increasing in volume.

The great size of the Niger delta suggests, on the other hand, that it may have reached the limit permitted by the strength of the crust. Subsidence may now intermittently keep pace with deposit. If the 1,000-meter contour has been located correctly, as shown in Fig. 3, it suggests that such may be the case, since it is seen that in contrast to the Nile delta the slopes are much steeper between the 1,000- to 2,000-meter than between the 200- to 1,000-meter contours. This can be explained by assuming that the steep slope lying below and beyond a flatter slope was once a foreset slope just below wave base, whereas it now lies at least 800 meters below. If such a subsidence has occurred, it appears, however, to have been confined to within the limits of the delta; since a peripheral overdeepening of the ocean floor is not evident. On the other hand, it is noted by Penck, but probably too sweepingly, that all bathymetric curves have their steepest slopes between 1,000 and 2,000 meters in depth.[1] Such a phenomenon might be due to lateral flow of sediment under a certain depth of load and without relation to subsidence of the base. The question whether the load of the Niger delta is as great as the crust can bear is therefore an open one.

The Gulf of Guinea, where now the delta is built, is regarded by many geologists as having originated since the Middle Mesozoic by a breaking-down from the continent of Gondwana, but the presence of Middle Cretaceous marine beds skirting much of the coast of West Africa suggests perhaps that the delta in its construction does not go back of the Tertiary. In fact it would seem possible from the youthful relief of the continental plateau that the delta built from its waste is of Upper Tertiary and Pleistocene growth.

A single delta might happen to be a mere veneer of sediment upon an originally slightly submerged projecting part of the coast. Such a fortuitous coincidence of unrelated circumstances may, however, be dismissed as highly improbable in the case of two great rivers draining in opposite directions from the same continent. The conclusion that these deltas are really externally constructive features and measure a real strain upon the crust is strengthened by noting the submarine deltas opposite the other great rivers of Africa, built into the ocean, even though the waves and currents have limited them by preventing their subaerial seaward growth.

In the mechanics of the relation of the delta to the stresses in the crust an important factor is the nature of the marginal land. Shores of the Pacific type have great mountain systems marginal

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[1] *Morphologie der Erdoberfläche*, I (1894), 146.

to the continents. Parallel to them the sea has great fore-deeps. It appears as though the mountain ranges had been piled too high by tangential forces, and, by virtue of the partial rigidity of the crust, had depressed the neighboring ocean bottoms. Erosion of the coastal mountains and deposition of their waste in the fore-deep would tend, up to a certain limit, to equalize the strain in the crust. In that case it might happen that, although the mass of the delta measures a stress, this might be opposite in character to pre-existing stresses, with the result that the strain upon the crust beneath the delta before the infilling might be as great or greater, but in an opposite direction. The greatest remaining strain within the sea-bottom could conceivably be an upward strain under the parts of the fore-deep not filled.

Such relations are not found around abyssal slopes of the Atlantic type. These are regarded by many geologists following the lead of Suess as made by marginal downbreaking of the continents. They have but little or no relation to the older folded structures and no excessive deeps parallel to the continental margins. If these relations of the Atlantic and Indian oceans to the continents are rightly interpreted as to cause, it is probable that the stresses which make for downsinking extend beyond the parts already foundered. The margin of continents and ocean basins are not likely to be depressed too low, but if remaining out of isostatic adjustment they would tend rather to stand too high. There is no theoretic reason to believe, therefore, that the Nile and Niger deltas have neutralized pre-existing strains. They are best regarded as real and present burdens sustained by the rigidity of the crust.

Whether or not, however, the building of deltas produced stresses of a character identical with, or opposite to, those previously existing in the region, the stress gradient between the areas of the delta and the surrounding areas would be measured by the weight of the sediments, and this would tend to produce differential flexure. It would seem to be a logical conclusion, therefore, from these tests, that certain parts of the earth's outer crust can resist for considerable periods of time vertical stresses at least equivalent to the weight in air of 10,000–25,000 cubic miles of rock in lenslike forms spread over areas of 40,000–75,000 square miles and reaching thicknesses in air over considerable areas of 4,000–5,000 feet.

The tabulation of the data regarding the deltas shows the area of the Niger delta to be equivalent to a circle 310 miles in diameter and that over this area the load of the delta is one two-hundredths the weight of the crust to a depth of 76 miles, this being the depth of the zone of isostatic compensation given by the latest determination of Hayford.

According to Hoskins, in a calculation made for Chamberlin and Salisbury,[1]

> a dome corresponding perfectly to the sphericity of the earth and formed of firm crystalline rock of the high crushing strength of 25,000 pounds to the square inch, and having a weight of 180 pounds to the cubic foot, would, if unsupported below, sustain only $\frac{1}{525}$ of its own weight. This result is essentially independent of the extent of the dome, and also its thickness, provided the former is continental and the latter does not exceed a small fraction of the earth's radius.

The delta, though large, is so limited in size in comparison with continental areas that it would be somewhat more effectively supported, but its externally convex form can hardly be supposed to give it added domal strength, since it consists of more or less unconsolidated material piled upon a concave floor.

The theory of isostasy holds that at a certain depth in the crust there is an approach to equal pressures, the larger relief of the surface being balanced in large part by subsurface variations in density. The larger segments of the crust tend to rise or sink until the elevations are in adjustment to the density beneath. A corollary of this theory is that unbalanced surface loads are largely sustained by the strength of the crust above this level of equal pressures; in other words, but little of the load is transmitted to the deeper earth below. For purposes of discussion it may then be assumed that the load of the Niger delta is supported by the outer 76 miles of crust. This depth is one-fourth of the diameter of the circle equivalent in area to the delta. The load over this area, as stated, is one two-hundredths of the weight of the supporting crust. Allowing something for the limited area of the delta, it is seen never-

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[1] *Geology*, I, 555, 1904.

theless to imply a strength of the crust about twice that assumed as a maximum by Hoskins as a basis for his calculation. There are several contributing factors which may explain the disagreement between the figures obtained by observation of the deltas and the calculation given by Hoskins and others: First, part of the stress is transmitted laterally to some extent into the deeper layers, but as the diameter of the loaded area is four times its depth this can be a partial explanation only and has, furthermore, been allowed for. Second, part of the stress may be transmitted into the deeper earth below the 76-mile zone of isostatic compensation. This is about equivalent to third, that the zone of isostatic compensation may extend deeper, at least locally, and fade out more after the suggestion made by Chamberlin.[1] Fourth, a consideration which the writer regards as most important is that the crust may in reality possess greater crushing strength than the 25,000 pounds per inch postulated by Hoskins. At the time that Hoskins made this calculation it seemed that this figure was the highest which could be chosen, since it is higher in fact than the crushing strength of the average surface rock when subjected for even a short time to compression in a testing machine, and in the earth the stresses must be carried for indefinite periods. The experiments by Adams[2] have shown, however, that under the conditions of cubic compression which exist in the earth the rocks are capable of sustaining for indefinite times far higher stress differences than they could bear even for a short time when subjected to stress in one direction only, as at the surface of the earth. These experiments showed that:

> At ordinary temperatures but under the conditions of hydrostatic pressure or cubic compression which exist within the earth's crust, granite will sustain a load of nearly 100 tons to the square inch, that is to say, a load rather more than seven times as great as that which will crush it at the surface of the earth under the conditions of the usual laboratory test.
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> Under the conditions of pressure and temperature which are believed to obtain within the earth's crust empty cavities may exist in granite to a depth of at least 11 miles.[3]

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[1] *Jour. Geol.*, XV (1907), 76.

[2] "An Experimental Contribution to the Question of the Depth of the Zone of Flow in the Earth's Crust," *Jour. Geol.*, XX (1902), 97–118.

[3] *Op. cit.*, p. 117.

It appears then that, even allowing for the great increase in temperature within the earth's crust at depths greater than can be reached by the limitations of experiment, the demands made upon the strength of the crust by the load of the Niger delta are not greater than can be explained by the theory of the mechanics of materials as now understood. This theory rests, however, even after Adams' experiments, upon only a limited range of laboratory observation, and extending over but limited periods only, thus demanding extrapolation both of stress and of time when applied to the whole thickness of the outer crust and over hundreds of thousands of years. Therefore the study of the direct evidence supplied by geologic observation is more convincing in regard to the limits of crustal strength.

These deltas point toward a measure of crustal rigidity capable of sustaining to a large degree the downward strains due to the piling-up and overthrusting of mountains built by tangential forces, or those resulting from the load of sediments in areas of deposition, or those upward strains produced by the erosion of plateaus previously uplifted toward isostatic equilibrium. A final conclusion must, however, await a further discussion in the later parts.

[*To be continued*]