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ZONES OF WEAKNESS IN THE EARTH'S CRUST

By Dr. WILLIAM BOWIE

U. S. COAST AND GEODETIC SURVEY

The advocates of the theory that the great deformations in the earth's crust have been caused by a cooling of the interior of the earth and the collapse of the crust to fit the reduced area of the surface of the nucleus have, in general, accepted isostasy as a scientific principle. They, however, seem to need zones of weakness within which uplift occurs in order to permit the crust to fit the shrinking nucleus. They also are of the opinion that the Airy idea of isostasy is the true one.

I am writing this paper in order to call attention to the idea that the areas which have been receiving vast amounts of sediments, possibly to depths of five or more miles, should not be the zones of greatest weakness in the earth's crust.

The heavy beds of sediments are laid down, in general, along margins of oceans or inland seas. At least this is the generally expressed opinion of the leading writers of geological literature. It has been shown in "Isostasy"[1] and in a number of publications of the Coast and Geodetic Survey that areas of heavy sedimentation are not out of equilibrium. It is evident, therefore, that the weight of the sediments pushes down the crust beneath. The lower part of the crust necessarily enters subcrustal space and there is a horizontal movement of the displaced subcrustal material in a direction towards the area from which the sediments were derived. The volume of subcrustal material displaced will not be as great as the volume of the sediments. This is because the upper part of the subcrustal material must be of greater density than that of the sediments. Of course, the unconsolidated sediments have very light density, probably not more than 2.4. It may be that the density is 2.2. When these sediments are consolidated, the density will probably rise somewhat over

[1] E. P. Dutton and Co., New York, 1927. Spec. Pubs. 40, 99, and Serial 366, U. S. Coast and Geodetic Survey.

2.5. Let us assume that the average density of the sedimentary material to a depth of 5 miles is 2.6 and that the density of the subcrustal material is 3.1. Then there will have been a thickness of subcrustal material pushed aside of 4.2 miles as a result of the deposition of 5 miles of sediments.

It is probable that the crust underlying the sediments will have been strengthened by an amount equal to the strength of the sedimentary beds or for a time, at least, this would be the case. It is only when the crustal matter which is pushed down into subcrustal space by the weight of the sediments takes on the temperature that is incident to the new zone it occupies that this crustal matter will have the physical characteristics of subcrustal material.

The term residual rigidity is frequently used in discussing earth problems. A material that is said to have residual rigidity is supposed to resist deformation unless the force exerted on it approaches the elastic limit of the material. In this sense the residual rigidity is equivalent to the term strength. A material lacking in this quality is assumed to change form even though the force exerted on it may be very small, provided it acts for a sufficiently long time.

That there is an outer strong shell of the earth seems to be certain. This shell or crust is composed of rock widely varying in density which has residual rigidity and can, therefore, withstand the stress differences incident to great differences in the elevation of contiguous parts of the earth's surface. Under the Himalayas, for instance, we have material that must be approximately 5 per cent. lighter than normal, while, in the Indo-Gangetic plain, a comparatively short distance south of the Himalayas, the crustal density may be assumed to be normal. We, therefore, have a column sixty miles in length under the Indo-Gangetic plain while under the Himalayas the length of the column would be approximately sixty-three miles. The mass of material in each column is the same, therefore throughout the crust there is a stress difference exerted in the direction from the Himalayas towards the plain. If the crustal material had no residual rigidity, there would be a slumping down of the prism of the earth under the Himalayas but this has not occurred in the past nor is it probable that it is occurring now. It would seem, from the above, that the physical characteristics of the crustal material are different from those of the material just below the crust. In the lower material there is practically no residual rigidity. If this were not so, then isostatic equilibrium could not be restored after it had been disturbed by erosion and sedimentation.

It would seem probable that the strength of the crust under the sedimentary zone should have been augmented rather than decreased by the consolidated sedimentary material. This statement is based on the assumption, which may or may not be true, that the increase in the temperature of the crustal material that has entered subcrustal space does not occur immediately upon the subsidence. There must be a lag in time.

If there are any weak zones of the earth's crust it would seem that they underlie the regions which have undergone very great erosion. Take, for instance, the Himalayan mountains. They have an average elevation of between two and three miles. Great masses of material have already been eroded from these mountains and enormous amounts must be eroded in the future prior to the base leveling of their area. If we assume that the average density of the material of the Himalayas from the surface to a depth of about five miles below the surface is 2.8 and that the density of the upper part of the subcrustal material is 3.1, we have a difference in density of 0.3. The difference is approximately 10 per cent.

Since isostatic equilibrium is maintained, or at least nearly so, we should have an upward movement of the crust below of about nine hundred feet when one thousand feet of material had been carried away from the surface. If the average elevation of the Himalayas is only two miles, it would seem that we should have to have approximately twenty miles of erosion before the area had been base leveled. This would mean that about eighteen miles of subcrustal material would have to enter crustal space in order to maintain equilibrium. This amount of erosion may be excessive. If so, it is because the difference between upper crustal density and upper subcrustal density is greater than 10 per cent. If we assume that the difference is 20 per cent., we should then require an erosion equivalent to ten miles of material from the Himalayan mountains to base level the area, if no other processes are involved in base leveling. If ten miles were removed from the Himalayan region, eight miles of subcrustal material would have to rise into crustal space to maintain the isostatic equilibrium.

If no cooling of the subcrustal material, which has entered crustal space, should occur prior to base leveling, then this subcrustal material would have no residual rigidity or strength. The portion of the crust under the base-leveled area would then be only about fifty-two miles thick. This contrasts with sixty-four miles, the thickness of the crust under the area of sedimentation. The added thickness here is due to the beds of new sedimentary material assumed to be five miles thick.

As soon as the subcrustal material which had moved upward had taken on a temperature normal to its new position it should have the characteristics of crustal matter and be able to offer resistance to stress differences; in other words, the depth of the strong material would then be normal, or sixty miles.

If the buckling of the earth's crust should occur during or just after the end of the base leveling activity, then surely the weak areas would be where the great erosion had taken place and, therefore, we should expect the crust under the erosion areas to bulge up. This would add to the height of the material that may exist above sea-level at the time. It would certainly seem improbable that the crust under the sedimentary, rather than the erosion, area would be pushed up by the contraction of the nucleus and the collapse of the crust.

Professor Gutenberg has estimated that the contraction of the earth, due to loss of heat, is equivalent to the shortening of the circumference of the earth at the rate of one or two centimeters per century. He stated, in a lecture recently given in Washington, D. C., that, in his opinion, the forces due to the contraction are accumulated in the crust till such time as they may be so great as to overcome the strength of crustal material. If, however, there is an accumulation of stresses in the crust rather than a continuous yielding of the crust due to the assumed shrinking of the nucleus, then we should have to postulate that there must be a void existing between the crust and the nucleus. This we may be sure can not be true. It is extremely doubtful that any void can exist in the earth at a depth as great as sixty miles.

It seems to me that the advocates of the contraction hypothesis have assumed that the interior of the earth is losing heat while the crust is maintaining its temperature. This assumption was advanced originally in order to give some rational explanation of the observed horizontal movements of strata. With the proof of isostasy it would seem most improbable that the contraction hypothesis is correct, for there are many points of weakness in it or, at least, there are points of weakness in the explanation of the processes which are involved in the changes of elevation of the earth's surface.

No one will deny that there have been horizontal movements of crustal material, but it would seem that these horizontal movements must be incident to the vertical movements involved in the surface changes.

Let us assume that a block of older strata like that composing Chief Mountain, Montana, has moved horizontally a distance of ten miles over younger strata.[2] This, in my judgment, does not prove that there has been a buckling of the earth's crust. In the first place, the Chief Mountain material has moved from its original position. This means that the base on which it formerly rested did not move with it. The base must have remained fixed. Then, again, since Chief Mountain moved over to a new position and is resting on newer rock, the crust now beneath the mountain must be in its original position for, otherwise, Chief Mountain would not be on it.

It seems probable that the evidence, found in any uplifted area in favor of horizontal movements, indicates that only a few miles of the outer crust are involved. These horizontal movements probably took place at depths less than five miles below the surface. Let us assume that the horizontal movements occurred in material that was only five miles in thickness. If this should be the limit of moving material, then it is rather difficult to see how forces acting through hundreds of thousands of miles of this outer thin layer could result in the buckling up of an area to form mountains from one to three miles in average height. If the outer five miles could have moved horizontally, with no horizontal movements of the remaining 55 miles of the crust, there should have been a piling up of material as extra loads added to the prism of the crust below. Of course, if isostatic adjustment had followed immediately on the piling up, the crust below would have been depressed by an amount proportional to the relation of the density of the surface material and that of the upper part of the subcrustal material. The difference in density of these two materials is probably not more than 10 or 20 per cent. If we assume that it is the latter, then there would have to be an accumulation of material by horizontal movement of the outer layer of fifteen or more miles in thickness in order that a mountain mass three miles high might have been formed. If there has been a mere piling up of material without isostatic balance, then gravity would have been badly disturbed and there would be indications of the presence of such extra loads in the gravimetric survey data for a mountain area. No such disturbance in the gravity surveys has been found for any mountain area.

The late Joseph Barrell in one of his series of papers on "The Strength of the Earth's Crust" made the statement that the uplift of a plateau region is certainly due to vertical movement and not to any buckling of the earth's crust. If the plateau regions are elevated by vertically acting forces, why can not the mountain areas be elevated in the same way?

A matter which has not received the proper attention in geological literature is the great amount of uplift in continental areas, and especially in plateau and mountain areas, that has been necessary to maintain the isostatic equilibrium as material is carried away by erosion. It has been shown in the early part of this paper that, to base level an area, it is necessary that more material be eroded from an ele-

[2] See p. 230, "Our Mobile Earth," R. A. Daly, 1926.

vated area than was originally present above sea-level in it. Of course, as soon as any area appears above tidal water erosion begins so that there is no such thing as having a mass uplifted to a given height in the mountain-building process without any erosion having occurred in that time. But let us assume that there has been an uplift of two miles on the average. Then, during the erosion, there will have been an upward movement of the crust below to restore the balance of from five to ten miles, perhaps more, before base leveling will have been accomplished. This upward movement occurs in a most irregular manner, in time and in place. The movements would necessarily be along lines of least resistance. These would be vertical in some cases while they would be inclined in others and again near the surface the moving material would at times follow a direction that is practically horizontal. These movements, tending to maintain the isostatic equilibrium, would cause much distortion, fracturing and tilting of strata. It is believed that much of this distortion, due to the maintenance of the isostatic equilibrium, has been erroneously attributed to horizontal movements of crustal material at the time the area was originally uplifted.

If there are zones of weakness in the earth's crust needed for the formation of mountain systems, I should advocate that the zones be placed where there has previously been great erosion, but having the zones in those locations does not fit into the plan of having the mountain systems formed where just previously there had been very heavy sedimentation. It would really appear as if there are no zones of weakness in the sense required by the advocates of the contraction hypothesis. It would seem, therefore, that the causes which change the configuration of the earth's surface are quite local. What affects one area to cause the uplift of a mountain or plateau has nothing to do, in my judgment, with the uplifting of the earth's surface at some other place far removed.

PERIODICALS FOR MATHEMATICIANS

By Professor EDWARD S. ALLEN

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IN 1927 there was published in SCIENCE[1] the result of an investigation of the references, in the volume of the *Journal* of the American Chemical Society for 1926, to other periodicals. This year a number of colleagues have cooperated with me in making a similar study in the field of mathematics. It is unnecessary to repeat what was said in the former article about the importance of an adequate department library even in a small institution, and about the value of such studies in helping librarians to choose the most useful periodicals.

We decided, at the outset, that it would be unfair to base any judgment on work quoted in one mathematical journal alone. The *Transactions* of the American Mathematical Society most nearly correspond to the *Journal* of the American Chemical Society, yet the number of citations and the range of subjects treated in any one year are an inadequate basis for reliable conclusions. We therefore at once took into consideration the volumes of the *Annals of Mathematics* and of the *American Journal of Mathematics* for 1928. Then, feeling that even these three would be unrepresentative of the needs of working mathematicians, we added the 1928 issues of six of the seven foreign journals which they most frequently mentioned. Crelle's *Journal* would also have been included but for the decision to restrict the representation of each European nation to one periodical. The following table gives the journals used and the number of references taken from each.

TABLE I

		No. of references
Trans. Am. Math. Soc.	vol. 30	249
Annals of Math.	vol. 29, no. 2–4 vol. 30, no. 1	309
Amer. Journ. of Math.	vol. 50	211
Proc. London Math. Soc.	vol. 27, parts 5, 6, 7 vol. 28 vol. 29, part 1	252
Math. Annalen	vol. 99, 100	454
Journ. de Math. (Liouville)	vol. 7	110
Rend. Circ. Mat. Palermo	vol. 52	151
Acta Math.	vol. 51, no. 3–4 vol. 52, no. 1–2	65
Fund. Math.	vol. 11, 12	364
Total		2,165

Of these nine journals, three are American, three predominantly British, German and French, respectively, and three international.

Thus, it will be seen, we have information with something of an American bias, yet probably no more than there should be in a list intended primarily to be helpful to American librarians.

[1] P. L. K. Gross and E. M. Gross, "College Libraries and Chemical Education," SCIENCE, 66: 385, 1927.