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EARTH STRUCTURE AND EARTH ORIGIN[1]

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IN his book "The Solar System and Its Origin,"[2] Henry Norris Russell presents a critique of the several theories of earth origin, which may fairly be taken as representative of the attitude of most astronomers toward this problem, responsibility for the solution of which they share with geologists. Full consideration is given to the planetesimal hypothesis of Chamberlin and Moulton and to the modifications of that hypothesis which have been proposed by Jeffreys and Jeans. The obstacles which forbid whole-hearted acceptance of any one of these hypotheses are forcefully presented. The conclusion is frankly stated "that no one can yet say how our system originated in detail."

It is nevertheless apparent that the most hopeful line of research leads toward some hypothesis of origin during an encounter between the sun and another heavenly body. In other words, the fundamental principle of the planetesimal hypothesis is accepted. Future investigators are most likely to work toward the discovery of the particular modification of that hypothesis which will best fit the facts now known or to be ascertained.

Commenting specifically upon the planetesimal and tidal theories, Professor Russell states: "It is here that the two theories part company—the planetesimal supposing that the existing planets were formed mainly by the slow agglomeration of small cold bodies, and the tidal that they were all once liquid and have picked up much less matter in later times. This difference, while very important to the geologist, is really rather small from the standpoint of the astronomer."[3]

[1] Address of the vice-president and chairman of Section E, American Association for the Advancement of Science, Richmond meeting, December 28, 1938.
[2] New York, 1935.
[3] *Loc. cit.*, p. 102.

Geologists, as such, are deeply concerned with the problem of earth origin primarily because they want to know whether the earth was essentially molten at some time in the past, after it had attained the state of a separate planetary body possessing approximately its present mass, or whether it was an essentially solid and relatively small planetary body to which has been added a considerable fraction of its present mass by some process of accretion. Upon the answer to that question depend some of the most fundamental ideas concerning diastrophism and vulcanism. No satisfactory theory concerning the processes of mountain-making, the origin of igneous rocks, the mechanism of volcanic eruptions or the dynamics of isostasy can be formulated without a commitment concerning that phase of the juvenile history of the earth.

Apparently, the geologist can not expect the astronomer to tell him the answer which he thus needs to learn. He must secure it for himself by investigating the structure of the earth's interior and by reasoning backward from observed geological phenomena to the antecedent conditions which alone can explain all the intricate details of the present structure of the earth's exterior.

That the earth has grown by the addition of extraterrestrial matter is of course a conclusion based on direct observation. Reliable estimates of the number and average weight of meteorites which have reached the earth during the last few years indicate that the daily accretion of meteoric dust is of the order of magnitude of 50,000 tons.[4] This would mean that the earth's mass is increasing at a rate of approximately 20,000,000 tons per year. At that rate the earth would have acquired 2×10^{16} tons of previously extra-terrestrial matter in a billion years and twice that amount, or 4×10^{16} tons, in the two billion years which seem to have elapsed since its birth. That stupendous mass is, however, only one one-hundred-and-twenty-five thousandths of the present mass of the earth, roughly 5×10^{21} tons. If one half or two thirds of the earth's body has been built up through planetesimal accretion, the rate of infall must have formerly been a hundred thousand times as great as it is to-day. This is of course explicitly accepted in the planetesimal hypothesis, but it throws the whole question back into the realm of speculative deduction. On the other hand, we may note that 4×10^{16} tons of matter with an average density of 3.0 would form a layer only a little more than 100 feet thick around the earth.

That fact probably has no real significance, but it at least serves to direct our attention at this point to the problem of the physical condition and chemical composition of the earth's interior. Geophysical research has yielded much important data during the last two decades, and ideas concerning the fundamental structure of the earth are now taking definite and trustworthy form.

The records of earthquakes indicate unmistakably that the earth has a stratiform structure. Its body is composed of several successive shells which differ from each other in elasticity, as indicated by the travel-times of the seismic vibrations. The central core of the earth, approximately 2,200 miles in radius, is notably different from the surrounding shells in its physical properties. The several shells and the earth core are separated from each other by surfaces or transition zones appropriately known to the seismologist as discontinuities. Most of the discontinuities are marked by a fairly abrupt change in the velocity of propagation of the seismic vibrations and hence are known as discontinuities of the first order. Some are marked by a variation in the rate of change in velocity with increased depth and hence are known as discontinuities of the second order.

The statements in the preceding paragraph would probably be accepted as valid by all competent investigators in this field and may therefore be used as basic data upon which any useful concept of earth structure must be constructed. They present in general terms the specifications which must be met by any satisfactory theory of earth origin. It is indeed the demonstration of the stratiform structure of the earth which more than anything else has caused many geologists to become skeptical of the adequacy of the planetesimal theory of earth origin and to look with favor upon a theory in which the juvenile earth is conceived to have been essentially a liquid globe at the time it possessed approximately its present mass.

There yet remain a multitude of unanswered questions concerning the earth shells and the earth core. Divergent interpretations of the same data have been made by several competent investigators. Essential data concerning the response to stress of earth materials under conditions of great pressure and high temperature are still lacking, and at present the deficiency can be met only by untrustworthy extrapolation or debatable assumption. The available information concerning travel-times, refractions and reflections of seismic vibrations is inadequate for the incontrovertible appraisal of the several working hypotheses and must be amplified by the study of records secured in the future at existing seismograph stations or at stations which should be established to complete the necessary network of such stations the world around. It should nevertheless prove helpful to review the present state of knowledge and inference, with special consideration of its bearing upon the problem of earth origin.

It would appear that no doubt can now remain con-

[4] *Cf.* H. H. Nininger, "Our Stone-Pelted Planet," p. 91. Boston, 1933.

cerning the crystalline nature of earth materials down to a depth of at least 60 kilometers. Above that depth, within continental segments, there seem to be at least three shells which differ from each other in their responses to stress. The outer shell beneath the surficial and discontinuous veneer of sedimentary or metamorphic rock is granitic in composition, the next is an intermediate zone which may be composed largely of diabasic or gabbroic rocks, and the third consists of materials which behave as either pyroxenite or dunite would probably behave at such depths.[5] The last-mentioned shell constitutes the "crystalline sima," as that term is used by Daly,[6] who, however, considers its composition to be more like that of gabbro than of peridotite. It is believed to be continuous beneath the oceans the world around. Readily recognized discontinuities of the first order separate these shells from each other. Thicknesses of the shells and hence depths to the discontinuities vary considerably from place to place. Most of the figures cited by those who have generalized upon the matter are average figures rather than specific ones.

The determination of the depth of a discontinuity depends at present upon the selection of certain assumptions from several which appear almost equally reasonable concerning the propagation of vibrations in the earth's interior as well as the choice of the particular measurement of wave velocities which shall be applied. Consequently, different investigators working with the same data have reached different conclusions, and diverse data secured at various localities have yielded notably different results. This, however, does not in the least invalidate the general principle that discontinuities are present and that the earth is composed of successive shells with unlike properties.

As expected, the limits within which our present knowledge confines the selection of data are much narrower for the shallow than for the greater depths. Laboratory conditions can be established which closely imitate the conditions of pressure and temperature existing at depths approximating 25 kilometers and of pressure at depths of at least twice that figure. Field studies involving the use of artificially generated vibrations include the accurate determination of travel-times for impulses originated by dynamite blasts transmitted for distances as great as 175 miles. Thus the depth of the discontinuity at the inner surface of the granitic shell beneath southern New England is rather definitely fixed as 14.5 kilometers.[7] Data from other localities, as interpreted by various geophysicists, indicate depths between 10 and 25 kilometers.

The intermediate zone is computed variously to have a thickness of 15 to 40 kilometers. The depth to the discontinuity at its inner surface is between 25 and 60 kilometers; Daly uses 40 kilometers as an average determination. Sharpe[8] computes its average depth beneath 17 widely scattered stations as 32 kilometers. Differences in the determinations are almost certainly due to actual variations in the thickness of the two outer earth-shells from place to place and not entirely to differences in interpretation of data.

The depth to which the crystalline sima extends is still a question for speculative consideration. The next clear-cut discontinuity of the first order, below the bottom of the intermediate zone, which has been generally recognized, is at a depth of approximately 475 kilometers. There are, however, some significant data concerning shadow-zones and wave amplitudes which have been interpreted by Gutenberg[9] as suggesting the presence of material having a slightly lower velocity beneath the high-speed crystalline sima at a depth of 60 or 70 kilometers. Daly computes[10] that the temperature below 60 kilometers is such that the sima must be in a vitreous rather than a crystalline state. This would of course explain the apparent retardation of the wave of dilatation at a depth of 60 or 70 kilometers and would thus be in keeping with the seismological specifications.

Temperatures and pressures at depths between 60 and 400 to 500 kilometers are such as to put rock materials very close to the boundary between the vitreous and crystalline states. It requires only a rather steep, but still perfectly plausible, temperature gradient to yield the computations upon which Daly bases his concept of a vitreous substratum. A slightly lower temperature gradient, offset by the increase in pressure, would permit the crystalline state to persist to greater depths; the precise temperature gradient, density distribution and chemical composition selected would determine the depth at which a vitreous rather than crystalline state would be found. Under reasonable assumptions it seems almost certain that beyond a depth of a few hundred kilometers, because of the great pressures there prevailing, the earth materials, if lithic rather than dominantly metallic, must be crystalline. As pointed out by Daly,[11] "the vitreous basaltic shell (must) be relatively thin, perhaps nowhere more than a few scores of kilometers in thickness." Possibly the 475 $\pm$ kilometer discontinuity marks the change from vitreous to crystalline materials rather than merely the increase in the intrinsic density re-

[5] Francis Birch and Dennison Bancroft, *Jour. Geol.*, 46: 59–87, 113–141, 1938.

[6] R. A. Daly, "Architecture of the Earth," pp. 51–59. New York, 1938.

[7] L. D. Leet, *Bull. Seismol. Soc. America*, 28: 45–48, 1938.

[8] J. A. Sharpe, *Bull. Seismol. Soc. America*, 25: 199–222, 1935.

[9] B. Gutenberg, Grundlagen der Erdbebenkunde, Berlin, 1927. See also Daly, *loc. cit.*, pp. 67–69.

[10] *Loc. cit.*, p. 62.

[11] *Loc. cit.*, p. 69.

quired to meet the specifications necessary to give the earth its known moment of inertia.

The unanswered question concerning the physical state of the material in this relatively thin substratum may never be resolved by seismic research. Birch and Bancroft[12] report that "the velocities in crystalline and vitreous gabbroic materials tend to become equal as the temperature increases." If this tendency actually establishes equivalent velocities, the question becomes meaningless so far as seismology is concerned.

There is, however, another question of great importance to both geologist and cosmogonist, although significant for different reasons when considered from one or other of these two view-points. That is the question of the intrinsic strength of the materials in this quasi-vitreous substratum. This is the zone, or a part of the zone, to which Barrell long ago applied the apt term, asthenosphere. Much evidence has accumulated to strengthen the geologist's belief in the correctness of the essentials of Barrell's concept. Only on the assumption that the substratum is unable to withstand any appreciable accumulation of long-continuing stress can one explain many of the observations concerning isostatic adjustment, as for example those pertaining to the phenomena of loading and unloading the earth's crust during a glacial episode. Daly[13] has recently emphasized anew the extreme weakness of the asthenosphere. Using data from Hirvonen and Witting, he finds that the maximum strength at a depth of 100 kilometers is less than 2.5 kilograms per square centimeter. This computation should be compared with Barrell's estimate of 200 to 300 kilograms per square centimeter and with Jeffreys' calculation of 100 kilograms per square centimeter.

Probing still deeper into the earth's inaccessible interior, we find that seismologists have recognized several discontinuities between 475 $\pm$ kilometers and 2,900 kilometers. The position of these discontinuities is, however, subject to almost constant revision as new data are obtained or old data are reinterpreted. At least one of them, located somewhere near 1,000 kilometers beneath the surface, is a discontinuity of the second order and it may prove at last that all of them are actually in this category, marking a change in the rate of increase of velocities rather than an abrupt change in the velocities themselves. Certainly there can be at present no confidence in the precision of any of the announced locations of supposed discontinuities of the first order in this subterranean region. Such discontinuities may exist, but if they do their position can not now be determined with anything like the accuracy which pertains to those at shallow depths beneath the continents.

On the other hand, it appears quite certain from a consideration of the requirements imposed by the earth's known moment of rotational inertia that the changes in density with depth in this zone are due to differences in the chemical composition of the materials, not merely to increased compaction of like materials under increased load. These requirements are best satisfied if we postulate the presence of a shell of rock material having the chemical composition of dunite or peridotite beneath the quasi-vitreous substratum. Toward the inner surface of this shell there must be increasing quantities of material "chemically like the iron-bearing stony meteorites"[14] and below a depth which may be in the neighborhood of 1,000 kilometers the earth shell must be essentially of that type of substance.

At approximately 2,900 kilometers there is a well-recognized discontinuity of the first order. Below that depth, earthquake waves encounter material giving much lower velocities than those which characterize their transmission in the immediately superjacent zone. This explains the well-known "shadow zone" between 105 and 142 degrees from the epicenter of world-shaking earthquakes.[15] This discontinuity marks the effective surface of the earth's core, frequently designated the "iron core," because a composition of iron and nickel in approximately the same ratio as those metals display in the iron meteorites would probably give the required velocities for longitudinal vibrations (waves of dilatation) under reasonable assumptions for temperature and pressure.

Thus far, no unchallengeable identification of a seismogram phase as due to a wave which passed through the earth's core as a shear wave (transverse vibration) has been announced. Such waves can not be transmitted through liquids, but it is probably misleading to say that it is therefore known that the iron core is a liquid core. To call it a quasi-liquid core would give a more accurate impression. There is at present no knowledge concerning the behavior of any metallic solid under the conditions of temperature and pressure which must maintain at great depth within the earth. The molecules of iron and nickel may be associated in the earth's core in ways that transcend all human experience with solids, liquids or vapors.

Turning then from conjectures that could hardly be profitable, we note the bearing which the concept of a stratiform earth may have upon the theories of earth origin. Any earth model capable of satisfying the requirements of modern knowledge concerning the

[12] Francis Birch and Dennison Bancroft, *Jour. Geol.*, 46: 141, 1938.

[13] R. A. Daly, *Trans. Am. Geophys. Union*, 19th Ann. Meeting, pp. 35–39, 1938.

[14] *Cf.* Daly, *loc. cit.*, p. 69.

[15] *Cf.* L. D. Leet, "Practical Seismology and Seismic Prospecting," pp. 161–168. New York, 1938.

physical properties of the earth's interior must inevitably present a challenge to the planetesimal theory. To provide a stratiform earth by specific gravity settling is a relatively simple proposition for a molten-earth theory such as the tidal theory of Jeffreys and Jeans, but it is not immediately apparent that an earth built in large part by planetesimal accretion would attain that structural configuration. Accepting this challenge, T. C. Chamberlin in his later presentations of the planetesimal theory[16] rejected the enticing detour which would involve the liquefaction of the planet after its growth by accretion had been practically completed. "There does not seem to be any cogent reason for assuming that molten planets would arise from this mode of aggregation, except in those cases in which the knots were very large."[17] He proposed instead that the stratiform structure arose in part from the selective nature of the processes of accretion and in part from selective vulcanism, both of which would tend to segregate the denser and more metallic or less silicic substances toward the center, and the less dense and more silicic substances toward the periphery of the juvenile earth. Chiefly because of skepticism concerning the quantitative effectiveness of these selective processes, Chamberlin's attempt to explain the stratiform structure within the framework of the planetesimal theory has never met with wide-spread approval.

In view, however, of our present knowledge of the behavior of crystalline and vitreous solids under conditions of great pressure and high temperature, it would appear that this stumbling-block has been removed. The intrinsic strength with which such solids resist deforming stress is astonishingly slight. Convection must occur in an asthenosphere as weak as the quasi-vitreous substratum appears to be, if there are appropriately located differences in density due either to variations in chemical composition or to changes in temperature. Ideomolecular reorganization of crystals is stimulated in crystalline solids under the conditions which prevail throughout the earth's interior beneath a thin surficial zone. It is indeed quite impossible to prevent the earth, regardless of initial heterogeneity of materials, from developing a stratiform arrangement of those materials according to density, as slow adjustment takes place within its body during its long history.

Thus an earth originally heterogeneous and always essentially crystalline would eventually be organized into its present structural form with a central core of intrinsically dense materials surrounded by concentric shells of progressively less dense substances. At all times it would react as an elastic solid to the sudden impacts or abrupt release of energy which initiate earthquake vibrations, but at all times it would be subject to "solid flow," which would tend inevitably toward specific gravity assortment. If this is true, the existing structure of the earth's interior could be explained with equal effectiveness regardless of its origin, whether by planetesimal growth or by condensation from a gaseous "filament." This would mean that the geologist would be unable to use the earth's fundamental structure as a criterion for appraising the relative merits of the planetesimal and the tidal hypotheses.

There is, however, another consideration which may put him in a better position to pass judgment in this particular court of appeal. Somewhere in his cosmogony he must find a place for the forces which have produced the folded structures in the earth's outermost shell and the fundamental differences between the continental and oceanic segments. The former involve the horizontal compression of certain portions of the lithosphere; the latter involve the segregation of granitic materials in the continental protuberances. Here there is an essential difference between the two theories of earth origin.

Several alternative theories of mountain-making diastrophism are worthy of attention. These include horizontal shifting of earth-blocks as a result of convection currents in the substratum, or of de-leveling, or of forces resulting from the earth's rotation as a planet with which a large satellite is associated. These avenues of investigation should be pursued, but at the moment none of them appear particularly promising. Volume changes due to local alterations in temperature seem wholly inadequate to explain the known crustal shortening. The oldest theory of all, circumferential shortening of a radially shrinking earth, appears to be still the most favorable lead. The effects of earth condensation would produce structures such as we find in every great chain of mountains; the efficiency of the process is unquestioned. The problem is to explain earth-shrinkage itself.

All investigators agree that the rate at which the earth loses its body heat is altogether too small to account for more than a trivial fraction of the shrinkage necessary to explain the amount of circumferential shortening revealed by post-Cretaceous mountain-making compression. We may say quite dogmatically that the cooling of the earth is not an adequate cause of the known horizontal compression of the lithosphere. There remains the possibility that physical and chemical reorganization of the materials composing the earth's interior has been such as to increase sufficiently their average density and thus produce the required decrease in volume for the earth as a whole. Chamberlin long ago appealed to this process in seeking an explanation for the diastrophism which pro-

[16] T. C. Chamberlin, "The Origin of the Earth," Chicago, 1916, and "The Two Solar Families," Chicago, 1928.

[17] T. C. Chamberlin, *loc. cit.*, 1916, p. 147.

duces folded and overthrust mountains. The argument is still valid. It applies, however, only to an earth constructed according to the planetesimal program; it is utterly ineffective in an earth which has solidified from a molten state. If at last we find no escape from the idea of a shrinking earth, we must render our verdict in favor of the planetesimal theory rather than the tidal.

The second basis for testing the theories of earth origin is found in the attempt to explain the segmentation of the lithosphere into continents and ocean basins. Here the problem is to account for the segregation of less dense, granitic materials beneath the protuberances and the denser, gabbroic material beneath the basins. Chamberlin's explanation was in terms of selective in-gathering of planetesimal debris under the influence of atmospheric circulation, combined with selective placement of the products of weathering by the agents of transportation and deposition. Under the tidal theory, the segmentation of the granitic shell, originally continuous the world around, must be accomplished during the rupture accompanying the birth of the moon. Both ideas must be critically reviewed in the light of any new knowledge which may be secured in the coming years. Neither can be whole-heartedly accepted or bluntly rejected at the present moment. The line of departure between the two is so clearly defined and leads to such far-reaching consequences that there is good reason to expect a definite verdict in the near future. The bearing of that verdict upon the theories of earth origin is obvious.

In summary, it would appear that the concept of earth structure based on recent geophysical and seismological research is not nearly so unfavorable to acceptance of the planetesimal theory of earth origin as many geologists have supposed it to be. On the contrary, in at least one particular—that which deals with the origin of folded mountains—modern investigations pertaining to the fundamental structures of the earth have brought renewed confidence in the basic principles of that theory.

OBITUARY

EDWIN HERBERT HALL

PROFESSOR EDWIN HERBERT HALL, universally known to physicists as the discoverer of the Hall effect, died on November 20, 1938, at the age of 83 years. He was born in Gorham, Maine, on November 7, 1855, fitted for college in Gorham Seminary, entered Bowdoin at 15, and graduated with the A.B. degree at the head of his class at 19. During 1875–76 he taught as principal at Gould's Academy in Bethel, Maine, and during 1876–77 was principal of the Brunswick High School. In 1877 he entered the Johns Hopkins University as a graduate student of physics, and from 1878 to 1880 was fellow in physics, working under Rowland and receiving the Ph.D. degree in 1880. He continued on as assistant in physics during 1880–81, when he was appointed to a Tyndall scholarship for study and travel abroad. During the summer he made measurements on the "Hall" effect in Helmholtz's laboratory in Berlin, and read a paper reporting these measurements at the York meeting of the British Association in the summer of the same year. He returned to this country in the fall of the same year to an instructorship in physics at Harvard, a position which he held until 1888. From 1888 to 1895 he was assistant professor at the same institution, professor from 1895 to 1914, Rumford professor from 1914 to 1921, and professor emeritus from 1921 till his death. He was a member of the A.A.A.S. (vice-president of the section of physics in 1904), of the American Physical Society, the American Academy of Arts and Sciences, the National Academy of Sciences, corresponding member of the British Association for the Advancement of Science and foreign member of the Société Hollandaise des Sciences. He received the LL.D. degree from Bowdoin in 1905, was a member of the Solvay Congress at Brussels in 1924 and of the Volta Congress in Como in 1927, and in 1937 received the award and medal of the American Association of Physics Teachers for notable contributions to the teaching of physics, and was made the first honorary member of the association.

Professor Hall's great contribution to the teaching of elementary physics was a pioneering contribution, made at a time when physical laboratories were almost unheard of in this country. In 1886 he published, with the encouragement of President Eliot, the well-known "Harvard Descriptive List of Elementary Physical Experiments." These had the unique merit of demanding apparatus simple enough so that it could in many cases be constructed by the teachers themselves without undue strain on their meagre budgets. This "list" was followed by several elementary text-books, the best known perhaps being "A Textbook of Physics" by Hall and Bergen in 1891. It would not be unfair to describe Professor Hall's work as entirely remolding the scheme of secondary school physics, and as such exerting a most important influence, but since this matter is freshly in mind through the articles in the *American Physics Teacher* for February, 1938, at the time of the award, it is not necessary to elaborate further here.

Of course Professor Hall will always be best known for the Hall effect, discovered while working for his