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ART. XXXVII.—*A Critical Review of Chamberlin's
Groundwork for the Study of Megadiastrophism*; by
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Summary of Thesis.

The evidence of earth rigidity and elasticity is here considered from the relative viewpoint and the conclusion is reached that while the earth may be highly rigid under tidal stress, that it is, beneath a superficial shell, in a yield state for stresses of diastrophic dimensions.

The evidence of seismic transmission apparently indicates a viscous liquid state for depths below 0.6 of the earth's radius for stresses of these dimensions, and the conclusion is reached that such a state for larger stresses will be nearer the surface.

Seismic transmission indicates an isotropically homogeneous state for the earth beneath a comparatively thin heterogeneous outer shell and this conclusion is in direct opposition to Chamberlin's postulated earth heterogeneity both in depth and laterally, and the evidence is taken as indicating a density stratification of the earth as a result of its having passed through a period of fusion.

The postulate of a continuously solid state for the earth is shown to rest on certain assumptions as to size of the earth nucleus and its rate of growth, and a solid heterogeneous earth with vulcanism a result of selective liquefaction is thought to be incompatible with the facts of occurrence of the igneous rocks.

Evidence is submitted to show that diastrophism can be readily accounted for by adjustment or lack of adjustment of a heterogeneous outer shell resting on an asthenosphere or yield zone, and does not require deep-seated variations of density or deep-seated diastrophic movements.

Introduction.

As a groundwork for the study of "megadiastrophism," a term introduced as applying to diastrophism on the large scale—continental or sub-oceanic, or even applying to the earth as a whole, T. C. Chamberlin has set forth in summary form in two recent papers¹ the salient deductions and conclusions he has drawn from his studies of the formative processes.² R. T. Chamberlin in a following paper³ reviews the intimations of deep deformation derived from structural cross-section studies of two folded and deformed belts, the results of which have been previously published.⁴

It is evident that the study in megadiastrophism is to be one of the application of wedge-dynamics to continental areas. To consider continental areas as the upper surfaces of deeply pointing wedges implies, of course, that the earth lacks an asthenosphere or yield zone. This postulate is fundamental. The issue is thus sharply drawn between the two schools of thought. The basic problems of diastrophism, isostasy, and vulcanism must be attacked and interpreted in two diametrically opposite ways by the two schools. The one school, as represented by T. C. and R. T. Chamberlin, interpret these problems from the viewpoint of an earth which has maintained perfect solidity through the formative eras and down to the present; an earth, heterogeneous in its makeup both laterally and in depth, in which, as R. T. Chamberlin says,⁵ "all thought of easy movement in the interior is to be scrupulously avoided." The other school, as represented by Daly and the late Barrell, interpret these problems, on the other hand, from the viewpoint of an

¹ Groundwork for the Study of Megadiastrophism, Pt. I. Summary statement of the groundwork already laid. T. C. Chamberlin, *Jour. Geology*, vol. 29, pp. 391-416, 1921.

Groundwork for the Earth's Diastrophism, T. C. Chamberlin, *Bull. Geol. Soc. America*, vol. 32, pp. 197-210, 1921.

² Thirteen papers in recent volumes *Journal of Geology*.

³ Groundwork for the Study of Megadiastrophism, Pt. II. The Intimation of Shell Deformation, R. T. Chamberlin, *Jour. Geology*, vol. 29, pp. 416-425, 1921.

⁴ R. T. Chamberlin: The Appalachian Folds of Central Pennsylvania, *Jour. Geology*, vol. 18, pp. 228-251, 1910.

The Building of the Colorado Rockies, *Jour. Geology*, vol. 27, pp. 145-164; 225-251, 1919.

⁵ *Jour. Geology*, vol. 29, p. 421, 1921.

earth which passed through a stage of fusion resulting in a coarse stratification by density and which, since crustification, has possessed a yield zone beneath a comparatively thin outer shell. This latter viewpoint is not, as Daly has pointed out,⁶ incompatible with the basic postulates of the planetesimal hypothesis of geogenesis.

The purpose of the present paper is to bring together in summary form from the various sources the evidence leading to the conclusions that the earth passed through a molten stage and that there exists at no great depth a zone which yields to diastrophic differential stresses. The writer believes that this evidence, much of it direct evidence of seismic transmission and close field studies, cannot be lightly set aside.

The Rigidity and Elasticity of the Earth.

General Considerations.—The term “rigidity” has been generally loosely interpreted. Rigidity is dependent not only on the stress applied but upon the time the stress is applied. A material may be rigid for one set of stress conditions and non-rigid for another set. The earth is spoken of as having a higher rigidity than steel. Another equally good way of stating the same fact is to say that the earth yields under the same conditions that steel will yield and, as a matter of fact, steel does yield quite readily. Even Adams⁷ and Bridgman’s⁸ experiments besides demonstrating the high strength of rocks under cubic compression also show that these same rocks eventually yield if the pressure is great enough and if the time the pressure is applied is long enough. Rigidity, then, is merely a relative term. Nothing that we know of has absolute rigidity. And plasticity, or yielding, is not necessarily dependent on the physical state of a material. Crystals become plastic at sufficiently high

⁶ R. A. Daly: The Planetesimal Hypothesis in Relation to the Earth, *Sci. Monthly*, May, 1920, p. 495.

⁷ F. D. Adams: An Experimental Contribution of the Question of Depth of the Zone of Flow in the Earth’s Crust, *Jour. Geology*, vol. 20, pp. 97-118, 1912.

On the Amount of Internal Friction developed in Rocks during Deformation and on the Relative Plasticity of Different Types of Rocks, *Jour. Geology*, vol. 25, pp. 597-637, 1917.

⁸ P. W. Bridgman: The Failure of Cavities in Crystals and Rocks under Pressure, this *Journal* (4) vol. 45, pp. 243-268, 1918.

pressures and so crystalline aggregates must become plastic.

Temperature increase, of course, materially facilitates yielding and so, as far as yielding by flowage is concerned, and where temperature and pressure both increase, a material will yield under a lower pressure than it would if pressure were increased alone. The fact of yielding implies differential pressures. True cubic compression no longer exists when yielding takes place. Certainly any terrestrial material we know of must be in a potential yield-state under the conditions of temperature and pressure at no very great depth beneath the surface of the earth whatever its physical state as regards homogeneity or heterogeneity, crystallinity or non-crystallinity and yet such a yield-state would be one of high rigidity in the ordinarily accepted sense of that term, that is, for any short time differential stress.

The term elasticity may have the same implication. A material may rebound under one set of stress conditions and not rebound under another set of conditions. Both these terms imply simply dependent states.

A material then, under any set of conditions as regards temperature and pressure, may have properties of rigidity and elasticity of a high order in so far as short-time stress differences are concerned and yet be non-rigid and non-elastic for stress differences of long duration and large magnitude, and these latter are the types of stress conditions we are concerned with in diastrophic movements. The statement that the earth is more rigid and elastic than steel should be qualified, therefore, with the statement that it possesses these properties for certain stress conditions—for example those imposed by tidal pulsations.

Now Chamberlin's interpretation of the evidences of this rigidity—that is the rigidity shown under tidal stress and seismic vibrations, implies that this state of rigidity and elasticity holds good for stress differences of all magnitudes and of all time durations. Under this interpretation the terms rigidity and elasticity become practically absolute instead of dependent. But such an interpretation is essential if he is to postulate the non-existence of a yield-state anywhere within the earth for almost any condition of stress. Under this conception

yielding can only take place by shearing or recrystallization. This is vital to deeply pointing wedge deformations.

Chamberlin deduces a holocrystalline state for the earth on the basis of its rigidity, elasticity and density. It is evident that both rigidity and elasticity are totally independent of crystallinity. Amorphous materials, like glass, or even paraffin wax, under sufficient pressure become more rigid than steel under similar pressure. Under differential stress of sufficient magnitude and duration such materials will flow because they are true liquids. While it is true that high pressure favors crystallization, since for most substances the crystalline form is the most dense, this is true for conditions of normal temperature. High pressure experiments seem to indicate that there is a limiting set of conditions as to pressure and temperature beyond which all directional molecular arrangement is destroyed. The material then becomes a highly viscous liquid. There is nothing to indicate that such limiting conditions may not exist at no very great depth within the earth and the resulting state might, and probably would, be one of ready yielding to long-imposed stresses and still be a state of high rigidity and elasticity under short-time stresses. For material to assume such fluid properties for short-time stresses required conditions of higher temperature and pressure. Seismic transmissions seem to indicate that such conditions do exist at depths below 0.6 of the earth's radius.

The great depth of deformation deduced by Chamberlin rests then upon conditions of rigidity and elasticity which are not proved by the evidence at hand. And this is vastly important, for this deduction makes it essential that all earth body deformation be deep-seated and due largely to tidal stress and its consequent kneading. The work of Michelson⁹ and others does not indicate in any sense that the tidal stresses are sufficient in time duration or magnitude to overcome the rigidity or elasticity attributed to the earth. Furthermore this same evidence does not prove that stress differences of diastrophic dimensions are not competent to overcome this same rigidity and elasticity and so cause plastic yielding.

⁹ A. A. Michelson & H. G. Gale: *The Rigidity of the Earth*. Jour. Geology, vol. 22, pp. 97-130, 1914; vol. 27, pp. 585-601, 1919.

Now temperature increase is so very much more effective in decreasing the density of material than pressure increase is in increasing its density that it is unsafe to assume that materials within the earth are in their most dense or crystalline state, much less to assume that some unknown compressional state exists. Again, so far as high pressure experiments have extended, the density increase upon pressure increase becomes negligible. The rigidity, however, progressively increases. The increase of density in the depths of the earth, it would seem, must be independent of high pressure and so independent of rigidity.

The Evidence of Seismic Vibrations.—Since records of the transmission of seismic vibrations constitute the only direct evidence we have of the state or states of the earth's interior an analysis of this evidence becomes imperative. Seismic disturbances send out vibrations of two types, compressional and distortional. These are called the primary and secondary waves respectively. The former waves are dependent on the elasticity or compressibility of the transmitting medium, while the latter waves are dependent both on the rigidity and the elasticity of the transmitting medium, for their propagation. The two types of waves travel at different velocities but can only become distinctly separated out in a homogeneous medium; that is, homogeneous as to stress effects or, in other words, isotropic. The resultant vibrations which travel circumferentially from the shock center pass through what we know is a heterogeneous medium. The wave types are not separated in the earth's surficial shell.

At a minimum distance of 700 miles, or 10 degrees of arc, from the epicenter a three-phase record becomes decipherable. The first phase vibrations to be recorded are the compressional or primary waves; next come the second phase distortional or secondary waves, and both these phases come through the earth. Finally the third phase, undifferentiated waves, reaches the recording device via a circumferential path.

From the mere fact that the primary and secondary waves are separated at distances above 10° of arc from the epicenter "it is clear," according to Davison,¹⁰ "that

¹⁰ C. Davison: *A Manual of Seismology*, Cambridge, 1921, p. 149.

the waves arriving there must, for part of their journey, have traversed some homogeneous material situated below a comparatively thin layer." In fact, the rays of these vibrations which emerge at the arc distance of 10° or 700 miles actually penetrate to a depth of only 100 kilometers. Here then is apparently direct proof of a transmitting medium which is isotropically homogeneous at a comparatively shallow depth beneath the surface.

Now Chamberlin interprets this necessary and demonstrated homogeneity as a medium possessing an average homogeneity but a minute heterogeneity.¹¹ Such an interpretation becomes, of course, essential under the hypothesis of deep crystallinity for the earth. If such a minutely heterogeneous medium would have the identical transmitting properties as an actually isotropic one, then one obstacle in the way of acceptance of the postulate is removed, but are there not other obstacles?

The necessary confinement of large heterogeneity to such a comparatively thin outer shell would seem to present a formidable difficulty in the way of Chamberlin's postulated process of the introduction of tongue melts from the deep interior to the more surficial portions of the earth, for certainly these introduced heterogeneities would not all insinuate themselves above such a shallow depth as the transmitted seismic waves make necessary.

The important point deserving special emphasis is that the splitting up of the two vibration phases at such shallow depths as are penetrated by rays emerging at a distance of 700 miles from the shock center indicate a profound change in physical state at a very shallow depth beneath the earth's surface. The suddenness of this change is further indicated by the apparent reflection of transmitted waves against the surface of demarkation. The most reasonable conclusion to be drawn is that this sudden change is from a heterogeneous outer shell to a non-crystalline isotropic material similar to "under-cooled" liquids. Chamberlin's statement¹² that "the hot interior of the earth is not a suitable environment for under-cooled liquids," does not take into account that this physical state is the combined result of temperature and pressure rather than of temperature alone.

¹¹ T. C. Chamberlin: *Jour. Geology*, vol. 29, p. 395, 1921.

¹² T. C. Chamberlin: *The Origin of the Earth*, Chicago, 1916, p. 181.

There is some disagreement in the interpretation of the records of transmitted vibrations which penetrate depths between the surface of demarkation as between outer shell and inner homogeneous material, and a depth of about half the earth's radius. Knott¹³ in his work, and Davison¹⁴ accepts his conclusions, shows an increasing rate of velocity for both phases of waves down to depths of 1,400 kilometers (.22R. R=earth's radius) for the secondary and 1,600 kilometers (.25R) for the primary waves. Slight decreases in the rates of velocity increase are indicated at a depth of about 750 kilometers. At these greater depths the velocities reach their maximum and from these points down slowly decline. Oldham on the other hand, both in his paper of 1906¹⁵ and in his discussion of 1918,¹⁶ concludes that there is a steady increase of the rate of transmission, with no marked break in regularity down to a depth of about one-half the earth's radius. The interpretations by Knott and Davison would imply a breakdown of the earth's rigidity and elasticity at .22R and .25R, respectively, while Oldham's interpretation would place the breakdown of these states at greater depths.

All these authorities, however, agree that below a depth of 3.825 kilometers (.6R) the earth body is non-rigid. Below this depth the secondary waves are either blotted out or, according to Oldham¹⁷ ".....are no longer represented in their typical form, but are replaced by a record of different character, probably not due to any form of wave, which has followed the direct path from the origin, and markedly delayed from the time at which they should have arrived."

The conclusions to be drawn from these facts are obvious. On them rests the conclusion of Oldham¹⁸ that the material in the central nucleus has a very low degree of rigidity even against stresses of only a few seconds

¹³ C. G. Knott: *The Propagation of Earthquake Waves through the Earth*, Proc. Royal Soc. Edinburgh, vol. 39, pp. 157-208, 1919.

¹⁴ C. Davidson: *Op. cit.*, p. 157.

¹⁵ R. D. Oldham: *The Constitution of the Interior of the Earth as revealed by Earthquakes*, Geol. Soc. London, Quart. Jour., vol. 62, pp. 135-174, 1906.

¹⁶ R. D. Oldham: *The Constitution of the Earth's Interior*. *Nature*, vol. 102, pp. 235-236, 1918.

¹⁷ *Op. cit.*, p. 235.

¹⁸ *Op. cit.*, p. 235.

duration, and Knott¹⁹ states that: "Within this nucleus of radius .4 the material of the earth has lost its elastic-solid character and can transmit only compressional (primary) waves" and "as the nucleus is approached the material of the earth is becoming less of an elastic-solid and more of an elastic, highly compressed liquid."

The evidence of a breakdown of rigidity in the earth's central portions is difficult to reconcile with Chamberlin's statement²⁰ that rigidity increases "towards the center faster than density.....all the way to the center." "This evidence is thus directly opposed to the conception of an earth core which is dense and rigid." The core is undoubtedly dense but its rigidity has vanished.

Now if rigidity breaks down no matter what the depth for the stress differences of such short duration and small amplitude as seismic waves impose, then the rigidity and elasticity for stress differences of diastrophic dimensions in time duration and magnitude must break down at much more superficial depths. At least no experimental evidence has yet been submitted which proves or even implies that the material within the earth cannot yield, under the long time differential stresses imposed by diastrophic movements, under the conditions of temperature and pressure which exist at not a great depth.

Earth Yielding.—An earth composed of crystalline material could apparently only yield through the dynamic influences of condensation. The adequacy of tidal stresses is questionable. In such an earth the major features of surface relief, such as continents and ocean basins, could hardly be the direct result of diastrophism but could exist only because of differences in density extending to great depths as a result in turn of selective growth with a less volume of dense material falling, during growth, per unit area on the oceanic areas than of less dense material on the continental areas.

It would seem evident that mere surficial loading or underloading of any possible dimensions could not, in a crystalline rigid earth, cause sinking or rising of the earth's surface. It is not even apparent how peneplanation would be followed by uplift and yet without excep-

¹⁹ Op. cit., p. 186.

²⁰ T. C. Chamberlin: Jour. Geology, vol. 29, p. 395, 1921, and Bull. Geol. Soc. Am., vol. 32, p. 224, 1921.

tion such areal denudation has always been followed by uplift of the denuded area. On the other hand, it is probably true that accumulations of sediments do not cause down-sagging though their weight may be additive. In a large measure sedimentation goes on because of down-sagging instead of down-sagging being the result of sedimentation. The fundamental difference in the effects of denudation and sedimentation is undoubtedly due to the relative areas they affect. Denudation is not constricted to narrow belts while sedimentation is, and in spite of the probability of greater load per unit area in depositional belts than underload per unit area in peneplaned areas, these latter areas respond to the underloading and rise. It is a question then, not of underload or overload per unit area, but of areal distribution of load. The evidence back of this is conclusive. The smaller, or narrower, the area the greater the load per unit area necessary to cause down-sinking. In a holocrystalline earth these vertical movements would be entirely controlled, in so far as surficial loading could cause movement, by load per unit area rather than areal distribution of load. If these loads are the result of greater or less density extending to great depths there is no apparent reason why a broad area so loaded should more easily sink or rise than a smaller area similarly loaded. The mere fact of the control by areal distribution rather than by unit area load implies a solid crust of some strength resting on a yield zone beneath.

Direct proof of ready yielding under not excessive load per unit area but broadly distributed is to be found in the very definite record of crustal sinking beneath the Pleistocene ice caps and the rebound following deglaciation. Furthermore, it is becoming increasingly evident that this sinking was accompanied by a corresponding upwarp²¹ at some distance in front of the advancing ice. The on-moving load, in this case, was actually "sliding on thin ice."

Furthermore the universal association of down-sag and upwarp through geologic history is difficult of explana-

²¹ Joseph Barrell: *Movements of the Strand-line in Pleistocene and Post-Pleistocene*, this Journal (4) vol. 40, p. 13, 1914.

R. A. Daly: *Oscillation of Level in Belts Peripheral to the Pleistocene Ice Caps*, Bull. Geol. Soc. Am., vol. 31, pp. 303-318, 1920.

tion on any other assumption than that the earth is, in a large sense, a yielding body.

Density Arrangement Within the Earth.—It is evident that the material within the earth is more dense than the visible material and it is also evident that the density becomes greater with depth though whether this increase continues to the earth's center is problematical. If now the earth is heterogeneous in its constitution from the surface downward then increase in density would be due to increasing pressure and the consequent condensation. This state, as postulated by Chamberlin, implies a chemical constitution throughout the earth, in general, similar to the visible terranes. While he has admitted the possibility of the accumulation of more dense material near the center through the process of selective liquefaction²² Chamberlin's final conclusion is that "the metallic theory fits only clumsily the growing evidence that the interior elasticity and rigidity rise faster than density,"²³ and again, "the tenor of accumulating evidence implies that the conditions which affected the progressive self-compression of the body were more important than those which affected the original assortment of the material."²⁴ The one-fifteenth volume "core" is given finally a density stratification since it was concentrated, by hypothesis, through a "gaseo-molten" line of descent and would "take on a more or less concentric structure similar to that logically assigned to the whole earth by the old-masters."²⁵ The final picture is then of a central core, one-fifteenth of the earth's volume, stratified by density; surrounded by a shell composed of crystalline heterogeneous material, the density of the whole mass being due to self-compression.

The large percentage of metallic alloy in meteorites, even taking into consideration the large number of stony meteorites which are unnoticed, would imply a similarly large percentage of metal in the earth, and if present, and not concentrated towards the center, the surficial earth material should contain more of it and have a

²² T. C. Chamberlin: *Origin of the Earth*, Chicago, 1916, p. 181 and p. 237.

²³ T. C. Chamberlin: *The Greater Earth*, *Bull. Geol. Soc. Am.*, vol. 32, p. 224, 1921.

²⁴ *Ibid.*, p. 223.

²⁵ *Ibid.*, p. 224.

higher density than is actually the case. As Daly has pointed out²⁶ the extrusive rocks should contain conspicuous proportions of the metallic alloys of low temperature fusion. Their absence from the visible extrusive rocks implies their absence from whence these rocks come. Either then the magmas are derived from surficial depths or the metals do not constitute even a small portion of the earth. But this conclusion is not compatible with meteoritic composition nor with the earth's magnetic properties.

Furthermore high pressure experiments indicate that density increases so slowly with increased pressure that even at normal temperatures the pressures within the earth could not give to visible rocks the required density. Again transmitted seismic waves imply a concentric arrangement not only of physical state but of material.

Nor can deductions favoring increase of density by self compression be safely drawn from a consideration of the masses and densities of nearby planets. Chamberlin has stated²⁷ that as between the Moon, Mars, Venus, and the earth there is "an accelerated rate of increase for each increment of mass," and that "this clearly implies that their densities arise from their own massiveness." This implication would carry more weight if the densities of the Moon and of Venus were more accurately known. In so far as the densities are determined these, when plotted against masses, do not fall on an increment curve. The earth's density is too low to even fall on a straight line drawn through the Mars and Moon points, much less showing an accelerated density increase. If the Earth, Venus and Mars points are taken as points on an increment curve, then the Moon's density is too low, and if the earth, Venus and Moon points are taken then the density of Mars is too high. The density of Venus is doubtful so if the Earth, Mars and Moon points be taken as points on a curve these three bodies show a decreasing rate of increase of density for each increment of mass rather than an increasing rate.

To say that "simple pressure experiments are incompetent to determine the limit of self-compression"²⁸ and

²⁶ R. A. Daly: *Igneous Rocks and Their Origin*, New York, 1914, p. 161.

²⁷ *Jour. Geology*, vol. 29, p. 401, 1921.

²⁸ T. C. Chamberlin: *Op. cit.*, p. 402.

then to, on this basis, deduce a great compression reduces the conclusion to an assumption. The reverse line of reasoning was adopted when the determinations of earth rigidity for seismic and tidal stress were taken to indicate a similar rigidity under diastrophic stress conditions.

An earth coarsely stratified by density due to composition rather than compression more readily conforms to the earth's seismic and magnetic properties and can also meet any requirements of rigidity placed upon it. Such an arrangement implies a stage of fusion.

The Molten Stage.

Rate of Growth of the Earth.—If the fundamental postulates of the planetesimal hypothesis be accepted then the question as to whether or not the earth passed through a molten stage at its present size rests upon the assumed size of the original earth nucleus and its rate of growth. Now any conclusion as to the size of this nucleus is pure assumption, but whatever its size at any rate, it passed through a stage of fusion. In order then to secure and maintain solidity through the period of growth only one set of assumptions can be adopted and there are, first, a nucleus of relatively small mass and, second, an exceedingly slow rate of growth. These constitute the basic foundations of the groundwork for the study of megadiastrophism.

The question of fusion is a question of heat generation per unit time, or temperature. It hinges then not so much on the size of the nucleus but on the rate of growth, for this would largely determine the temperatures attained. Rate of growth in turn depends largely upon the orbital dynamics of the interplanetary dispersed material and the ability of the earth nucleus to gather it in.

Chamberlin pictures as the task set for the nucleus, which he assumes to have a diameter of 6,000 miles, the clearing up of a belt 55 by 58 by 592 million miles.²⁰ Gravitation is ignored and growth is assumed to be due entirely to orbital conjunction. Can gravity be so ignored?

²⁰ Op. cit., p. 409, 410.

The earth's sphere of control is approximately 700,000 by 900,000 miles in cross-section area. For the nucleus it would be smaller but still large. It would seem evident that any smaller body passing within these limits would either be entrapped or thrown into a satellitic orbit unless velocity gave to it a sufficient momentum to carry it through. But by hypothesis the planetesimals were "moving in the same general direction, at somewhat similar speeds."³⁰ Relative velocities were thus materially reduced. It would seem that the orbital arrangements then would favor a quite rapid entrapment. The task of the nucleus is thus materially reduced but even approximate determination of growth rate is speculative since the size of the nucleus is also speculative. There is no direct evidence, however, to show that the growth may not have been quite rapid.

Size of Planetesimals.—As Barrell has pointed out³¹ the only direct evidence we have as to size of planetesimals is to be sought in the asteroids. These bodies range in size and numbers from a few over several hundred miles in diameter to many ten miles in diameter and probably many more of still smaller size. The lunar pits offer only questionable evidence, for the cause of these features is not known. But if, as Daly points out,³² the pits are due to impact, then they constitute the record of the last infall since they are not veneered over by finer material.

If there was any great amount of interplanetary dispersed material doubtless much of it, or most of it, was finely divided, but there is no evidence to show that there were not, and there is some evidence to show that there were, numerous bodies of sizes up to some hundreds of miles in diameter. These larger bodies would avoid entrapment the longest owing to their great momentum. The infall may very possibly have been of a larger proportion of finer material at first, with only occasional larger bodies, and finally of a greater proportion of larger bodies.

³⁰ T. C. Chamberlin: *Ibid.*, p. 40.

³¹ Joseph Barrell and Others: *The Evolution of the Earth*. Yale Univ. Press, New Haven, Ct., 1920, p. 26.

³² R. A. Daly: *The Planetesimal Hypothesis in Relation to the Earth*, *Scientific Monthly*, May, 1920, p. 489.

Heat of Impact.—The efficacy of the heat generated by impact of planetesimals is doubted though probably the additive effect if the larger sized bodies were pelted into a molten or nearly molten surface would be greater than if pelted onto a solid surface. The heat problem is more concerned with the rate of growth rather than with size of planetesimals and their impact effect.

Résumé.—In the speculative field of geogenesis there seems to be no direct or conclusive evidence which forbids belief in a molten stage for the earth at approximately its present size. To assume that the original earth nucleus was about the same size as the present planet and was, by hypothesis, molten seems just as reasonable as to assume that the nucleus was small and grew slowly. But any conclusion in this field is rendered indefinite by some pure assumption with no evidence back of it. More direct evidence is to be sought in a consideration of the present physical state of the earth, previously discussed in its recorded diastrophic history, and in the field relationships of the igneous rocks. As Daly concludes:³³ "As critical facts are slowly accumulated, the greatly appealing planetesimal hypothesis of Chamberlin and his co-workers may well serve as a foundation for geological philosophy, though the subsidiary doctrine of essential crystallinity for the earth throughout geological time be not accepted."

The Earth's Diastrophism.

The evidence submitted by Chamberlin on the diastrophic capabilities of the earth as indicating a solid, crystalline, and heterogeneous state throughout does not seem conclusive and is susceptible of more than one interpretation.

A "gaseo-molten" earth is pictured by Chamberlin as wasting its dynamic energy in maintaining fluidity leaving "little possibility of shrinkage left except the meagre amount that could arise from further cooling."³⁴ But is not this "meagre amount" sufficient to have produced the visible diastrophic record? To attempt to trace a pre-Archean diastrophism far greater in amount than all

³³ R. A. Daly: Op. cit., p. 495.

³⁴ T. C. Chamberlin: Bull. Geol. Soc. Am., vol. 32, p. 199, 1921.

of that recorded would seem to be unnecessary. But then with the prior assumption of a crystalline heterogeneous earth it becomes necessary, of course, to further assume a very great and deep-seated diastrophism of long duration. Daly has clearly shown³⁵ that simple cooling may be far less effective in volume change than that due to changes in state, both from liquid to solid and from one solid form to another as a result of static metamorphism. These changes together with contraction due to secular cooling would, it seems, be amply sufficient to cause all the lateral deformation of which we have record.

The actual total circumferential shortening of the earth since Proterozoic time, as recorded on any great circle, is not over 200 miles and is probably nearer 100 miles. If it is 150 miles the total radial shrinkage is then about 24 miles. The amount of shortening and shrinkage that can be allotted to pre-Paleozoic time is, of course, indefinite. It may not be as much as is generally supposed. Structural deformation of at least Proterozoic terranes is not generally excessive and the Archean rocks are largely igneous, bespeaking great magmatic engulfment and intrusion. Magmatic engulfment and intrusion on such a large scale may well be potent factors in themselves in lateral deformation. Where these pre-Paleozoic terranes do show isoclinal folding they have usually been involved in later deformation. At least their close association with belts of later folding is significant.

If the earth has suffered any such radial shrinkage as 700 miles, as deduced by Chamberlin by the hazardous method of density mass comparisons as between the earth and its nearby neighbors,³⁶ then a major part of this shrinkage was taken up during the period of growth and the resulting diastrophic record lies in depths forever hidden from view.

If now diastrophism is the expression of deep-seated inner reorganization due to condensation upon mass increase, what is to provide the diastrophic energies after the cessation of growth? Are we to conclude that this inner reorganization in favor of greater density is to continue without additional mass increase? Either way these questions are answered, it would seem that diastro-

³⁵ R. A. Daly: *Igneous Rocks and their Origin*, New York, 1914, p. 176.

³⁶ *Jour. Geology*, vol. 29, p. 400, 1921.

phism should grow progressively less after cessation of growth. But this conclusion is difficult to reconcile with Cenozoic deformation which far transcends all other post-Proterozoic orogeny.

On the other hand, with a slowly thickening crust resting on a yield zone (asthenosphere), crustal yielding, both in time and degree, is a factor of crustal strength. Periodicity of deformations in crescendoes to a high point indicate increasing crustal strength and so an increasing capacity for accumulating stresses before the breaking point is reached. Under this view the pre-Paleozoic deformations represent the rather easy yielding of a comparatively thin crust and its widespread magmatic engulfment. From the viewpoint of an earth whose diastrophic energies arise in the deep interior it is rather difficult to explain periodic deformation, for the forces must be continuously active and, since the surficial portions of such an earth would be weaker than any underlying portions, deformation could hardly result from accumulative stresses.

Even if the postulated method of very slow growth by planetesimal accretion with its consequent state of absolute solidity for the earth be accepted, the existence of any great reserve of diastrophic energy may be seriously questioned. If this growth took three or four billion years it would seem that this would give ample time for a very complete inner reorganization *pari passu*, leaving an earth practically immune to deformational stress.

The Earth's Volcanism and the Evidence of the Igneous Rocks.

Volcanism, of course, using the term in its broadest sense, finds little place in the groundwork for studies in megadiastrophism. It is considered as merely an "accessory" to a "profoundly metamorphic earth." A once molten earth would, according to Chamberlin, not only waste its dynamic energy and become diastrophically sterile but "there should have been developed and brought to the surface *all*³⁷ the gaseous material in the earth substance which high heat could set free," and "an earth-body formed in this way should be unsuited

³⁷ The italics are mine—W. F. J.

to give rise to such a degree of gaseous volcanism as is actually manifested."³⁸

The first statement quoted needs some qualification, for the amount of gas set free is not only a question of heat but also of pressure. Very evidently under the pressure conditions existing at no great depth very material quantities of gas would remain entrapped.

The second statement quoted also requires some discussion for it is doubtful if the major manifestations of volcanism require any such great stores of gaseous material as are implied. By far the larger part of volcanism has been expressed in fissure eruptions and deep-seated intrusions. The mechanisms of both of these do not call into use any mechanical force from gaseous expansion. In fact, the greater lava floods are very often free of vesicularity. Volcanic eruptivity of the central vent type is not conspicuous in the igneous record of pre-Tertiary time. Only in late-Tertiary and recent times have the dying phases of an era of great volcanism expressed themselves in vent eruptivity on what may possibly be called a worldwide scale. Such is to be expected under the conception of a slowly thickening crust. Furthermore, volcanic vent eruptions call into use only localized concentrations of the juvenile gases in their underlying diatremes or cupolas.

The broad facts of the occurrence of igneous rock types become extremely difficult of explanation under the conception of an earth composed throughout of material similar to the visible rocks from which magmas are derived by deep-seated selective liquefaction. Chamberlin states³⁹ ".....if magmas consist merely of partial solutions of heterogeneous mixtures, they would quite certainly become highly diversified in the making. The primary problem would then lie in the generation of the magmas; in the ascent of magmas rather than their descent. *While differentiation in the process of solidification would still remain a factor, it would be a secondary matter, in the sense that it was necessarily conditioned by the previous generative process.*"⁴⁰ Each

³⁸ Bull. Geol. Soc. Am., vol. 32, p. 207, 1921.

³⁹ Op. cit., p. 208.

⁴⁰ The italics are mine—W. F. J.

particular case presents an *a posteriori* problem of its own. It is wholly unembarrassed by any requirements that its factors shall sum up into a speculative primitive magma.”

From this scheme of magma derivation two broad conclusions may be drawn: First, the tongue melts reaching the surface should be, at least, within continental areas, generally acidic in composition, since they are supposedly derived from the selective liquefaction of the more fusible constituents of an earth whose composition is similar to the visible rocks and this composition is that of common granite; second, the acidity should decrease towards basicity with time since the process implies the liquefaction of less and less fusible constituents as interior condensation progresses.

On the other hand the outstanding fact of the occurrence of the igneous rocks is the striking uniformity in composition of the great extrusive flows, this similarity extending in time from the most ancient extrusive masses of Archean age down to the present, and in location world wide. Diversification is absent. And the composition of these extrusives is predominantly basaltic. Acidic extrusives are conspicuous by their almost complete absence. Derivation of these great and persistent outpourings of basaltic material from an essentially acidic earth is not only difficult to explain by the process of selective liquefaction but, on the other hand, if they are considered as differentiates of a more acidic magma, then, as Daly has pointed out:⁴¹ “The acid pole of such a hypothetical splitting ought to be on a similarly large scale.” Nor can the acid intrusive masses fill the need, in this case, of the acidic derivative, for then a further explanation would be necessary to account for the predominant intrusive form of the acid and the predominant extrusive form of the basic poles. Furthermore, the fact of discordancy of the batholithic contacts together with the fact that the structural delineaments of roof and wall rocks are merely truncated at the contact surfaces rather than altered implies that large masses of these rocks have been engulfed and have added their high acidity to a previously more basic magma.

⁴¹ R. A. Daly: Op. cit., p. 164.

Bearings on Isostasy.

It is, of course, an evident fact as Chamberlin states⁴² that: "a liquid earth should be an ideal example of perfect isostasy in the highest sense—that is, isostasy in perfect horizontal as well as vertical adjustment," but is the further statement that: "the earth's crust, as it began to form, should have inherited this quality in full perfection"⁴³ true in its implications? This statement implies that any subsequent deformation of the crust would merely act as an upsetting influence to this perfect isostatic state. Now perfect isostatic adjustment in a "horizontal" direction does not mean, of course, perfect leveling of the surface unless, of course, in the case of a crustified earth, the crust is of uniform composition and thickness in a worldwide sense. Such an ideal state may possibly have obtained immediately after crustification. But this thin crust must have been very weak and readily subject to disruption. Fragmentation would involve engulfment, the outpouring of more basic materials and their solidification would then introduce heterogeneities of density in the crust and those portions so weighted down would seek their level of adjustment. The broader the area so weighted down, the more perfect would that adjustment be. In fact, the suggestion has been made by Willis and Barrell⁴⁴ that the ocean basins owe their origin to such a process as this.

A state of perfect isostasy is, under this view, possible only within the limitations imposed by the strength of the earth's crust and that strength becomes small for broadly distributed loads and great for more constricted loads and so an almost perfect state of isostatic adjustment must prevail as between oceanic depressions and continental areas. There is no antagonism here between isostasy and diastrophism. The strength of the earth's crust merely interposes as a barrier to perfect adjustment. Diastrophism is the expression of the final overthrow of the crustal resistive power and this overthrow

⁴² *Op. cit.*, p. 209.

⁴³ *Idem.*, p. 209.

⁴⁴ Joseph Barrell & Others: *The Evolution of the Earth*, 1920, pp. 39-43.
Bailey Willis: *The Discoidal Structure of the Lithosphere*, *Bull. Geol. Soc. Am.*, vol. 31, p. 298, 1920.

results in a more nearly perfect isostatic balance. Diastrophism is then the corrective. This is the view so ably developed by Barrell in his monumental treatise on "The Strength of the Earth's Crust."⁴⁵ Heterogeneities of load whether due to erosion, deposition, or to the introduction of intrusive or extrusive masses control, within the limits imposed by crustal strength and distribution, the degree of adjustment attained. These heterogeneities are for the most part visible and determinate. Beneath this heterogeneous layer, according to the evidence both of the igneous rocks and transmitted seismic vibrations, there lies homogeneous material which is capable of yielding under the larger differential stresses to which it is subjected. Broad scale heterogeneities of the surface shell must result in similarly broad scale and generally permanent major reliefs. This view is based upon what we can see. The opposing view—that of Chamberlin—must be built upon an assumed asymmetric earth core upon which was laid down, over a period covering several billion years and through the whims of the atmosphere, a selective rain of planetesimal dust. This constitutes the foundation for the study of "megadiastrophism." Is that foundation secure?

But the conception of an isostatic heterogeneous shell resting upon a homogeneous yield zone does not, of course, permit the application of deeply pointing wedge deformation to areas of continental dimensions.

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⁴⁵ Joseph Barrell: *The Strength of the Earth's Crust*: Jour. Geology, vols. 22, 23, 1914-1915.