ART. XXIX.—The Earth’s Crust and its Stability; by Reginald A. Daly, Harvard University.

Reality of a crystalline crust resting on a non-crystalline substratum.

Thickness of the crust.

Evidence of thermal gradients.

Evidence from seismology.

Evidence from cosmogony.

Supposed evidence from geodesy.

Stability of the crust.

Hypothesis of the sliding of the continents.

Summary.

_Reality of a Crystalline Crust Resting on a Non-crystalline Substratum._

A half-century ago geologists were accustomed to use the expression “earth’s crust” as meaning a crystalline superficial shell everywhere supported by non-crystalline material, the substratum. According to some geologists of the present day, the demonstrated high rigidity of the globe, tested by its behavior under short-period stresses, imply crystallinity for the earth’s substance down to very great depth, if not to the center itself. This belief is held in spite of the fact that rock-glass, like commercial glass, is highly rigid at ordinary temperatures. Moreover, the same authorities attribute the observed mean rigidity of the earth—variously estimated to be from three to ten times that of the stiffest granite—more to internal pressure than to holocrystallinity of the material. Under increasing cubic compression, glass is stiffened more rapidly than is granite or diabase. Evidently, therefore, the earth’s rigidity does not of itself prove crystallinity for the earth-shells to any great depth below the surface. On the other hand, better criteria seem to agree in showing that the old conception of the “earth’s crust” is well justified, though the accessory postulate of considerable mobility for the substratum has been proved erroneous.

The matter is of fundamental importance in connection with large problems, including those relating to the stability of the lithosphere, mountain-building, the horizontal movement of continents, igneous action, and the nature and depth of isostatic compensation. The following paper is intended to summarize the independently derived facts and reasonable inferences which all tend to prove the relative thinness of the crust. Variation in its thickness is indicated. The average density of the crust is found to be greater than the density of the upper part of the substratum. This implies instability for the crust, under certain conditions. The paper closes with an application of the meaning of the new facts and deductions for the theory of tangential displacements, and a brief sketch of the theoretical evolution of the crust. The sketch includes a new version of the sliding hypothesis, which has been developed in explanation of the cordilleras, the younger ocean-basins, and the mystery of the "land-bridges" between the continents.

The writer wishes to express his gratitude to many colleagues for their helpful discussions of the many hard problems involved; especially to Professor P. W. Bridgman of Harvard University, Mr. W. D. Lambert of the United States Coast and Geodetic Survey, and Dr. C. E. Van Orstrand of the United States Geological Survey. None of these gentlemen should in any way be held responsible for the errors which may be found in the ensuing, wide-ranging speculations.

**Thickness of the Crust.**

Estimates of the actual thickness of the crust have been made from two quite different sets of data, namely, temperature observations and the characteristics of seismic vibrations. These estimates agree as to order of magnitude, both between themselves and with the thickness deduced from the best theory of cosmogony and from the theory of isostatic adjustment.

**Evidence of Thermal Gradients.** The temperature gradients in the suboceanic crust can not be directly measured. The gradients under continental surfaces are highly variable, for reasons both obvious and hidden. The mean surface gradient in places removed from the
influence of recent igneous or orogenic action is usually stated to be about 3° C. per 100 meters of depth. This is not far from a fair average for Europe; painstaking measurements in North America give a different average.

For the purpose of comparing the two means, Prestwich's useful summary of the older observations and also the newer, reliable figures for deep borings may best be used. Only those results should be employed that refer to geologically comparable districts in the two continents. The best data come from central and western Europe and from the eastern part of the United States. The Armorican-Herecynian mountain system and associated plateaus match well with the Appalachian system and associated plateaus, in lithology and geological history, so far as surface rocks are concerned. Neither region has undergone intense deformation or significant igneous invasion since the close of the Mesozoic era. In fact, few other parts of these continents are likely to give a better idea of a systematic difference in the thermal gradients, if such difference exists.

Averages are preferable to single determinations, however carefully made. On the other hand, the averages should be compiled only from the best determinations. In general the latter have been made at deep borings, but, to broaden the basis of reasoning, Prestwich's averages for coal-mines may also be noted. His mean gradient for eight British and Belgian mines is 1° C. per 26.9 meters of depth; that for three West Virginia mines is 1° per 37.3 meters.1

The more reliable determinations in deep borings are worthy of more detailed description, which is here given in tabular form. The figures have been taken from Prestwich; from W. Trabert's Lehrbuch der Kosmischen Physik; from G. S. Rogers' Professional Paper No. 117 of the United States Geological Survey (1919); from C. E. Van Orstrand's report in the 1918 volume of the West Virginia Geological Survey; from an article by I. C. White in the Ohio Gas and Oil Men's Journal, September, 1919; from N. H. Darton's bulletin (No. 701) of the United States Geological Survey, 1920; and from an article by J. Koenigsberger and M. Mühlberg in B. Bd. 31 of the Neues Jahrbuch für Mineralogie, etc., 1911.

### Thermal Gradients in European Borings

<table>
<thead>
<tr>
<th>Location</th>
<th>Total depth (meters)</th>
<th>Gradient (meters per 1° C.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kentish Town</td>
<td>335</td>
<td>28.7</td>
</tr>
<tr>
<td>Richmond</td>
<td>407</td>
<td>28.3</td>
</tr>
<tr>
<td>Searle</td>
<td>609</td>
<td>37.8</td>
</tr>
<tr>
<td>Grenelle</td>
<td>401</td>
<td>30.2</td>
</tr>
<tr>
<td>Ecole Militaire, Paris</td>
<td>173</td>
<td>29.6</td>
</tr>
<tr>
<td>Rochefort</td>
<td>857</td>
<td>27.4</td>
</tr>
<tr>
<td>Creuzot</td>
<td>816</td>
<td>28.5</td>
</tr>
<tr>
<td>Pont-à-Mousson</td>
<td>1556</td>
<td>30.2</td>
</tr>
<tr>
<td>Martincourt</td>
<td>1200</td>
<td>31.0</td>
</tr>
<tr>
<td>Ratum, Holland</td>
<td>1309</td>
<td>34.0</td>
</tr>
<tr>
<td>Maris, Holland</td>
<td>1300</td>
<td>27.7</td>
</tr>
<tr>
<td>Sperenberg</td>
<td>1066</td>
<td>33.7</td>
</tr>
<tr>
<td>Schladebach</td>
<td>1748</td>
<td>35.7</td>
</tr>
<tr>
<td>Sennewitz, near Halle</td>
<td>1084</td>
<td>36.5</td>
</tr>
<tr>
<td>Lieth, near Altona</td>
<td>1259</td>
<td>35.0</td>
</tr>
<tr>
<td>Sudenburg, near Magdeburg</td>
<td>508</td>
<td>32.3</td>
</tr>
<tr>
<td>Paruschowitz</td>
<td>2003</td>
<td>31.8</td>
</tr>
<tr>
<td>Czuchow</td>
<td>2240</td>
<td>31.8</td>
</tr>
</tbody>
</table>

**Average**: 31.7

### Thermal Gradients in North American Borings

<table>
<thead>
<tr>
<th>Location</th>
<th>Total depth (meters)</th>
<th>Gradient (meters per 1° C.)</th>
<th>Means by States</th>
</tr>
</thead>
<tbody>
<tr>
<td>Columbus, Ohio</td>
<td>785</td>
<td>40.0</td>
<td>40.0</td>
</tr>
<tr>
<td>Louisville, Kentucky</td>
<td>636</td>
<td>41.1</td>
<td>41.1</td>
</tr>
<tr>
<td>St. Louis, Missouri</td>
<td>923</td>
<td>42.9</td>
<td>42.9</td>
</tr>
<tr>
<td>St. John, Illinois</td>
<td>1138</td>
<td>45.8</td>
<td></td>
</tr>
<tr>
<td>Chicago, Illinois</td>
<td>229</td>
<td>48.3</td>
<td>47.0</td>
</tr>
<tr>
<td>Bay City, Michigan</td>
<td>1053</td>
<td>37.5</td>
<td>37.5</td>
</tr>
<tr>
<td>McDonald, Pennsylvania</td>
<td>2126</td>
<td>41.2</td>
<td>40.7</td>
</tr>
<tr>
<td>West Elizabeth, Pennsylvania</td>
<td>1524</td>
<td>40.2</td>
<td></td>
</tr>
<tr>
<td>Wheeling, West Virginia</td>
<td>1359</td>
<td>45.5</td>
<td></td>
</tr>
<tr>
<td>Chelyan, West Virginia</td>
<td>1596</td>
<td>40.2</td>
<td></td>
</tr>
<tr>
<td>Mannington, W. Va. (mean of 6 wells)</td>
<td>603 to 983</td>
<td>53.7</td>
<td></td>
</tr>
<tr>
<td>Bridgeport, West Virginia</td>
<td>2198</td>
<td>38.4</td>
<td></td>
</tr>
<tr>
<td>Prickett’s Creek, West Virginia</td>
<td>2286</td>
<td>35.7</td>
<td></td>
</tr>
</tbody>
</table>

**Mean of 15 West Virginia wells**: 579 to 2286

**Grand Average**: 41.8
The average gradients given in the two tables are strikingly different. Considering the depths of these holes and the high quality of the physical observations, the eighteen European and twenty-three American cases furnish no mean material for comparison. The result is the suggestion that the surface rocks of North America are considerably cooler than the surface rocks of Europe.\footnote{A conceivable explanation may be found in the comparatively recent sliding of North America over the sunken crust of the old, Greater-Pacific basin. The consequent chilling of this earth-sector and perhaps also its more rapid cooling before the epoch of sliding may still affect the North American gradient.}

Because of insufficient data good averages for similarly large areas in the other continents can not yet be estimated.

Since surface conditions cause the gradient to vary more or less erratically, attention should be confined to the deeper borings when the attempt is made to discover any systematic relation of the gradient to depth. The following table shows roughly the nature of the curve near the top and near the bottom of each of eight of the best-studied borings of North and South America and Europe. On account of the strong influence of natural gas on the temperature of bore-holes, only those records are used which are not seriously affected by the outflow of gas. The records of no wells less than 2,000 feet in depth are entered. The great depths of the West Virginia holes and the carefulness of the observations by Van Orstrand have prompted the entry of as many as four borings from this one State.

Each bore-hole gives a more rapid rate of temperature increase at the bottom than near the top. No one of the pairs of figures nor the respective averages can, of course, be taken as properly expressing the mean rate of the change in gradient within the first kilometer or more beneath the earth's surface. Yet the qualitative result is clear. Dr. Van Orstrand of the United States Geological Survey has made an elaborate analysis of many hundreds of borings and has come to the same qualitative conclusion (verbal communication). Corroboration from his masterly and much more complete study gives confidence in the result obtained from the few serial records which may be safely used by one who is not especially experienced in the technique of this kind of investigation.
Thermal Gradients near Top and Bottom of Borings—showing in meters per 1° C. the average gradients between the depth limits given in columns 2 and 3; and in columns 4 and 5, the differences of temperature for the different pairs of limits.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Limits above (meters)</th>
<th>Limits below (meters)</th>
<th>Diff. T. C. above</th>
<th>Diff. T. C. below</th>
<th>Gradient above</th>
<th>Gradient below</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volcano Jn., W. Va. ......</td>
<td>152-305</td>
<td>1143-1265</td>
<td>3.10</td>
<td>5.30</td>
<td>49.2</td>
<td>28.8</td>
</tr>
<tr>
<td>Grantsville, W. Va. ......</td>
<td>610-814</td>
<td>1067-1341</td>
<td>7.05</td>
<td>8.70</td>
<td>43.2</td>
<td>35.1</td>
</tr>
<tr>
<td>Valley Falls, W. Va. ......</td>
<td>305-610</td>
<td>1391-2286</td>
<td>7.14</td>
<td>7.80</td>
<td>42.7</td>
<td>39.1</td>
</tr>
<tr>
<td>Bridgeport, W. Va. ......</td>
<td>1929-2198</td>
<td>7.06</td>
<td>14.90</td>
<td></td>
<td>43.1</td>
<td>26.8</td>
</tr>
<tr>
<td>Simple averages for the four West Virginia wells</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>44.5</td>
<td>33.2</td>
</tr>
<tr>
<td>Bay City, Michigan .......</td>
<td>397-546</td>
<td>804-1063</td>
<td>3.33</td>
<td>3.81</td>
<td>44.7</td>
<td>41.8</td>
</tr>
<tr>
<td>Schlaedebach ..............</td>
<td>36-336</td>
<td>936-1236</td>
<td>8.00</td>
<td>8.38</td>
<td>37.5</td>
<td>35.8</td>
</tr>
<tr>
<td>Parushowitz ...............</td>
<td>99-502</td>
<td>1556-1959</td>
<td>10.00</td>
<td>14.30</td>
<td>40.3</td>
<td>28.2</td>
</tr>
<tr>
<td>St. John del Rey, Brazil*</td>
<td>1228-1503</td>
<td>1685-1871</td>
<td>3.7</td>
<td>3.4</td>
<td>74.1</td>
<td>54.7</td>
</tr>
</tbody>
</table>

* From information supplied by Dr. C. E. Van Orstrand.

Incidentally some suggestions as to cause may be noted. Dr. Van Orstrand suspects the influence of water, specially abundant near the surface. Perhaps more important is the lowering of conductivity, and therefore also diffusivity, by increase of temperature in rock minerals.\(^3\) The opposite effect of increasing pressure on the conductivity of these substances is probably far less significant, as suggested by experiments by Lees on granite and marble and by analogous experiments of Bridgman on metals.\(^4\) Almost certainly a given crust-pressure counteracts but little the effect of the corresponding temperature on the conductivity of the crystalline material. Hence an acceleration of the increase of temperature, down to the depth of a few kilometers, is not surprising, even if the circulation of water were of negligible importance.


\(^4\) G. H. Lees, Mem. Lit. and Phil. Soc. Manchester, vol. 43, No. 8, 1898-9; P. W. Bridgman, Proc. Acad. Arts and Sciences, vol. 57, p. 77, 1922. New unpublished experiments by Professor Bridgman show that 12,000 atmospheres of pressure increase the conductivity of limestone, slate, and pipestone no more than in the case of metals like lead or tin.
Doubtless the acceleration diminishes to zero at the depth of some kilometers below the bottom of the deepest bore-hole listed, but to that greater depth the rate of increase of temperature is higher than that determined from existing bore-holes, mines, and tunnels. Still deeper, the acceleration becomes negative very slowly.

The accepted gradient of about 3° per 100 meters has actually been determined from openings averaging less than about 600 meters in depth. Down to a depth of 40 kilometers the average gradient is likely to be nearly the same, though it may be nearer 3.5° per 100 meters. In western and central Europe, therefore, the temperature at this depth is probably more than 1200° C.

Vogt, Barus, and others have shown that the pressures ruling in the first hundred kilometers of depth in the earth have, when compared with the corresponding temperatures, practically negligible importance on the melting temperature of diabase. According to Vogt the pressure of 1,000 atmospheres raises the melting temperature of this rock only about 5°. The pressure at 40 kilometers is about 12,000 atmospheres. At atmospheric pressure diabase begins to melt well below 1200°. If Vogt is right, diabase can not be holocryustalline at the depth of 40 kilometers below the surface of western Europe, unless the thermal gradient there changes below surface in a way contrary to both experience and theoretical expectation. The facts of igneous geology show that diabase is a good representative of the kind of material which underlies the visible rocks at the depth of a few tens of kilometers.

This diabasic or basaltic substratum lies somewhat deeper in eastern North America than in western Europe, if the testimony of the bore-holes can be trusted.

Judging from volcanic products and from the control of isostasy over the greater reliefs of the globe, one is justified in assuming an approximate basaltic composition for both the crust and substratum under the deep oceans. An idea of the average thermal gradient in these vast areas has not been obtained from borings. As noted below, a quantitative estimate of it has been derived from the study of seismic vibrations. A more qualitative conception is possible if an assumption is

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made regarding the cause of the earth’s internal temperature.

If the heat of the interior were wholly primitive and the existing gradients were due to the cooling of a globe possessing a primitive gradient, the rate of temperature increase under the oceans should now be greater than the rate ruling under the continental surfaces. This conclusion would follow, since the diffusivity of the saline, continental rocks is considerably higher than the diffusivity of basaltic or trappean rocks. A committee of the British Association for the Advancement of Science (1881 session) found that the diffusivity of traps and whinstones at low temperatures averages 0.0067 in C. G. S. units. Stadler’s specially careful determinations of the diffusivity of granite (typical of continental rocks) at low temperatures gave a mean of 0.01647 in the same units. The rate of change of diffusivity for each rock type with simultaneous increase of temperature and pressure is unknown, but it is reasonable to suppose that it will be nearly the same in the two cases. If so, the relative thickness of a granitic layer and a trappean or gabbroid layer, with identical respective temperatures on the hot and cool faces, can be roughly estimated; under the assumed conditions the continental crust would be thicker than the suboceanic crust, the substratum being basaltic in each case.

On the other hand, granite or orthogneiss appears to be nearly four times as radioactive as rocks of basaltic composition. If, with Holmes, the heat responsible for the surface gradient be regarded as largely of radioactive origin, it follows that the rate of temperature increase in continental areas with increase of depth should be higher than the rate in oceanic sectors, the influence of differential diffusivity being overpowered. On this assumption the suboceanic crust is to be considered thicker than the crust under the continental surface; the crust under the center of the oldest ocean-basin should be slightly thicker than near its edge, and the thinnest crust should be near the center of the largest continental block, that of Eurasia-Africa.

_Evidence from Seismology._—In 1906, from his study of earthquake records, Oldham concluded that the outer

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crust of the earth "cannot be more than about a score of miles thick." He estimated the material, to a depth of some hundreds of kilometers below the surface, to have an average modulus of resistance to distortion approximating 15 times that of granite; yet stated that this high rigidity is "quite compatible with the yielding to stresses of long duration, which is required by the known facts of structural geology and need not necessarily be inconsistent with those movements of convection currents which Mr. Fisher believes to exist in the interior of the earth." Also in 1906, Milne, for similar reasons, wrote that 30 miles is "a maximum depth at which we should look for materials having similar physical properties to those we see on the earth's surface." The next year Wiechert published his deduction that there is a distinct change in the character of the material at about 35 kilometers below the surface. Though the material below that level is endowed with shearing elasticity, it yields "so completely to the slowly changing stresses brought into play by the shifting of masses during geological periods, that the earth's crust seems to float on a liquid substratum." Similarly, Knott writes: "There is nothing physically unsound in the hypothesis that the nucleus of the earth is capable of transmitting distortional as well as compressional vibrations, but is at the same time incapable of resisting indefinitely continued action of steady distortional stresses. . . . Fluidity and elasticity of form are not of necessity incompatible or mutually antagonistic." Love concluded his study of earthquake waves with the remark: "There is a veritable 'crust of the earth.'"

In 1913 Oldham placed the depth of the first decided change in elastic constants at 16 kilometers below the surface, but noted that seismograms do not exclude the possibility of further change between the depths of 16 kilometers and 160 kilometers. Five years later he wrote: "Three distinct divisions can be recognized in the

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interior of the earth:—(1) The outer crust of solid matter possessing a high degree of rigidity, whether against permanent or temporary stress, of comparatively small thickness amounting to about one-half of one per cent and not more than one per cent of the radius; (2) a shell of material of thickness about one-half of the radius which has high rigidity as against stress of the duration involved in the production of the tides, or of shorter duration, but, in the outer part at least, a comparatively low power of resistance to stress of secular duration; and (3) a central nucleus of material which has a very low degree of rigidity even against stress of only a few seconds’ duration. The transition from the first to the second of these three divisions is somewhat abrupt, sufficiently so to give rise to reflection; between the second and third the passage is more gradual, and lies at about 4/10 or 5/10 of the radius from the center of the earth.”

These authorities have deduced the existence of a discontinuity corresponding to that at the contact of a crust and substratum. They agree as to the order of thickness possessed by the crust. They do not agree as to the mobility of the substratum, and there are reasons for doubting Wiechert’s conclusion that this shell can be fairly called a “Magmaschicht.” The significant point is that a strong discontinuity must be assumed in order to explain the transmission of transverse waves along the earth’s surface. The discontinuity itself is most easily understood if it be conditioned by the contrast of a homogeneous, vitreous shell underlying a heterogeneous, crystalline crust.

The seismologists have, thus, found a discontinuity at an average depth of about 35 kilometers, a depth closely similar to the depth of the crystalline shell, as estimated by reasonable extrapolation from surface gradients. Quite recently, Angenheister has gone a step further and from seismograms has read out the average thickness of the sub-Pacific crust as 41 kilometers and the average thickness under the surface of Eurasia as 28 kilometers. If correct in principle, his conclusion is highly significant. The fact which he has discovered seems to find

explanation in differential radioactivity, as above suggested.

Evidence from Cosmogony.—Some geologists believe that the tidal-disruption theory of the solar system is incompatible with the existence of a thin, crystalline crust resting on a non-crystalline substratum. More specifically, this belief is shared by those who have adopted that form of the tidal-disruption theory developed by Chamberlin and Moulton. If the earth grew from a very small knot or nucleus, and if the growth depended on the very slow accretion of planetesimals, it is conceivable that the earth’s temperature never rose to the amount required for the liquefaction (vitrification) of the material at and near the surface. Yet the four outer planets of the solar system, syngenetic with the earth, are now hot enough to have the densities of gaseous globes. No one has yet shown reason to believe that the rate of accretional heating in the case of the earth was much slower than in these other cases, to the extent of forbidding belief in liquidity of the earth at its surface, after our planet had attained its present mass. The writer is of opinion that geologists may well ponder the conclusion of Jeans, who thinks the accretion of planetesimals to have been much less important in the development of the planets. He prefers the view that the tidal disruption of the sun produced gaseous nuclei nearly as massive as the existing planets. He considers the four outer planets to have been gaseous from the beginning, but leaves open the question as to the state of the material of the evolving earth. However, he is not averse to the hypothesis of a former molten condition for the earth’s surface shell. Jeffreys positively favors this hypothesis.¹⁴

The latest and apparently the soundest scheme of cosmogony thus seems to permit the hypothesis that the earth was once fluid at the surface. On that hypothesis it becomes possible to understand the distribution of densities in the earth’s interior. The ellipticities of the

internal shells of respectively uniform density are almost exactly those calculated for a fluid, heterogeneous globe rotating with the angular velocity of the earth. Geophysicists are now agreed in the view that the actual arrangement of densities is not to be explained merely by pressure acting on a homogeneous substance or on a homogeneous mixture of substances. The increase of density with depth is attributed largely to intrinsic differences in the chemical composition of the successive shells. The various discontinuities discovered in the earth’s body by the seismologists illustrate those differences. Within the earth there has been a pretty thorough sorting of chemically distinct materials, a sorting carried almost to the point of perfectly hydrostatic conditions at all depths. Is it reasonable to believe that an initially heterogeneous and solid-crystalline earth could so re-arrange its constituents during any finite time? Must not an adequate cosmogony include among its assumptions those which inevitably demand a molten, if not gaseous, state for the earth after it had practically attained its present mass?

But one who postulates a former fluid state is bound to doubt holocrystallinity for the earth’s interior at its present stage. Even if the planet is a billion years old, its crust, formed by radiation of heat and consequent crystallization, can not be very thick, especially if radioactivity has been important.\(^\text{15}\)

Supposed Evidence from Geodesy.—Many writers have assumed that the crust has a thickness of about 120 kilometers, because this is the most probable depth of the layer of isostatic compensation on the assumption of uniform compensation in depth. The artificial and highly improbable nature of this assumption is therewith ignored. The geodesists have proved the center of gravity of the compensation for the average relief to be located at a depth of 30 to 60 kilometers. They are as definite in that conclusion as they are open-minded regarding the mode of distribution of the compensation and the depth of the layer. A brief discussion must here suffice to indicate the grounds for belief in the consistency of the idea of a crust, approximating 40 kilometers in thickness, with the rule of isostasy and with the probable mechanism of isostatic adjustment.

The earth's crust is essentially holocrystalline and its mean ultimate strength was estimated by Barrell as about equal to that of good granite. He estimated the ultimate strength of the underlying shell—the asthenosphere—to be about 5 per cent. of that of granite. This means that the asthenosphere is capable of supporting stress-differences equivalent to the pressure of 50 to 100 atmospheres. He explained the strength of this shell by assuming it to be holocrystalline, though very hot. Its crystallinity was deduced by Barrell because he shared the common doubt that one can safely extrapolate from the observed thermal gradient. However, the new evidence outlined above seems to allow of little choice in the matter; at the depth of about 40 kilometers holocrystallinity is highly improbable. The long persistence of stress-differences in the asthenosphere must, apparently, be explained in some other way.

In the present writer's opinion the explanation is probably to be found in the behavior of hot (basaltic) glass, which constitutes the substratum or upper part of the asthenosphere at least. At one atmosphere of pressure, hot glass is an elastico-viscous substance. Under short-period stresses it exhibits rigidity to a degree depending on the temperature. As a given stress is prolonged at a constant temperature, the rigidity breaks down; some flow takes place and by so much the stress is relieved. The glass has attained a permanent set. The time of relaxation varies rapidly with temperature, and, according to Adams and Williamson, it varies inversely with the square of the stress. The effects of cubic compression on hot glass have never been quantitatively determined, but it seems highly probable that such compression increases not only the rigidity but the time of relaxation as well, at least in the temperature range represented in the first 100 or 200 kilometers of depth in the earth. Admitting the two effects of pressure, one has little difficulty in imagining the asthenospheric glass to have rigidity and modulus of relaxation meeting the requirements of a proper theory of tidal, nutational, and seismic strains. At the same time the subcrustal shell permits isostatic undertow, with additional yielding in

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deeper interior, so that a nearly hydrostatic condition of the earth is preserved in spite of the transfer of masses on the surface. In other words, the substratum yields almost as if it were a viscous liquid, and practically quite like a plastic solid with a very low limit of elasticity. Because geological time is not infinitely long, the hot substratum has, practically, an elastic limit and some "strength," even after a small stress has been applied to it for a period so great as 100,000,000 years.

Isostatic undertow and other phenomena show the "strength" of the substratum to be very small. It seems to be much less than that attributed to it by Barrell, but space can not be taken for a statement of the grounds for this conclusion.

Other high authorities agree with Oldham in the view that the elasto-viscous shell passes rapidly downward into "a central nucleus consisting of matter having little or no rigidity, even against stresses of very short duration. Here the material may be described as fluid, whether liquid or gas." 28

Attempts have been made to explain isostatic undertow by the re-crystallization of holocrystalline material under the stresses set up because of differential loading. This conception has not been tested quantitatively, but, in view of the magnitudes of the stress-differences due to the actual loads which have been put on the crust, it seems incredible that flow by re-crystallization could ever produce the observed degree of isostasy in the earth. On the other hand, the restoration of isostatic balance after prolonged denudation is not so hard to understand if the earth is composed of a solid-elastic crust, a thick elasto-viscous shell, and a "fluid" core with the radius calculated by Oldham and Knott, namely, about 2500 kilometers.

After a load of given span has overcome the strength of the crystalline crust, the substratum, a hot glass obey- ing the Adams-Williams law of relaxation, yields by flow. The load thus becomes more widely spread. The pressure gradient and maximum stress-difference due to the load naturally become smaller, but, in addition, further flow near the surface of the elasto-

viscous shell tends to be inhibited by the elastic distortion of the earth. Calculation shows the latter effect to be so important, in the case of a load of wide span, as to prevent indefinitely the restoration of isostatic balance by flow near the bottom of the crust. The restoration can be completed only by flow at great depth.

There seem to be two possibilities. The required flow may take place wholly in the elastico-viscous shell; or it may be completed by the yielding of the "fluid" core. In either case the bottom of the shell of compensation is located at great depth. This follows from the fact that the compressibility of the earth-shells is at a maximum at the surface. The radial displacements described bring the more compressible material in the loaded sector nearer the earth's center of gravity, thus increasing the weight and the compression of that material. Elsewhere the more compressible shells lose weight, and somewhat expand, because forced away from the earth's center of gravity. The compression of the loaded sector and expansion of the unloaded sector give a warping of the crust in the same sense as that determined by the initial loading. When isostatic balance is finally attained, the whole earth has taken on a shape somewhat different from the original shape. It has been elastically distorted, and so it remains as long as any rigidity persists in the elastico-viscous shell.

Thus the layer of isostatic compensation is here not regarded as equivalent to the crust or lithosphere. The bottom of the layer is located at a depth much greater—perhaps 100 times greater—than that of the bottom of the crystalline crust. Most of the compensation occurs above a level passing through the bottom of the sub-oceanic crust. At the intersection of any given vertical with that level the rest of the compensation is likely to have its maximum and thence to decline slowly to zero at a level which is deep, but no deeper than the surface of the "fluid" core.

This implication of a theory of the earth's constitution can not be fully discussed on the present occasion. From the writings of Hayford, Bowie, Love, and Helmert, it appears that this particular distribution of isostatic compensation may be acceptable to the geodesists.

The conclusion of immediate importance is a negative conclusion: the shell of isostatic compensation is not
identical with the crystalline crust, but is much thicker. The argument has followed but one line; the conclusion may be derived also from the assumption that the contrast of crust-thickness in the Pacific and Eurasian areas is due to differential cooling in those great sectors. In that case the hot glass under the sub-Pacific crust must be denser than the hot glass under the continental part of the crust, and that to a depth of hundreds of kilometers.

**Stability of the Crust.**

Assuming that the suboceanic crust is essentially crystalline basalt, and allowing for the effects of temperature and pressure, the specific gravity of this part of the crust averages about 2.95. If the world-circling substratum is a basaltic glass, its specific gravity must be less, probably not more than 2.75, perhaps to the depth of 100 kilometers. On account of this difference of density, the stability of the suboceanic crust would be threatened if it were affected by forces sufficient to overcome its own strength and any residual rigidity of the substratum, and also to cause immersion in the substratum. Under these conditions the immersed part of the suboceanic crust would tend to founder, because the substratum is a hot glass, an elastico-viscous substance. Chiefly composed of salic rocks, the continental part of the crust more nearly approaches the substratum material in density. Since there is no way of knowing what thickness of substratum basalt is frozen to the bottom of the more salic, surface shell, it is not easy to estimate the tendency to instability for the crust underlying the continental surfaces.

Catastrophic foundering is impossible in the actual case where the crust is continuous and, under the oceans, about 40 kilometers thick. The crust is not only strong; it is also self-healing when its continuity as a solid shell is locally and temporarily broken by the injection of dikes. Under ordinary conditions deep immersion of any part of the crust can not take place. Unless the immersion is deep, the strength of the crust is ample to prevent foundering of a partially sunken element.

On the other hand, if tangential compression causes the suboceanic crust to be locally depressed, ruptured,
and underthrust, the downward pull due to differential density becomes increasingly important. The immersed part of the crust tends to pull down with it the horizontal part to which it is solidly attached. Further shearing under the action of the horizontally-directed force is thus facilitated, the friction of crystalline solid on crystalline solid being now largely replaced by the friction of solid on elastico-viscous glass.

**Hypothesis of the Sliding of Continents.**

Is not this cause of crustal instability significant in connection with the hypothesis of extensive horizontal movement of continental blocks?

In 1910 F. B. Taylor published the revolutionary idea that the continents are gigantic land-floes which have not been fixed in latitude and longitude. He suggested the hypothesis of their sliding through long distances during the Tertiary orogenic crisis. Downstream each floe has crushed geosynclinal sediments into cordilleras, typified by the Andes and Himalayas; upstream each has left behind a new ocean-basin, typified by the Atlantic and Arctic depressions. So novel was the central idea of Taylor's ably written paper that it did not at first win, nor has yet won, the attention it deserves.

Independently A. Wegener conceived a somewhat similar explanation of the earth's plan, and printed a preliminary statement in 1912, a more detailed account in the first, 1915, edition of his book on the subject, followed by the second and third, largely re-written editions of 1920 and 1922. Since the appearance of Wegener's book, geologists have begun to take increasing interest in the speculation. For the greater part the discussion has centered around Wegener's book, but it must not be overlooked that Taylor has the distinction of being the first to formulate clearly and at the same time comprehensively the root idea of the horizontal displacement of continents, coupled with concrete illustrations of its meaning for dynamical and structural geology. Taylor

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has shown the greater tact in drawing conclusions from available facts and his statement is not marred by certain highly doubtful and even obviously erroneous assumptions made by Wegener.

Analogies may make the main principle of the sliding hypothesis more readily understood. Each moving continent was like a tabular iceberg, which, urged by some force, exerts horizontal pressure on one (the downstream) side and leaves a "lane" of open water on the opposite side. A closer analogy may be found in the sliding of the crust or scum as it forms on the surface of the lava lake at Kilauea. The deformation of that surface and the resulting potential are connected with the two-phase character of the magma—a special condition. A still closer analogy appears in the case of an ordinary lava flow, which, after solidification of its upper part, continues to move, the thick, upper, elastic layer sliding on the deeper, hotter, more purely viscous part of the flow. Downstream the solid layer is seen to be folded, overfolded, and broken into thrust-blocks; upstream this layer has been torn apart, with the development of vertical walls overlooking trenches transverse to the direction of flow. Excellent examples have recently been studied by the writer among the basalts of Ascension Island. Miniature cordilleras and "lanes" or basins of the "Atlantic" type have thus been formed in many other lava-fields.

Some geologists are inclined to reject the sliding hypothesis because they assume the elastic resistance to be too great. If the earth were crystalline to great depth, their contention would be quite just, but the objection loses weight if the crystalline shell is thin and rests on hot, basaltic glass. Once the solid-elastic crust is ruptured, the shearing of the crust over the substratum is possible even if the sliding-slope is quite moderate.

Sliding means falling, the existence of a gravitational potential. A crust resting on a less dense substratum evidently has potential. Has its potential been increased by deleveling since the consistentior status was established? Serious attention paid to this problem soon shows that its full solution is an enormously complex undertaking, which must necessarily be based on unproved assumptions regarding the nature of the earth's interior. With assumptions matching the facts above-
described, the writer has been led to entertain the possibility of the secular generation of sliding-slopes on the large scale.

The postulates include a terrestrial constitution which may be again summarized as follows: 1. A thin crust possessing elasticity of figure; 2. A thick elastico-viscous shell obeying the Adams-Williamson law of relaxation, the rigidity of this shell and also its time of relaxation for a given stress increasing to maxima at the depth of 2,000 to 3,000 kilometers; 3. A “fluid” core with radius of the order of 2,500 kilometers. The elastico-viscous shell is supposed to have minimum “strength” at top and bottom. Its upper layer is the asthenosphere, whose rigidity becomes very small but not zero under a stress applied for geological time. The asthenosphere passes rather rapidly down into the much “stronger,” middle part of the shell; this part may for convenience be called the “sthenosphere” (sphere of strength). The Wiechert law of density, modified to allow for the increase of density by compression, is assumed. Rigidity and incompressibility for successive levels, down to the “fluid” core, are then computed from the velocities of the preliminary seismic waves, allowance being made for the probability that the fundamental equations give somewhat too high values for the elastic constants.

The greater part of such a heterogeneous earth is elastic. Within its very low, mean limit of elasticity, such an earth obeys the laws of elasticity. If external forces delevel the crust, the resulting inequalities tend to be long preserved by the elasticity of crust and elastico-viscous shell. Those external forces which seem worthy of attention include: the weight of the ocean, the tidal force leading to the slow diminution of the rotational speed, and the forces represented in the transfer of masses by secular denudation. The internal forces set up by the contraction of the earth (which is differentially heated by radioactive elements) would seem to coöperate with the external forces in producing large-scale distortion of the globe and deleveling of the crust. Contraction may, indeed, be the dominating control.

From the writings of G. H. Darwin, Chree, Rudzki, Woodward, and Terazawa, one can find suggestions as to the amount of elastic distortion affecting a homogeneous earth by regional loads which have the simple forms of
spherical caps or of zonal harmonics. The distortion of the actual, heterogeneous earth represents a still more formidable problem which awaits the skilled attack of the highly trained mathematical physicist. To ask his sympathy with the sliding hypothesis and his help in its proper discussion is one of the main purposes of the present note. This hypothesis implies that, in pre-Jurassic time, there was but one continent, the rest of the earth's crust being covered by the Greater-Pacific Ocean. The facts of geology appear to warrant the hypothesis that the continental part of the crust gradually became develed in such a way that sliding-slopes were generated; one set directed toward the Greater-Pacific, on all sides of that basin, and a second set directed in the sense of the meridian.

Paleogeographic maps and other evidences show the amplitudes of the inequalities not to have been very great, but their spans were of continental or subcontinental magnitudes. So long as the solid crust remained intact, the tangential pressures due to these inequalities were of a low order. After the rupture of the crust the pressures may have reached, by concentration, thousands of atmospheres at interfaces of limited extent. If a continental part of the crust slid some distance over the sub-Pacific crust, the mass in the sector of overthrust was at once made greater than the mass in the "lane" sector on the upstream side of the sliding block. The body of the elastic earth was correspondingly distorted and the geoid was temporarily deformed. Hence the sliding-slope tended to be temporarily preserved, if not actually increased. Orogenic crises are thus assigned to epochs when the secularly-generated inequalities "collapsed."

Space can not be taken for a fuller statement of the writer's speculative explanation of continental displacements, but a few supplementary remarks seem necessary. Taylor conceives that sliding-slopes were possibly developed by an increase of the earth's rate of spin. Against this view is the general opinion of astronomers that the earth is actually slowing down. In the following paper the present writer asks the question how the crust of the heterogeneous, somewhat compressible earth would be deformed, if the rotational velocity were decreased. Taylor made his suggestion with due reserve, but emphasized his conclusion that the sliding of continents was directed primarily from the poles toward the equator.
Wegener also assumes the "Polflucht" and, to explain it, relies on the minute force directed equatorward, due to the projection of a continent above the suboceanic crust. Three years ago the present writer requested Mr. Lambert to calculate the value of this force; the result has been published and proves the insignificance of the force.\footnote{W. D. Lambert, this Journal, vol. 2, p. 156, 1921; P. S. Epstein (Die Naturwissenschaften, vol. 9, p. 499, 1921) independently showed the negligible value of the force.}

In addition, Wegener conceives a westward movement of all the continents. His theory thus leaves unexplained the structures and forms of the Asiatic arcs, that is, the very facts which prompted Taylor to announce the hypothesis of the systematic displacement of continental blocks. The westward shearing under the precessional forces, which are also very minute, can hardly be regarded as of geological importance.\footnote{See W. Schweydar, Zeit. Ges. für Erdkunde, Berlin, p. 124, 1921.}

Wegener could permit himself to think of these small forces as adequate because he postulates no strength in the substratum and none in the simatic (basaltic) crust under the ocean. Since crystallized basalt is actually stronger than granite or gneiss, the staple rocks of the continents, this assumption can not be accepted; its advocacy has seriously lessened the value of Wegener's argument. If held at all, the sliding hypothesis must reckon with considerable strength in the suboceanic crust and with the finite, though small, residual rigidity of the substratum.\footnote{The writer can not accept several other assumptions and arguments stated by Wegener. Among these are: the idea of extensive wanderings of the earth's pole of rotation; the Pleistocene date of the separation of Greenland from Europe and from North America; the postulate of a thickness of about 120 kilometers for the crust; and the assigned values of contemporary continental displacements (the latter are not sufficiently trustworthy). Taylor's presentation of the general hypothesis is not injured by these conceptions, which are sure to obscure the real issues, if not to lead the mind into blind alleys.}

If the Arctic, Atlantic, and Indian ocean-basins are "lanes," and if all six of the existing continents were formerly one continent, another query is inevitable: Can this primitive, unique continent, dominantly composed of the deformed rocks of the pre-Cambrian complex, be explained as due to the sliding of a once-continuous, world-circleing, salic crust into one hemisphere? Did the pole of that hemisphere pass through a gravitational
focus, toward which the primeval crust glided, in the form of crumpling, upending, and perhaps ultimately foundering blocks (these constituting the pre-Cambrian complex?23) After the new basaltic crust froze and the ocean water deepened in the opposite hemisphere, was a new gravitational focus established, whereby fragments of the salic, primitive continent were drawn toward the other side of the globe, but halted to form the continents of the present day? Were the circum-Pacific cordilleras thereby formed, and were such chains as the Altaides and Alpides formed by correlative sliding of the continental crust in the sense of the meridian? Until the mathematical physicist has passed on the case, it is idle to attempt any final answer to these questions. Elsewhere the writer may publish some new geological evidence favoring a sympathetic reception of the sliding hypothesis, but meanwhile one may hope that more light shall come as the result of mathematical and geophysical inquiry.24

Summary.

The thermal gradient under the surface of central and western Europe is about 32 meters per degree Centigrade. That under the surface of the eastern United States is about 42 meters per degree. In Europe, North America, and South America at least, the rate of temperature increase itself increases down to maximum

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24 Among the by-products of the sliding hypothesis is a possible explanation of the important uplift of cordilleran belts long after folding has ceased. The solid rock-material which has been underthrust or downthrust in the act of sliding (and folding), must ultimately change state, expanding at least five per cent, as it becomes vitrified. To calculate the time that must elapse before the expansion takes place is a problem made complex by the variations in the conductivity of rocks at different temperatures and in the crystalline and glassy states, and by uncertainty regarding the part played by radioactivity. Is it possible, too, that the high viscosity developed by pressures of from 10,000 to 30,000 atmospheres may permit of some superheating of the deeply buried crystalline rock, after the manner experimentally demonstrated by Day and Allen in the case of the feldspars at the pressure of one atmosphere? (See A. L. Day and E. T. Allen, Publication 31, Carnegie Institution of Washington, 1905, p. 50.) In any case, however, it seems clear that there must be a long time-lag between the folding of a mountain range and the change of state of the overridden crust or the downthrust parts of the folds. If crust and substratum have the densities assumed in this paper, the surface of a mountain range, just formed, is likely to have been close to, or below, the level of the sea. Its present high elevation is here speculatively explained by the long-postponed expansion of the subsurface material. Indeed, the whole broad problem of epeirogenic warping is affected by the sliding hypothesis.
depths of more than two kilometers. This fact tends to warrant extrapolation to the depth of about 40 kilometers, at which depth rock-matter can not be holocrystalline; the true crust of the earth is relatively thin.

That conclusion seems to be borne out by the results of seismological studies. Angenheister’s discovery of a greater thickness of the crust under the Pacific than under Eurasia is noted and explanation sought in differential radioactivity. Neither the cosmogonist, nor the elastician, nor the student of isostasy has as yet produced valid evidence against the postulate of a thin, crystalline crust, overlying a non-crystalline or glassy shell.

Assuming the dominance of elastico-viscosity in the subcrustal material, the crust is seen to be in a state of potential instability. This is especially clear in the case of the sub-Pacific crust, which must founder in the substratum if immersed in it deeply enough. A second condition for crustal instability is found in the secular deleveling of the crust, giving sliding-slopes. During post-Archean time one set of the slopes is thought to have been directed in the sense of the meridian; the other set, directed toward the central Pacific, from all sides of that basin. Very briefly the conceived causes for the generation of these gravitational potentials are indicated. A modification of the Taylor-Wegener hypothesis of continental displacement is outlined. Many questions are asked, in the hope that the mathematical physicist, who alone is competent, may be led to declare whether sufficient deleveling of the crust has taken place because of the secular, elastic distortion of the globe.

Finally, a remark of a general nature may be permitted. Small as may be the immediate success in the search for the force or forces which could tear a continent to pieces, it seems eminently wise to retain as a working hypothesis the daring and yet majestic idea of Taylor and Wegener. In Europe its discussion is lively and many geologists, as well as geophysicists, are convinced that the hypothesis of continental displacement on the large scale should not be summarily rejected. As yet American geologists have not done their share in developing the possibilities and probabilities of the case. A hypothesis which explains so many details and major features of the earth’s plan merits their best thought in an exceptionally difficult field of investigation.