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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Continental Structure and Drift

G. J. F. MacDonald

Phil. Trans. R. Soc. Lond. A 1965 **258**, 215-227
doi: 10.1098/rsta.1965.0036

D. PHYSICS OF CONVECTION CURRENTS IN THE EARTH'S MANTLE

XIX. Continental structure and drift

By G. J. F. MacDonald

Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California

Gravity and heat flow observations indicate that the structural and chemical differences between oceanic and continental regions extend to depths of several hundred kilometres. A theory of continental drift must account for the maintenance of the deep structure of continents. A comparison of the figure of the Earth obtained from satellite observations with that calculated on the assumption that the Earth is in hydrostatic equilibrium demonstrates that stress differences of the order of 100 bars exist within the mantle. If these stress differences are to be maintained by convective flow, then the mantle must have an average viscosity of 10^{26} c.g.s.

In recent years, many workers have deduced, from measurements of the direction of remnant magnetism in rocks, that the continental masses have moved, relative both to each other and to the Earth's axis of rotation. Others would attribute the palaeomagnetic data to past variations in the Earth's magnetic field. These arguments require that, in the past, the Earth's field was substantially different from the present field, in that the higher-order moments of the field were of a relatively greater magnitude and the field's axes may have been inclined at relatively large angles to the rotational axis.

In considering the possibility of continental drift, it is necessary to inquire whether the present geophysical knowledge of the Earth's interior permits recent large continental displacement. The most pertinent observations are those that deal with the subcrustal structure of continents and ocean basins and the mechanical properties of the mantle. Recent evidence indicates that large scale differences between continents and oceans are not restricted to the upper layers, but may extend to several hundred kilometres. We cannot, of course, directly observe that continents extend to great depths; it is the conclusion demanded by the analysis of heat flow and gravity observations scattered over the surface of the globe, combined with seismological data and new and important information secured from observations of Earth satellites. If, indeed, the differences between continents and oceans extend to great depths, then a theory for continental drift must be very different than that imagined by Wegener. The new data also permits an estimate of the mechanical properties of the mantle for amplitudes and time scales relevant to continental drift. The derived mechanical properties are far different than those assumed by Wegener; he requires a weak oceanic crust extending to the ocean bottom, and the continents are pictured as stiff plates pushed through the weak oceanic crust.

The requirements on the theory of drift deduced from our present knowledge of the structure and mechanical properties of the Earth's interior may be sufficiently severe that alternatives to a theory of continental drift should be examined. The magnetic explanation for the palaeomagnetic data has not been explored in detail (Blackett, Clegg & Stubbs

1960). While it is generally agreed that the magnetic field originates through motions of the conducting fluid core of the Earth, the characteristics of these motions are not well understood. Radioactive heating and, possibly, potential energy released by the settling of iron towards the Earth's centre may provide energy for the convection currents. Alternatively, the field may have an astronomical origin and be due to momentum transfer resulting from the differential precession of the core and mantle (Malkus 1963). Because of these uncertainties, few attempts have been made to quantitatively interpret palaeomagnetic data on the basis of a changing magnetic field.

Earth's gravity field and the long-term mechanical properties of the mantle

Studies of the Earth's gravity field have long since shown that the amount of mass under continents very nearly equals that under the ocean (Jeffreys 1959). Knowledge of the Earth's gravity field has increased significantly in recent years, principally through observations of close satellite orbits. These studies establish that regional variations of gravity exist over large horizontal distances which cannot be accounted for in terms of near-surface crustal structure (Munk & MacDonald 1960*a*).

We write the external gravitational potential of the Earth as

$$U = \frac{\mu}{r}\left[1 + \sum_{n=2}^{\infty}\sum_{m=0}^{n}\left(\frac{R}{r}\right)^n P_n^m(\sin\beta)\,(C_n^m\cos m\lambda + S_n^m\sin m\lambda)\right], \tag{1}$$

where $\mu = GM_{\oplus}$, r = distance from centre of the Earth, R = mean equatorial radius of the Earth, P_n^m = associated Legendre polynomial, β = latitude, λ = longitude. The coefficients, C_n^m and S_n^m, are dimensionless quantities, specifying the contribution of each harmonic to the external potential.

Table 1. Comparison of observed potential and that calculated for a compensated crust

(Dimensionless, unit = 10^{-6})

order of harmonic				isostatic
n	m	observed	non-hydrostatic	continents (1000 fm.)
2	—	1082·5	+12·5	−0·42
3	—	−2·6	2·6	−0·17
4	—	−1·8	0·5	−0·34
5	—	−0·06	−0·06	+0·56
6	—	0·39	0·39	−0·18
7	—	−0·47	−0·47	+0·34
8	—	−0·02	−0·02	+0·03
2	2*C*	0·75	0·75	+0·20
—	2*S*	−0·61	−0·61	+0·12
3	1*C*	0·87	0·87	+0·02
—	1*S*	−0·27	−0·27	+0·01
4	1*C*	−0·17	−0·17	+0·02
—	1*S*	−0·24	−0·24	−0·01

The zonal harmonics, C_n^0, lead to long term secular effects on close satellite orbits. A large number of papers have been published listing improved numerical estimates of the C_n^0. Table 1 lists the values obtained by Kozai (1962). The sectorial and tesseral harmonics give rise to observable short period oscillations in the orbit. The determination of these high frequency terms in the orbit is subject to far greater uncertainty than the long period and secular terms. For the most part, Baker–Nunn observations have been used in the reductions. A most comprehensive study has been given by Izsak (1964), who has reduced over 15000 Baker–Nunn camera observations of ten artificial satellites. Table 1 lists those sectorial harmonics obtained by Izsak which are in approximate agreement with earlier studies (Kaula 1963 *a*, *b*). Izsak's determination of the equipotential surface is shown in figure 1, where the geoid height in metres is plotted relative to an ellipsoid with a flattening of 1/298·3. Izsak's representation uses all terms up through the sixth order. This differs from earlier constructions principally in the North Atlantic and Europe (Kaula 1963 *a*, *b*; Uotila 1962).

Comparison of observed anomalies and anomalies for an isostatically compensated crust

If the Earth were a fluid devoid of strength, the odd-order zonal harmonics (n odd, $m = 0$) would vanish, and the Earth's rotation and its internal distribution of density would determine the even-order harmonics. The tesseral and sectorial harmonics should also vanish for a fluid Earth. The difference between the observed values and the values appropriate for a fluid Earth rotating at the same velocity and having the same density distribution as the real Earth is shown in table 1.

Part of the observed nonhydrostatic contribution to the external gravitational potential could arise from an isostatically compensated crust. We recall that the vacuum gravitational field can be interpreted in terms of the number of lines of gravitational force per unit area. An isostatically compensated mass will give rise to a second-order anomaly over continents because of the relatively larger area through which the same number of lines of force pass, since the number of lines per steradian is constant. Table 1 lists the gravitational anomaly expected from an isostatically compensated crust where the crustal structure is that of Worzel & Shurbet (1954). The anomalous potential due to the continents is calculated on the assumption that the continental crust extends to the 1000 fm. line.

A comparison between the observed values of the potential and those calculated for an isostatically compensated crust shows two striking features. For the low order harmonics, the gravitational anomaly expected from the continental crust is small compared with the observed potential, and is of opposite sign. The small magnitude of the crustal contribution indicates that the mass anomaly must reside within the mantle and not in the outer 30 km of the Earth. The fact that the low order harmonics are consistently of opposite sign suggests that these mass anomalies within the mantle are associated with the continent–ocean topography. The magnitude and sign of the non-hydrostatic anomalies demonstrate that a standard crust in isostatic balance cannot account for the observed nonhydrostatic part of the external potential.

In current treatments of isostasy, mass is usually calculated above a certain level, usually 30 to 40 km; the columns under continents and oceans are found to have approximately the same mass, provided reasonable values are assigned to the density of the constituent materials (Hess 1962). Implicit in such calculations is the assumption that the mantle

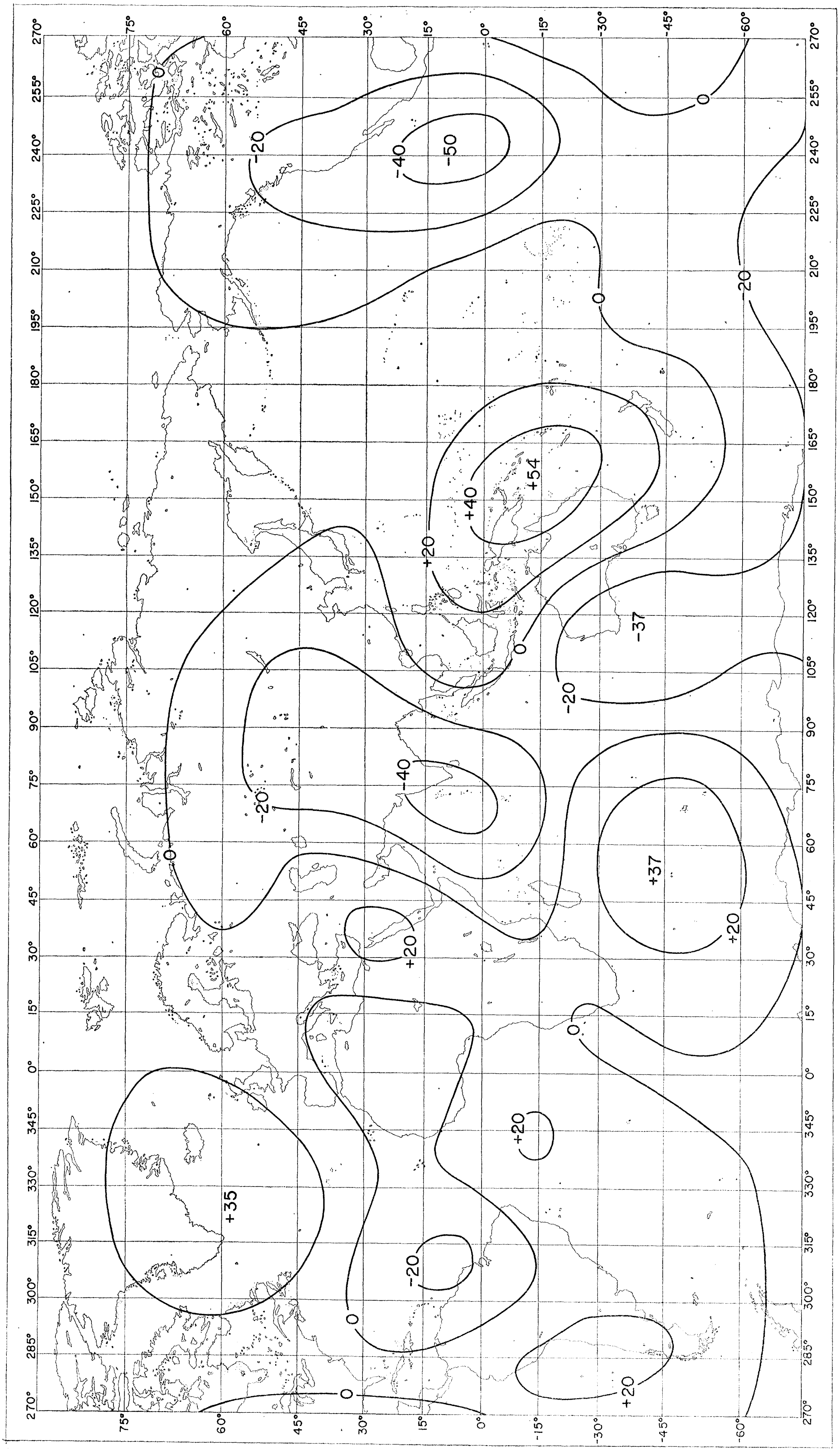

FIGURE 1. Geoid height in metres referred to an ellipsoid with a flattening of 1/298·3. (After Izsak 1964.)

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below a given level is horizontally homogeneous. Unless all crustal material of the continents is extracted from a very thin layer of mantle, this assumption must be invalid. The difference in chemical composition of the continent and oceanic crust requires a difference in chemical composition over some depth within the mantle. The difference in chemical composition will be reflected in density differences. The correlation of the large scale anomalies in the external potential with the continent–ocean structure substantiates the implied density difference between oceanic and continental mantle.

Secular and anelasticity of the mantle

The largest deviation from hydrostatic equilibrium is in the term C_2^0. The present equatorial bulge of the Earth is larger than that to be expected from an equivalent rotating fluid. In terms of flattening, the current flattening is 1/298·3, while the equilibrium flattening is 1/299·8. Munk & MacDonald (1960*b*) note that the deviation from equilibrium is that expected for a gradually decelerating Earth. At the current rate of deceleration, the present bulge corresponds to the equilibrium figure of about 10^7 y ago. The magnitude of the bulge and the time scale for the deformation provide significant data concerning the mechanical properties of the mantle. Because of the long time scale and large amplitude, properties so deduced are of particular significance to continental drift.

The observed bulge and time scale can be interpreted in terms of three models of the mechanical behaviour of the mantle:

1. The mantle behaves as an elastic solid below a critical yield stress. At stresses above the critical yield stress, the material fractures or ruptures, with consequent plastic flow. Kaula (1963*c*) calculated the magnitude of the stresses corresponding to the observed non-hydrostatic external potential. Using the Gutenberg model of the elastic parameters, Kaula found that the C_2^0 anomaly generates a maximum stress difference of 163 b at the base of the mantle. Other terms in the gravitational potential generate stress differences ranging from 10 to 100 b. Thus, if the mantle material can be approximated as an elastic solid with a finite yield stress, then the yield stress is in excess of about 160 b. In this model, the tidal deceleration of the Earth would build up stress differences within the Earth until the yield stress is reached. At this time, a violent readjustment takes place, through fracture and/or flow of the material.

2. The material in the mantle can be considered an elastoviscous material. The time of 10^7 y for the retardation in the rate of rotation is then interpreted as relaxation time. This time, coupled with an elastic modulus, gives a viscosity of the order of 10^{26} c.g.s. (MacDonald 1963). This value applies to the entire mantle; at least, this figure represents a mean value with the mean taken in a presently undetermined way. This value of 10^{26} c.g.s. for viscosity is about four orders of magnitude greater than that usually quoted for the mantle. The classical numbers for viscosity, as determined from an interpretation of the Fenno–Scandian uplift, however, are open to question. The measurements may not describe a true viscous unloading, but may represent an elastic rebound (Orowan 1960). Indeed, there is some evidence that the rebound is not confined to glaciated regions, but extends over much larger portions of the continental crust (Lyustikh 1957). Jeffreys (1959) has criticized the Fenno–Scandian value for the viscosity because of the short time scale that is

implied for vertical motion. Even a viscosity as high as 10^{26} is hard to reconcile with the existence of ancient geologic features associated with large gravity anomalies.

3. The third interpretation is that the adjustment of the bulge to the changing rate of rotation can result from continuous creep of the mantle at a stress difference fixed by the strain rate. In this interpretation, a finite creep strength must be exceeded, and the current stress difference on the order of 200 b is the sum of the creep stress plus the stress due to the non-Newtonian viscosity associated with creep.

Flow of heat from the Earth's interior

Bullard (1954) found in the Atlantic, and Revelle & Maxwell (1952) in the Pacific, that the heat flow of the two oceans was of the same order as the thermal flux in continental areas. Since then, over 1000 heat flow determinations scattered over the surface of the globe have confirmed this finding. Lee & MacDonald (1963) have analysed over 900 measurements of surface heat flow. An orthogonal function representation of 757 values yields a global mean of $63{\cdot}9 \pm 3{\cdot}4$ ergs $cm^{-2}\,s^{-1}$. The average over continents is 68·9 ergs $cm^{-2}\,s^{-1}$, while the average over oceans is 62·0 ergs $cm^{-2}\,s^{-1}$. The averages represent 92 continental measurements and 665 oceanic measurements.

While the principal results of the thermal investigations show that the heat flows through continents and oceans do not differ significantly on the average, a number of anomalous regions have been discovered. Figure 2 shows the large scale regional variations in the heat flow, derived through the harmonic analysis of the available data. This analysis averages out many of the fine variations that exist in the heat flow field; none the less, it appears that the heat flow is regionally high in the eastern Pacific and low in the western Pacific and Atlantic. The lack of adequate measurements makes the indicated high for central Asia most uncertain. The representation of the heat flow variation shows some similarity to the representation of the geoid. The two representations are not directly comparable, since the gravity field is based on an analysis through the sixth order, while only second-order terms enter into the representation of the heat flow field. None the less, the high in the eastern Pacific and the low in the western Pacific appear to coincide with a low and high in the geoid respectively.

Interpretation of continent–ocean heat flow

Radioactive heat production of rocks, exposed at or near the surface of continents and in ocean basins, differs greatly. Since the heat flows through the continental surface and ocean bottoms are approximately equal, the consequent differences in the vertical distribution of radioactive materials require quantiative assessment (Bullard 1954). Let us suppose that the values for intermediate rock of table 2 represent the heat production in the continental crust. The heat production within the crust is then about 45 ergs $cm^{-2}\,s^{-1}$. If the range of values included under the intermediate rock category are examined, then the heat production might lie between 30 and 60 ergs $cm^{-2}\,s^{-1}$. Since the continental heat flow is about 69 ergs $cm^{-2}\,s^{-1}$, the heat flowing from below a depth of 30 to 40 km is between 9 and 39 ergs $cm^{-2}\,s^{-1}$. In the ocean, the material above 35 km produces heat at a rate of about 3 to 5 ergs $cm^{-2}\,s^{-1}$, provided the volcanic material in the ocean basin is

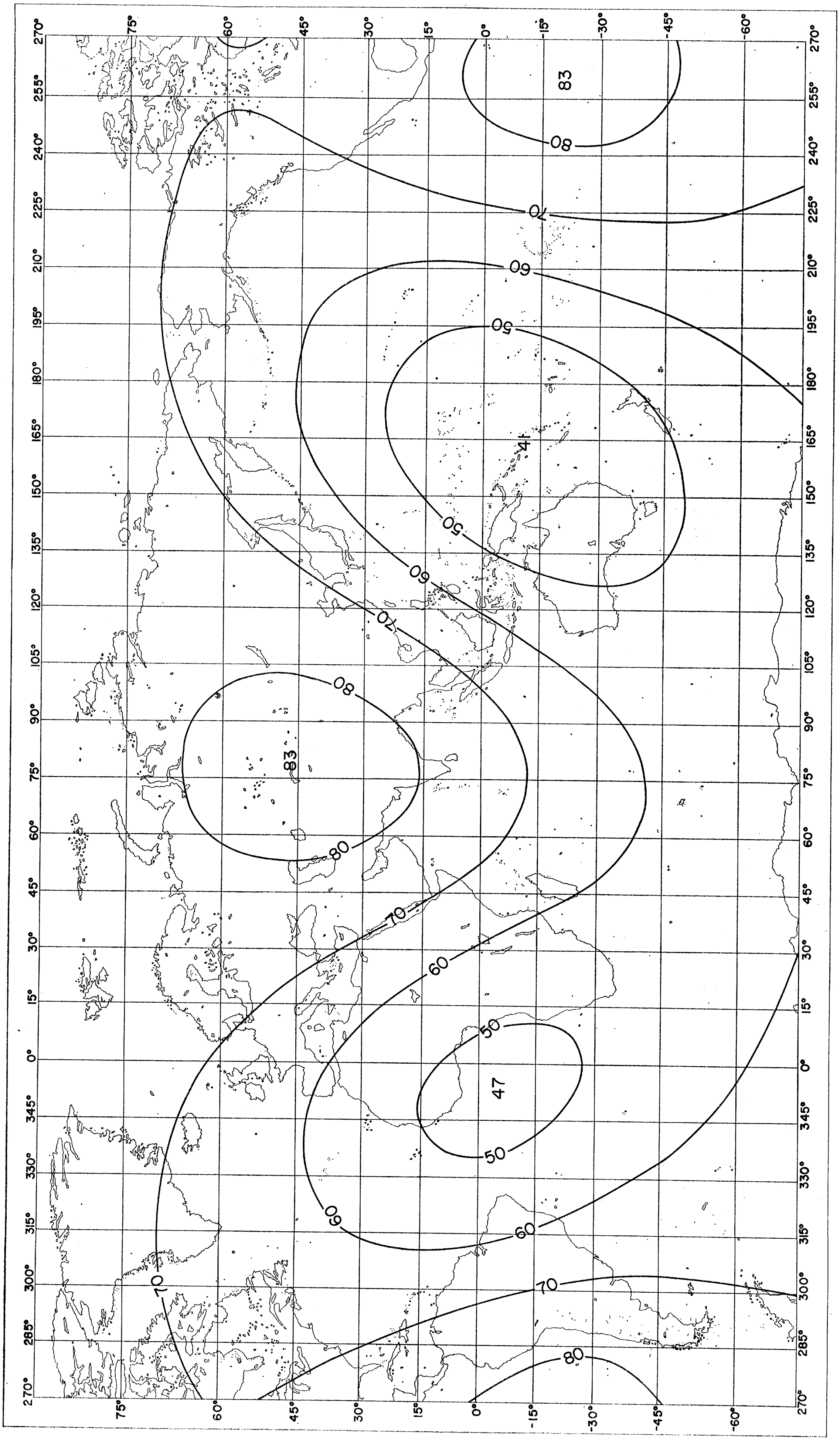

FIGURE 2. Orthogonal function representation of 757 heat flow values (Lee & MacDonald 1963). Contours are in units of ergs cm^{-2} s^{-1}.

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basalt; the sediments have a radioactivity of intermediate rock, and subcrustal material is eclogite or peridotite. A flux in oceanic regions of 62 ergs $cm^{-2} s^{-1}$ implies that between 56 and 59 ergs $cm^{-2} s^{-1}$ must be flowing from the interior into the region above 35 km. The difference in flux between continents and oceans at a depth of 35 km is then between 17 and 50 ergs $cm^{-2} s^{-1}$. Even when we take the extreme limits of error in the values of heat production and heat flow as a basis of calculation, we find a considerable difference in the amounts of heat flowing into the crust beneath the land and sea.

TABLE 2. HEAT PRODUCTION IN ROCKS

rock	average concentration (parts/10^6) uranium	potassium	thorium	average total heat production (ergs g^{-1} y^{-1})
granite (1)	4·75	37900	18·5	340
intermediate (2)	2·0	18000	—	143
basalt (1)	0·6	8400	2·7	50
eclogite (3, 4, 5)				
low uranium	0·048	360	0·18	3·4
high uranium	0·25	2600	0·45	14·3
peridotite (3)	0·006	10	—	0·38
dunite (3)	0·001	10	—	0·08

(1) Heier & Rogers (1963).
(2) Evans & Goodman (1941); Senftle & Keevil (1947).
(3) Tilton & Reed (1963).
(4) Heier (1963).
(5) Lovering & Morgan (1963).

The difference in outward heat flow at a depth of 35 km implies deep seated differences in temperatures under continents and oceans. These, in turn, will produce inequalities in density if the materials underlying the continents and oceans are identical in composition and phase. Temperatures under the oceans should be higher, and if the subcontinental and oceanic material are identical in both composition and phase, oceanic regions should stand higher than continental regions. That they do not implies that the elements concentrated in the continental crust form denser compounds at depth. We take a continental crust 35 km thick with a mean density of 2·75. The same material with a 20% greater density of 3·33 should be 29·1 km thick; thus, a continental crust of this material with a density 2·75, having the same mass as a 35 km thick region of density 3·33, would stand 5·85 km above the ocean floor. The 20% difference in density corresponds approximately to the increase in density observed in a large number of phase transitions in silicates at pressures above 10 kb. Since the observed difference in height between continents and ocean floor is about 4·1 km, a 1·7 km discrepancy exists, and this can be attributed to thermal effects. If the suboceanic material is, on the average, 100 °C warmer than the subcontinental material at depths between 35 and 700 km, thermal expansion accounts for the 1·7 km discrepancy.

The foregoing considerations imply that the elements forming low density phases in the continental crust are found in higher-density form at depth. This requirement demands, not that the Mohorovičić discontinuity be a phase transition, but that within the upper mantle those materials relatively abundant in the continental crust (alkalis, and aluminum and silicon compounds) occupy volumes about 20% less than the same elements occupy in the common crustal materials.

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In summary, the heat-flow observations taken with the radioactive heat productions of common rocks establish that major differences in chemical composition exist between the subcontinental and suboceanic portions of the mantle. These considerations provide evidence, additional to that of gravity, that the continental structure extends to considerable depths within the mantle, and that the continental crust cannot be imagined as a thin block overlying a horizontally homogeneous mantle.

Seismic evidence of the deep structure of continents

As yet, studies of the propagation of body and surface waves do not yield a detailed picture of the differences between continental and oceanic mantle. However, there are several important indications that the mantle under the ocean does indeed differ from that under continents, and that there may be variations under continents related to the continental structure. The distribution of earthquake foci provides additional indirect evidence that there are major differences in continent and ocean structure extending to a depth of several hundred kilometres.

The classical distributions of elastic wave velocity in the mantle, as determined by Jeffreys (1939) and Gutenberg & Richter (1935, 1936), deviate principally in the upper 500 km of the mantle; at greater depths, the two distributions are very similar. Evidence that the mantle at depths of greater than 500 km is homogeneous on a large scale and can be described by a radial velocity distribution comes from studies of the free oscillations. The close agreement obtained by various workers (Pekeris, Alterman & Jarosch 1961; MacDonald & Ness 1961) between observed and calculated low order spheroidal and toroidal oscillations clearly indicates that, on the average, the deep mantle can be described by velocity distributions that are a function of depth alone. However, the low order oscillations are not at all sensitive to variations in mantle properties at shallow depths.

The principal evidence for a difference in continental and oceanic structure comes from studies of surface waves. Dorman, Ewing & Oliver (1960) showed the low velocity zone is present at a depth between 50 and 250 km under the oceans, and the minimum velocity is about 4·3 km/s. Dorman *et al.* also noted that the beginning of the low velocity zone is deeper under continents, though Aki & Press (1961) suggest that the depths to the low velocity zone may be the same; however, the minimum velocity is greater under oceans. Sutton, Ewing & Major (1960) find results similar to those obtained by Dorman *et al.* for surface waves travelling across the North Pacific. Comparable results have been obtained with Love wave dispersion curves by Sykes, Landisman & Saito (1962) and Kovach & Anderson (1962). Takeuchi *et al.* (1962) find that the Lehmann model fits surface wave propagation across continents. In this model, the low velocity zone is at 120 to 220 km, with a minimum velocity of 4·3 km/s. Brune & Dorman (1963) have carried out a detailed study of surface waves having strictly continental paths across predominantly Precambrian shield areas. The low velocity zone is present between 120 and approximately 300 km, and the minimum velocity is about 4·5 km/s, which is substantially higher than for oceanic regions.

The interpretation of the surface wave dispersion data is not unique. Various combinations of velocity distributions yield good agreement with observations. However, it appears that recent interpretations all lead to the conclusion that continents and oceans do differ at least in the upper 300 km.

It has long been known that the principal earthquake zones are at continent–ocean interfaces. No earthquake foci have been found below approximately 720 km. Below about 650 km, the frequency of earthquakes decreases rapidly (Gutenberg & Richter 1954, 1956*a*, *b*). The association of earthquake foci with continental borders is particularly marked for those earthquakes which have foci at a depth greater than 300 km (Gutenberg & Richter 1954; MacDonald 1963). The interpretation of the association of earthquake zones with continental borders, and the limitation of earthquakes to the upper 500 km of the Earth, depends on the mechanism by which earthquakes are generated. Earthquakes release strain energy developed through processes that elastically deform the earth. Differences in heat production and in rate of heat loss build up thermal strains. MacDonald (1963) argues that the difference in heat source distribution between continents and oceans is primarily responsible for the concentration of earthquake zones along young continent–ocean boundaries. While the differential thermal loss may not be the major contributor to strain energy, this mechanism provides a means of obtaining faults with vertical displacements along continental borders. These zones of weakness are then the loci of energy release due to elastic distortion not directly associated with differential heat production and loss.

The limitation of earthquakes to the region in the upper 500 km of the Earth can be interpreted either in terms of a first order change in the mechanical properties of material at this depth, or of the vanishing of the effects of differential thermal losses in the regions below a few hundred kilometres. Thus, if the continents are formed by the upward concentration of mantle material, and if this process has affected the upper 500 km of the mantle, then thermal stresses will be associated with continent–ocean boundaries down to depths on the order of 500 km. Below this depth, radioactive sources are horizontally homogeneous, and thermal stresses due to differential thermal losses do not develop.

The association of earthquake zones with continental borders, plus the depth limitation, can be interpreted in terms of a continental structure extending to depths on the order of 500 km. This conclusion is concordant with conclusions demanded by heat flow, gravity, and direct seismic observations.

Conclusions regarding deep continental structure

Observations of heat flow and gravity suggest that continental structure extends to depths of about 500 km. Preliminary studies of surface waves tentatively confirm the assumed existence of regional differences between continental and oceanic mantle. The distribution of earthquake foci along continental borders and the concentration of deep-focus earthquakes at the borders similarly imply differences in thermal structure extending to depths on the order of a few hundred kilometres. MacDonald (1963) has carried out calculations on the thermal regime, taking into account continent–ocean differences. The calculations demonstrate that rather wide differences in vertical distribution of heat sources lead to very nearly equal heat flows under continents and oceans, provided that the differences in vertical distribution do not extend to depths greater than 500 km. In these calculations, the temperature under oceans exceeds that under continents, on the average, by about 100 degC over the uppermost 500 km in the mantle. This temperature difference produces a density difference which must be compensated. Phase changes in the materials making up the continental crust are sufficient to provide the temperature-induced differences in density, as well as the differences in height between continents and oceans.

Continental drift and convection

The sole mechanism so far proposed that is qualitatively adequate to explain continental drift is convection (Jeffreys 1959; Runcorn 1962). While the details of such a mechanism are far from clear, the general picture seems to be that the effect of a system of convection currents would be to sweep the floating material toward the places where the currents sink. This type of large scale convection is not to be confused with penetrative convection, where local regions undergo melting, and rise through fractures in the overlying material. There can be no doubt that this latter type of motion occurs; however, the existence of large scale organized convective systems, the type required to move continents, remains in doubt.

If, indeed, continental structure extends to depths on the order of hundreds of kilometres, it is no longer possible to imagine thin continental blocks carried along by a flowing mantle. The large horizontal motion extending near the surface would tend to homogenize the upper mantle and destroy differences between the continent–ocean structure. This objection to upper mantle convection is emphasized by considerations of the thermal time scale; the thermal time scale for a layer 500 km thick is on the order of 10^9 y or longer, depending on the efficiency of radiative transfer (MacDonald 1959). The long time scale implies that the presently observed differences between continents and oceans have persisted for times on the order of 10^9 y. Alternatively, it may be assumed that continental drift involves not only the surface expressions, but also the upper mantle down to a depth of some hundreds of kilometres. Such a hypothesis, however, emphasizes the well known difficulty of how continents maintain their integrity during drift. The question now is, not only how continents, but also how subcrustal materials, maintain their integrity.

A further difficulty to mantle-wide convection is posed by observations on the mechanical properties of the mantle. As Runcorn (1962) has properly emphasized, the anelasticity observed at high frequencies and small amplitudes has little application to problems connected with mantle convection. Gravity observations provide data on the mechanical response of the mantle to large amplitude deformations with a time scale of 10^7 y. The result is that, if one wishes to assume an elastoviscous material, the mantle must have a viscosity on the order of 10^{26} c.g.s. This viscosity is so high that, in order to derive convection currents, a heat flow an order of magnitude larger than that observed would be required (MacDonald 1963). Alternatively, the inequality in figure associated with the equatorial bulge may represent the response of material with a creep strength of about 100 to 200 b. The mechanics of convection in such a material which departs so widely from Newtonian viscosity remains very uncertain.

In summary, it would seem that both the deep structure of continents and the mechanical properties of the mantle make untenable any hypothesis linking large scale convective currents with continental drift. Alternatively, it would appear highly desirable to closely examine the notion that in the past the Earth's magnetic field may have had a far more complicated character than it does today. The possible complexities of planetary magnetic fields are illustrated by the recent observation that the magnetic moment vector of Jupiter is displaced by over 0·7 of the planet's radius from the centre (Warwick 1963).

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