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Changes in the Convection Pattern in the Earth's Mantle and Continental Drift: Evidence for a Cold Origin of the Earth

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XX. Changes in the convection pattern in the Earth's mantle and continental drift: evidence for a cold origin of the Earth

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Continental displacements of thousands of kilometres point to flow patterns in the mantle of similar dimensions. As creep depends exponentially on temperature and as it is known that the temperature of the crust increases rapidly with depth, we can in this context suppose the mantle to have a sharp transition between a rigid crust and a fluid mantle at 50 to 100 km depth. Recently the coefficients of the tesseral harmonics of the geopotential from satellite observations have been determined. These departures from hydrostatic equilibrium seem to be caused by flow in the mantle, for from these coefficients can be computed the tractions exerted by the flow on the crust, assuming Navier–Stokes's equations, and the resulting pattern accords well with the world-wide tectonic features. Rising flow is associated with the East Pacific Ocean Rise, the Mid-Atlantic Ridge and the Mid-Indian Ocean Rise. Descending currents coincide with the Andes, the Alps and the Japan trench.

The strong fifth harmonic in the satellite gravity data suggests that a flow pattern of this degree is at present establishing itself. On the other hand, continental reconstructions prior to Wegenerian drift suggest the presence of a strong fourth harmonic in the flow pattern. The theory of marginal stability in thermal convection, discussed by S. Chandrasekhar, shows that convection in a spherical shell under a uniform radial gravitational field gives the critical ratio of the radii of the inner to outer surfaces (η) at which the fifth order is more likely to develop than the fourth as 0·54. The closeness of this value of η to the present one of 0·55 provides a clue to the most puzzling feature of continental drift; that it should have occurred in the last 5 % of the Earth's history. H. C. Urey suggested that, on the accretion theory of the Earth's origin, the separation of iron towards the centre might have gradually occurred through the Earth's life. A growth of the core from 0·54 to 0·55 in the last 100–200 My does not conflict with the known rate of change in the length of the day.

This explanation of the flow in terms of convection and changes in the degree of the flow pattern as a result of growth of the core implies earlier epochs of continental displacements, which are identified with peaks in the histograms of radiometric ages in the various continents. The law of growth of the core, so obtained, explains why so few rocks of greater age than 3000 My are found.

1. Introduction

Most attempts to trace the evolution of the Earth have concentrated on its thermal history. It was recognized (Slichter 1941) that the key to the Earth's origin lies in its internal temperature distribution since an object as large as the Earth has a long thermal time constant. In either of the conflicting theories, that the Earth has cooled from a gaseous body or has accreted from a dust cloud, its initial temperature distribution is an important boundary condition which might be recovered in the study of the Earth's relatively recent thermal history. Further it has been recognized (Verhoogen 1956) that the heat flow through the Earth's surface is an energy flux 10 to 100 times greater than the rate of energy dissipation in geological processes and it can therefore be argued that the thermal history of the earth is quite fundamental to the understanding of dynamic geology. There have therefore been attempts to compute the thermal history of the earth, making various assumptions con-

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cerning the internal distribution of its heat sources (Jacobs 1956; MacDonald 1959, 1961). Because these computations have been based on the arbitrary assumption that the only processes of heat transfer in the Earth are conduction and radiation and because the radioactive content of the deep interior of the mantle is unknown, the results have not yielded new insights into the more fundamental questions. A major difficulty is that our only quantitative knowledge is the present heat flow through the ocean floor, the mean value of which is $1{\cdot}4\times10^{-6}\,\mathrm{cal\,cm^{-2}\,s^{-1}}$. Suppose that we knew how this had varied through an appreciable portion of the Earth's life: the number of possible solutions to the problem of the Earth's evolution would be drastically reduced. In fact all the geophysical quantities used in the classical studies of geophysics have had the same limitation: neither values of gravity nor seismic velocities for the geological past can be found. Thus one key of increasing importance to the study of the Earth's evolution is palaeomagnetism—the only geophysical quantity of planetary significance for which a record exists over the last thousand million years. The displacements of the continents inferred from these data cannot be ignored in theories of the motions and energy changes within the earth, if they are to be other than mathematical exercises. A suggestion has recently been advanced by which the earth's rotational velocity can be determined in the past (Wells 1963) and a further one by Scrutton (1964) concerns the Moon's orbital period. These studies, when further observations are obtained, will, for the same reasons as given above in the case of palaeomagnetism, be of critical importance in the study of the Earth's physical evolution.

2. The convection current hypothesis

Speculation concerning the existence of convection currents in the Earth's mantle has a long history (Holmes 1931; Griggs 1939). Originally the hypothesis was put forward to explain the compression in orogenic belts. Sources of heat are known to be available within the earth, and convection is a satisfactory way of obtaining motion from them. However, the physical theory of convection is still in a rudimentary state. While the theory of marginal stability has been fully developed (Chandrasekhar 1961), not a great deal is known concerning the non-linear region in which finite heat is transported. However, the convecting part of the mantle is blanketed by a rigid crust through which heat must travel by conduction and it may be that the convection currents transport little heat. However, once the reality of continental displacements of thousands of kilometres is accepted, we are already in possession of important information on the nature of the flow patterns in the Earth's mantle. Compared with continental drift, the much smaller displacements involved in strike-slip faults and in mountain building, though of prime interest to the geologist, must be regarded by the geophysicist as second-order effects. They are unlikely to be understood until an adequate theory of continental drift and the convection pattern are found.

Various conceptions of the nature of convection in the mantle might, in theory, be entertained. It might be supposed to be entirely disordered or turbulent or to consist of a very large number of eddies. Both views may be rejected, for they fail to explain how the various continents have moved uniformly in one direction for at least 10^8 y (see S. K. Runcorn and K. M. Creer in this volume). Thus the convection pattern in the mantle seems most likely to consist of large scale eddies, the flow being laminar over thousands of kilometres.

To assume the absence of turbulence is theoretically satisfactory, for the Reynold's number for the mantle is low. The rates of movement of the strike-slip faults are between 1 and 10 cm/y (see C. R. Allen, this volume). Runcorn (1963) suggested that the velocities of flow in the mantle might be greater, perhaps of the order of a metre per year. It is not possible to say whether over geological periods the rheology of the mantle is that of Newtonian viscosity. However the original work of Haskell (1935) on the uplift of Fenno-Scandia and the recent studies of Crittenden (1963) on Lake Bonneville show that at least for the upper part of the mantle the viscosity is, within an order of magnitude, 10^{21} P. The Reynolds number calculated from these figures is 10^{-18}. Theory and observation, thus, agree that the mantle is not turbulent. On the other hand, the Rayleigh number is high, and the implication of this concerning the number of cells is not understood.

Vening Meinesz (1951) became interested in Prey's (1922) demonstration that there is a certain regularity in the positioning of the continents. Prey had taken values of the height of the land above and the depth of the ocean below sea level, counting the latter negative, and had expressed them as a series of spherical harmonics. The predominant term is, of course, of degree $n = 1$: the continents are almost concentrated in a single hemisphere. The terms $n = 2$ and those above $n = 5$ are relatively weak, the terms $n = 3$, 4 and 5 being strong. As terms of odd degree have opposite signs at antipodal points, Prey's analysis simply gives mathematical expression to a feature which seemed significant to an older generation of geologists, that the continents are antipodal to oceans. This was the starting point of their theory that the Earth was cooling and the already cold crust had to take a tetrahedral shape to enclose the smaller volume. The faces formed the oceans and the vertices became the continents. The theory of isostasy destroyed this interpretation. However the geophysical fact that only 3 % of the area of the continent is antipodal to continent certainly requires explanation. Vening Meinesz (1951) reasoned that this element of regularity in the positions of the continents today could result from a large scale, regular pattern of convective motions in the mantle similar to that predicted by the Rayleigh theory. The continental material would tend to be pushed to the places where the currents were descending. Chandrasekhar (1953) showed that, for a core of the present size, 0·55 of the Earth's radius, harmonics $n = 3$, 4 and 5 are almost equally likely to be excited at marginal stability.

Chandrasekhar, however, took a free surface as the upper boundary condition. In the discussion of convection in the Earth's mantle a rigid outer boundary may be more realistic. We know, from faulting, that when stresses become too great, the crust breaks, like an elastic solid. Below a certain depth in the mantle we have seen that flow occurs and so, as a first approximation, we consider it as a Newtonian fluid (on a long time scale). As the mantle is a solid over short time scales we are dealing with a creep process. Creep processes are strongly dependent on temperature and as the temperature of the earth near the surface rises very rapidly with depth (at about 25 degC/km), the transition between an essentially rigid crust and a flowing mantle is probably quite sharp. It is clearly necessary to suppose that the temperature gradient diminishes sharply at a depth of about 50 or 100 km, otherwise the melting point of the silicates would be exceeded and convection has been suggested to explain this (Bullard, Maxwell & Revelle 1956). The temperature difference between 100 km depth and the surface of the core depends on the adiabatic gradient and is of the order of a thousand degrees and the rheological properties may vary more slowly in this region.

If these boundary conditions—the outer rigid and the inner free—are used, then Runcorn (1963) showed, using results of Chandrasekhar (1961), that the present radius of the core is only 2 % greater than that at which the fifth degree harmonic would be favoured at marginal stability over the fourth. The present theory is based on this calculation.

3. The interpretation of the low degree harmonics in the geopotential

Before discussing what changes in convection could have brought about continental drift, it is necessary to ask whether there is more direct evidence that convection is now occurring in the mantle. As an explanation of mountain building and continental drift, convection is a speculative, if attractive, hypothesis and it is most desirable to develop a method by which the present pattern of convection in the mantle may be quantitatively investigated. The determinations of the tesseral harmonics of low degree of the Earth's gravitational potential, which have recently been made from satellite orbits, enables this task to be begun. Jeffreys (1952) thought that the mantle had a finite strength and sought for evidence of its non-hydrostatic behaviour to support this theory. He analysed the available land and sea observations of gravity in terms of a series of tesseral harmonics up to and including the third degree. The expansion in spherical harmonics effectively smooths out local variations of gravity which arise from density inhomogeneities in the rigid crust. Thus the existence of non-axial low degree harmonics proves a non-hydrostatic condition in the mantle. However, the paucity of observations in certain areas threw grave doubt on the reliability of the harmonic coefficients of low degree so determined. The map of the undulations of the geoid which Jeffreys computed from these coefficients is shown in figure 1. The negative anomaly south of India, the positive in Europe, and the negative near Central America, should be compared with the results of Izsak (1963) who computed the geoidal surface from the harmonic coefficients included the fourth degree of the potential determined from observations of the positions of satellites. It is significant that the geoid so determined is in reasonable agreement with that of Uotila (1962), who like Jeffreys, used land and sea observations though with many more data. Uotila and Izsak's maps are shown superposed in figure 2. Apart from the central Pacific, the agreement between the major features, the low around India, the positive in Europe, the negative in the middle of the Atlantic, the positive near the Andes, and the positive in the East Indies, is acceptable. Thus I conclude that the coefficients of the lower harmonics up to the fourth are reasonably reliable.

Izsak's latest map (1964) is based on the coefficients up to and including the sixth degree and differs considerably from those of figure 2 especially in the Atlantic. The lower harmonics are easier to determine from the satellite orbits, because the on-track and off-track time discrepancies can build up to greater values for a lower harmonic than for a higher. So that although the earlier geoid is based on a smaller number of harmonic coefficients it may be the better. Although both Izsak's earlier geoid and Uotila's are determined from the same number of harmonics, the data are based on two very different sampling patterns, so that the reasonable agreement of the maps throws doubt on the reliability of Izsak's determination of the fifth and sixth degree coefficients. Guier & Newton (1965) have determined the coefficients up to and including the eighth degree. As their observations are obtained by Doppler tracking, these coefficients are probably the most reliable. They confirm the main features of figures 1 and 2 but, of course, greatly increase the detail.

Jeffreys (1952) argued that these deviations from hydrostatic equilibrium show that the mantle has finite strength and calculated that the stresses in the mantle are of the order of

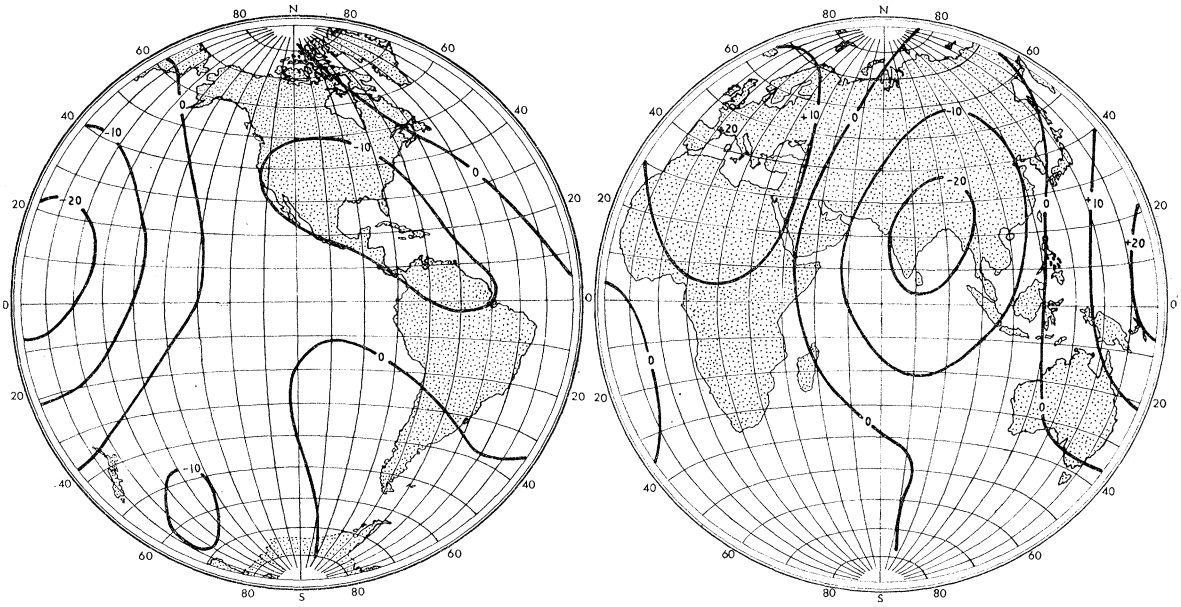

Figure 1. Gravity map based on land and sea observations, according to Jeffreys (milligals); three harmonics only used.

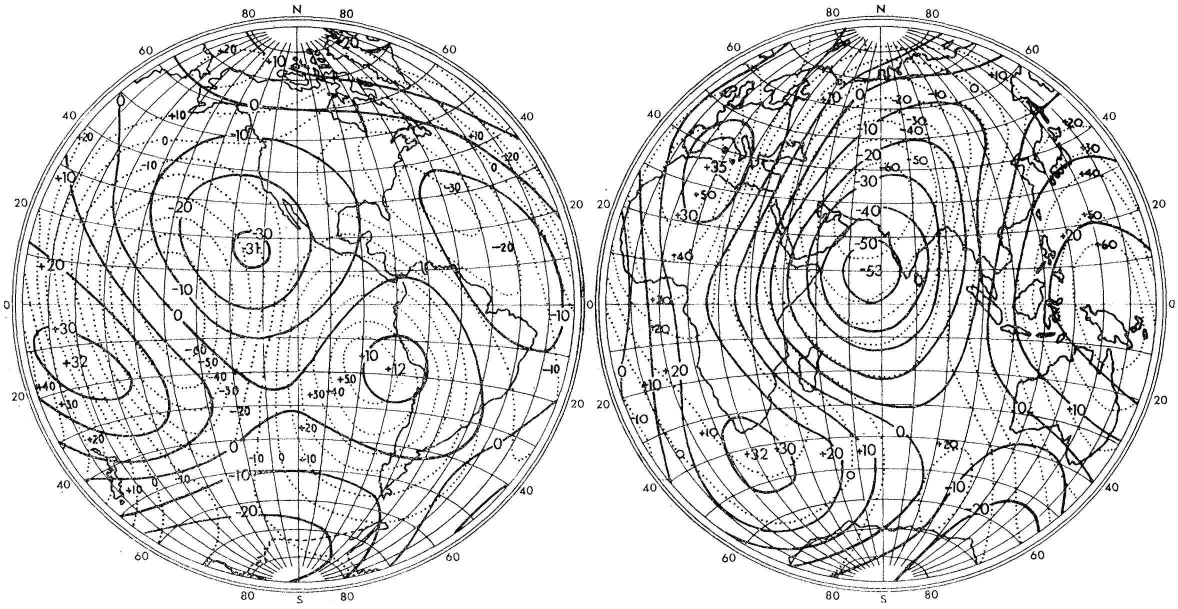

Figure 2. Geoid according to Uotila (dotted lines) and Izsak (full lines) (geoid height contours in metres); four harmonics used.

50 b. In this conclusion he has been followed by the writers on the gravity data (Kaula 1963; King-Hele 1963). An unsatisfactory feature of this theory is that the origin of the density differences in the mantle, from which the gravity anomalies arise, is left obscure. Cook (1963) showed that, because of their scale, the low degree harmonic gravity anomalies have

sources located in the deeper parts of the mantle and not in the crust. The inferred deep-seated inequalities of density in the mantle would, if flow were to be ruled out because of the finite strength of the mantle, result from events in the remote past of the Earth. For example, it might be held that they were chemical inhomogeneities associated with the process of separation of the continents. O'Keefe (1964) suggested that they are the 'scars' left in the earth by the breaking away of the Moon. In either case these inhomogeneities of matter have persisted for over 10^9 y. Implicit in the finite strength theory, therefore, is that stresses below a limit of about 50 b will not cause flow, even if the stresses are maintained over 10^9 y. Whether this was physically plausible was not asked. At one time there seemed to be incontrovertible support for this theory from the case of the moon, for the differences in its moments of inertia are 17 times those calculated on the hypothesis of hydrostatic equilibrium. Baldwin (1963), from the geometric librations, finds a bulge towards the Earth of about 2 km in height. This has been interpreted by Jeffreys (1959) as a fossil tidal bulge, produced at the time (10^9 y ago) when the moon was much closer to the earth. The internal stress difference required to support this bulge is 20 b, about 5 % of the breaking stress of granite under ordinary temperatures and pressures. If the mantles of the Moon and Earth have finite strengths over 10^9 y, the creep rates must be extraordinarily small. For example, the Moon's bulge could be removed completely by a strain of 10^{-3}. If this has not occurred in 3×10^9 y, the creep rate must have been less than $10^{-20}\,\mathrm{s}^{-1}$. The most delicate experiments on creep carried out by metallurgists or workers in rock mechanics fail to measure slower rates of creep than $10^{-8}\,\mathrm{s}^{-1}$. Yet creep is found to be widespread in solids at temperatures well below the melting point under stresses less than a few parts per cent of the breaking stress. It seems unlikely that the mantles of the moon and earth have creep rates less than 10^{-12} of those encountered in the laboratory under stresses of about 5 % of the breaking stress of rocks.

It is therefore desirable to examine whether these departures of the Earth and Moon from hydrostatic equilibrium can be explained by postulating slow flow in its 'solid' interior. Convection has been suggested as an alternative explanation of the Moon's non-equilibrium figure (Runcorn 1962*a*).

Runcorn (1963) argues that the low-degree harmonics of the Earth's gravitational field may result from the density differences associated with convection currents. An order of magnitude argument establishes that this solution for the Earth is possible. Runcorn (1961) showed that if the viscosity of the mantle is taken as 10^{21} P, and the velocities of the convection currents are inferred from the rate of displacement of the continents, the temperature differences between the rising and falling streams on the equipotential surfaces are of the order of $\frac{1}{3}$ degC. Taking a volume coefficient of expansion for the mantle of 10^{-5} per degC we get a deficiency of mass per unit surface area in the uprising column compared with the downgoing one of about $15 \times 10^3\,\mathrm{g/cm^2}$. This gives a gravity anomaly of the order of $10^{-2}\,\mathrm{cm/s^2}$ (10 mgal or about 30 m in geoid height). These are of the order of the gravity anomalies found from the satellite gravity observations.

On the convection current hypothesis, the continents would be expected to lie over the descending currents. Jeffreys (1959) shows that on any reasonable isostatic hypothesis, the gravitational attraction of the continental masses would be annulled by the deficiencies of mass supporting them from below to about a milligal. Consequently a correlation between the coefficients of the terms in the spherical harmonic expansion of the heights of the surface with those of the gravity observations was expected, were the latter caused by convection but not otherwise. Munk & MacDonald (1960) found none, and MacDonald (1963) argues that this lack of correlation between the earth's topography and the gravity is evidence against convection.

Paradoxically, a difficulty also arose from the study of the ocean floor in spite of the increasing evidence for the convection hypothesis obtained from this subject (Menard 1964) The central rifts in the oceanic rises found in the Atlantic and Carlsberg ridges are explained if convection currents are rising under the ridges, resulting in tension in the ocean floor. But the lack of any obvious relation between the satellite gravity observations and these essentially linear features has hitherto prevented a causal connexion between the two phenomena from being recognized. Runcorn (1963) argued that a connexion does, in fact, exist between these phenomena, but had been obscured by an erroneous assumption about the nature of the flow patterns beneath the ridges.

4. The relation between the ocean rises and the geoid

The mantle is compressible but if the density ρ is taken as the difference between the actual density and that corresponding to the adiabatic gradient, the velocity vector $\mathbf{v}$ can be treated as solenoidal. The density field reflects the departure of the temperature from

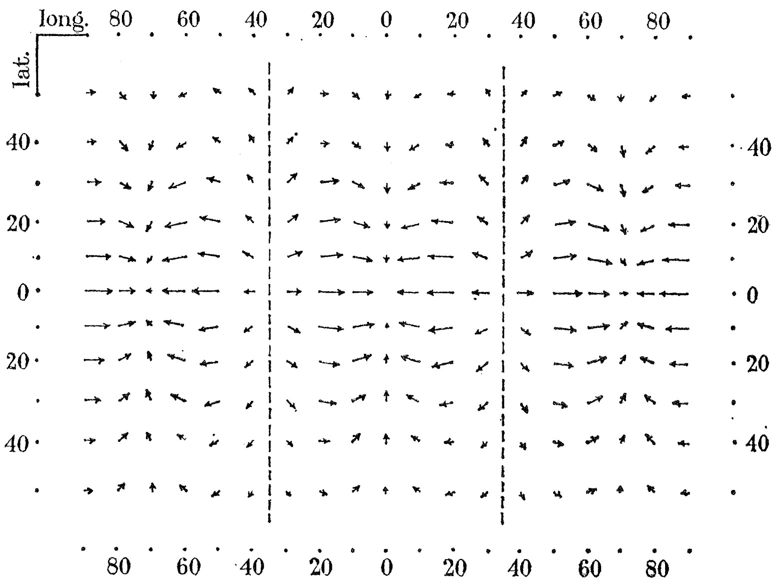

Figure 3. Horizontal velocities for a fifth degree sectorial harmonic convection current. (Mercator projection: lengths of arrows are proportional to velocity.)

the adiabatic one and results in buoyancy forces causing flow. Thus $\mathbf{v} = \operatorname{curl} \mathbf{A}$, where the vector potential $\mathbf{A}$ can be written in terms of two scalar functions V and W. Thus

$$\mathbf{A} = \mathbf{r}V + \mathbf{r} \times \nabla W.$$

From the first term we obtain the toroidal velocity field

$$\mathbf{v} = -\mathbf{r} \times \nabla V,$$

and from the second the poloidal velocity field

$$\mathbf{v} = -\nabla\, \mathrm{d}(rW)/\mathrm{d}r + \mathbf{r}\nabla^2 W = \nabla \times (\mathbf{r} \times \nabla W) = -\nabla \times \nabla \times \mathbf{r}W. \tag{4·1}$$

Convection current velocities in a sphere or spherical shell have a radial component and hence can be described by the poloidal function W, which is the sum of terms, each being the product of a function of the radius and a spherical harmonic function $S_n(\theta, \phi)$, where ϕ is the colatitude and ϕ the longitude.

Figure 3 shows the horizontal velocity pattern for the fifth-degree sectorial harmonic, which, as we have seen, is thought to be prominent in the present flow in the mantle. The dotted lines are two of the five lines of longitude from which flow diverges. Along these lines tension will develop forming the central rifts. But, because of the fact that the divergence of the velocity vector is zero, the components of flow along a ridge line cannot be zero all along the ridge. This is shown in figure 3 in which along the ridge in the southern hemisphere there is a southward component of flow parallel to the ridge, and in the northern hemisphere a northward component. Only on the equator at intervals of 36° of longitude does the horizontal flow completely vanish. These are above the rising and falling columns of fluid. This is an example of a general theorem. The northward and eastward horizontal velocity components are

$$V_N = \frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}\theta}\frac{\mathrm{d}}{\mathrm{d}r}(rW), \tag{4·2}$$

$$V_E = -\frac{1}{r\sin\theta}\frac{\mathrm{d}}{\mathrm{d}\phi}\frac{\mathrm{d}(rW)}{\mathrm{d}r}, \tag{4·3}$$

respectively. In general the condition that either vanishes defines a line on the sphere but both vanish together only at points.

From this theorem, Runcorn (1963) developed an intuitive approach to determine the relation between the ocean-bottom topography and the negative and positive gravity anomalies. The oceanic rise is taken to be a line from which flow diverges but it must have a component of flow along it. Where two oceanic rises intersect, the horizontal velocity must vanish, for the velocity perpendicular to each is zero. This locates the position of the main rising columns. Figure 4 shows the distribution of the oceanic rises after Menard (1958). There appear to be five places where the ridges bifurcate or sharply change direction: (1) the intersection of the Pacific–Antarctic rise with the Melanese rise running northward into New Zealand; (2) the join of the Carlsberg and Mid-Indian Ocean rises; (3) the join of the North and South Atlantic rises, associated with a remarkable series of east-west fractures near the equator; (4) the join of the East Pacific rise with the Pacific–Antarctic rise; and (5) the northern extremity of the East Pacific rise in the Gulf of California. Off South Africa the mid-Atlantic ridge swings round to join the Mid-Indian Ocean ridge, but the change of direction is gradual and it seems reasonable not to include it in the above list. These five places are close to the gravity lows of Izsak's map. Correlation also exists between the gravity highs and the zones of crustal compression in the Alps, the Andes, the Tonga and the Japan trenches. It is therefore desirable to follow up this approach quantitatively.

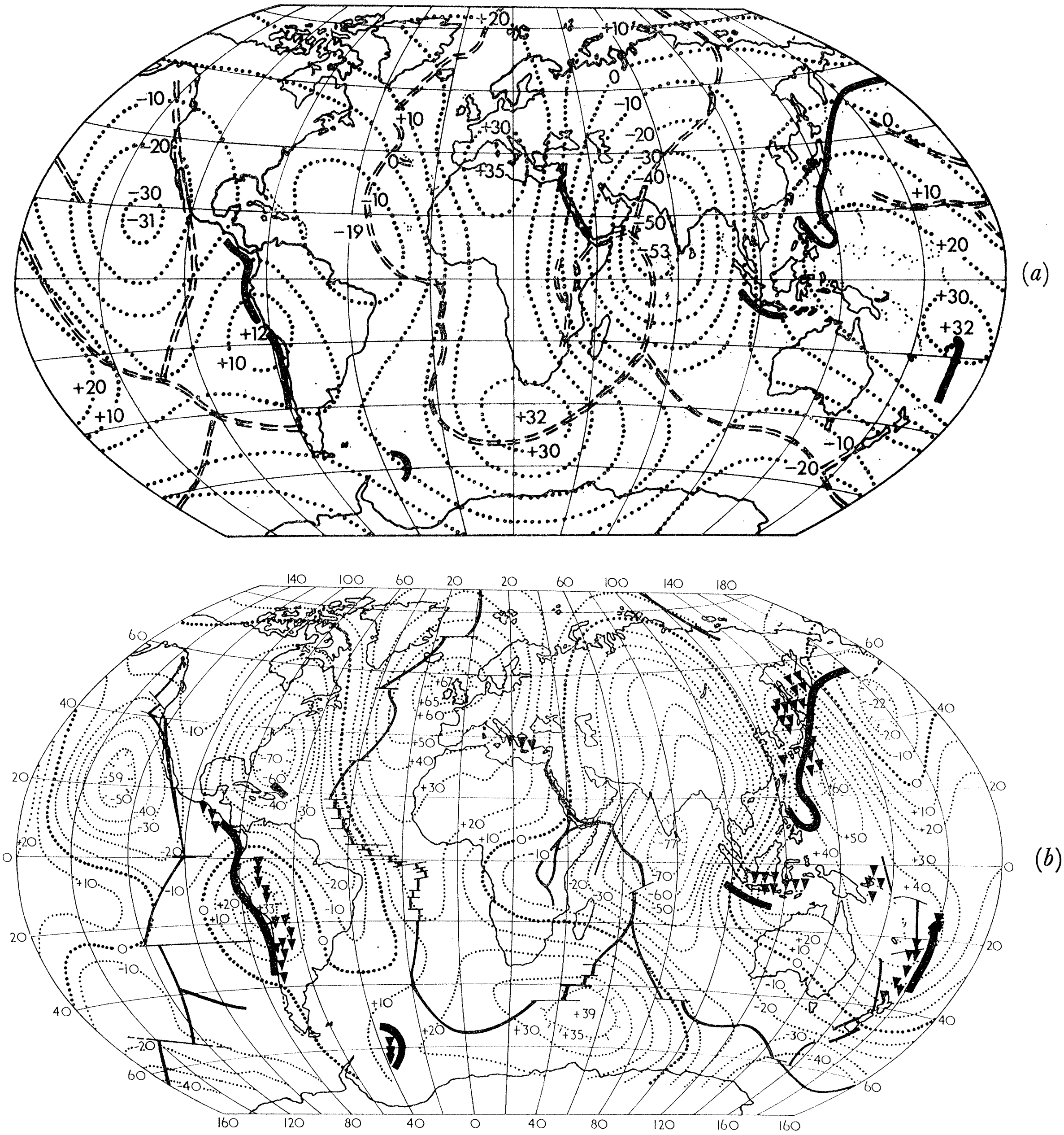

Figure 4. Distribution of ocean rises and trenches (key in figure 5). Dotted lines are the contours of the geoidal surface (in metres) according to (a) Izsak (1963), (b) Guier & Newton (1965).

5. Computation of stress patterns produced by the convection on the Earth's crust

Because the geoid surface is related to the density distribution causing the convection currents, the pattern of the latter can be derived analytically from the former, as Runcorn (1964*b*) showed. The analysis is here further generalized for the case of a mantle in which the viscosity varies radially. Runcorn (1964*b*) shows that the Coriolis, acceleration and inertial forces are negligible compared to the viscous term. The Navier–Stokes hydrodynamic equation then states that (Milne-Thompson 1950)

$$\mu\nabla\times\nabla\times\mathbf{v}-\tfrac{4}{3}\mu\nabla(\nabla.\mathbf{v})-2(\nabla\mu.\nabla)\,\mathbf{v}-\nabla\mu\times(\nabla\times\mathbf{v})+\tfrac{2}{3}(\nabla.\mathbf{v})\,\nabla\mu=-\nabla p+\mathbf{g}\rho, \qquad (5\cdot1)$$

where p is the pressure, ρ the variable density, $\mathbf{g}$ gravity and μ is the variable coefficient of viscosity. The small variations of gravity due to the density differences which cause the motions can be neglected in this equation. In the Earth's mantle g is nearly constant.

If μ varies radially and $(\nabla . \mathbf{v}) = 0$ then equation (5·1) simplifies to

$$-\mu\nabla^2\mathbf{v} - 2\frac{\mathrm{d}\mu}{\mathrm{d}r}\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}r} - \frac{1}{r}\frac{\mathrm{d}\mu}{\mathrm{d}r}\mathbf{r}\times(\nabla\times\mathbf{v}) = -\nabla p + \mathbf{g}\rho. \tag{5·2}$$

Substituting (4·1) we obtain

$$\mu\nabla\nabla^2\left(\frac{\mathrm{d}(rW)}{\mathrm{d}r}\right) - \mu\nabla^2(\mathbf{r}\nabla^2W) + 2\frac{\mathrm{d}\mu}{\mathrm{d}r}\frac{\mathrm{d}}{\mathrm{d}r}\nabla\times\nabla\times(\mathbf{r}W) - r\frac{\mathrm{d}\mu}{\mathrm{d}r}\nabla\nabla^2W + \left(\frac{\mathrm{d}\mu}{\mathrm{d}r}\frac{\mathrm{d}\nabla^2W}{\mathrm{d}r}\right)\mathbf{r} = \nabla p + \mathbf{g}\rho. \tag{5·3}$$

Taking the curl of both sides of (5·3) we have

$$\mathbf{r}\frac{g}{r}\times\nabla\rho = \frac{1}{r}\frac{\mathrm{d}\mu}{\mathrm{d}r}\mathbf{r}\times\nabla\nabla^2\frac{\mathrm{d}(rW)}{\mathrm{d}r} - \frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left(r\frac{\mathrm{d}\mu}{\mathrm{d}r}\right)\mathbf{r}\times\nabla\nabla^2W + \mathbf{r}\times\nabla\left(\frac{\mathrm{d}\mu}{\mathrm{d}r}\frac{\mathrm{d}\nabla^2W}{\mathrm{d}r}\right)$$
$$+\mathbf{r}\times\nabla(\mu\nabla^4W) + \left(\frac{2}{r^2}\frac{\mathrm{d}^2\mu}{\mathrm{d}r^2} - \frac{2}{r^3}\frac{\mathrm{d}\mu}{\mathrm{d}r}\right)\mathbf{r}\times\nabla\left(r^2\frac{\mathrm{d}^2W}{\mathrm{d}r^2} + r\frac{\mathrm{d}W}{\mathrm{d}r} - W\right).$$

As each term is the vector product of $\mathbf{r}$ and the gradient of a scalar and as the gradient of μ and its derivatives are scalars times $\mathbf{r}$ we may write

$$\mathbf{r}\times\nabla\left(\frac{g\rho}{r}\right) = \mathbf{r}\times\nabla\left(\frac{1}{r}\frac{\mathrm{d}\mu}{\mathrm{d}r}\nabla^2\frac{\mathrm{d}(rW)}{\mathrm{d}r}\right) - \mathbf{r}\times\nabla\left\{\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left(r\frac{\mathrm{d}\mu}{\mathrm{d}r}\right)\nabla^2W\right\}$$
$$+\mathbf{r}\times\nabla\left(\frac{\mathrm{d}\mu}{\mathrm{d}r}\frac{\mathrm{d}\nabla^2W}{\mathrm{d}r}\right) + \mathbf{r}\times\nabla(\mu\nabla^4W)$$
$$+\mathbf{r}\times\nabla\left(\frac{2}{r^2}\frac{\mathrm{d}^2\mu}{\mathrm{d}r^2} - \frac{2}{r^3}\frac{\mathrm{d}\mu}{\mathrm{d}r}\right)\left(r^2\frac{\mathrm{d}^2W}{\mathrm{d}r^2} + r\frac{\mathrm{d}W}{\mathrm{d}r} - W\right).$$

We next remove $\mathbf{r}\times\nabla$, the unknown function of integration being omitted as it depends on r only and plays no part in the convection problem.

We also use the vector identity

$$\nabla^2(\phi\psi) = \phi\nabla^2\psi + \psi\nabla^2\phi + 2\nabla\phi . \nabla\psi$$

$$g\rho = \mu r\nabla^4W + \frac{\mathrm{d}\mu}{\mathrm{d}r}\nabla^2\left(r\frac{\mathrm{d}W}{\mathrm{d}r}\right) + \frac{\mathrm{d}\mu}{\mathrm{d}r}r\frac{\mathrm{d}\nabla^2W}{\mathrm{d}r} - 2\frac{\mathrm{d}\mu}{\mathrm{d}r}\left(\frac{\mathrm{d}^2W}{\mathrm{d}r^2} + \frac{1}{r}\frac{\mathrm{d}W}{\mathrm{d}r} - \frac{W}{r^2}\right)$$
$$+\frac{\mathrm{d}^2\mu}{\mathrm{d}r^2}\left(-r\nabla^2W + 2r\frac{\mathrm{d}^2W}{\mathrm{d}r^2} + 2\frac{\mathrm{d}W}{\mathrm{d}r} - 2\frac{W}{r}\right).$$

There are two extreme models of viscosity variation with radius, one constant, one in which the viscosity rises rapidly with depth approximately as if the viscosity is constant and finite in the upper mantle and jumps discontinuously to infinity in the lower mantle. In the latter case, the lower surface of the convecting region of the mantle will be higher than the core-mantle interface. The non-convecting part of the mantle is assumed to be homogeneous. Elsasser (1963) suggested that the viscosity is strongly dependent on the difference between the melting point and the actual temperature of the mantle. On this theory, as the melting-point gradient in the mantle is many times the adiabatic gradient, the viscosity would increase by many orders of magnitude between the upper and lower mantle. Our two models would appear to bracket Elsasser's model.

$$g\rho = \nabla^2(\mu r \nabla^2 W) - \nabla^2\left[2W\left(r\frac{\mathrm{d}^2\mu}{\mathrm{d}r^2}+\frac{\mathrm{d}\mu}{\mathrm{d}r}+\frac{\mu}{r}\right)\right] - \nabla^2\left(2\mu\frac{\mathrm{d}W}{\mathrm{d}r}\right),$$

plus terms in which W, $\mathrm{d}W/\mathrm{d}r$ and $\mathrm{d}^2W/\mathrm{d}r^2$ are multiplied by sums of the viscosity and its derivatives which do not vanish for any law of viscosity variation. The results to be obtained therefore apply to the two idealized models. The second-order perturbation of gravity $\boldsymbol{g}$ resulting from the density differences in the mantle can be expressed as the gradient of the geopotential, U and $\nabla^2 U = -4\pi G\rho$ where G is the gravitational constant. Hence, substituting for ρ, we obtain if μ is constant

$$U = -\left(\frac{4\pi G\mu r}{g}\right)\nabla^2 W + \text{terms in } W \text{ and } \frac{\mathrm{d}W}{\mathrm{d}r},$$

as Runcorn (1964*b*) showed, if the viscosity and g/r are assumed to be constant. The harmonics $\Sigma(A_n r^{-(n+1)} + B_n r^n)\,S_n(\theta,\phi)$ must be added to satisfy the boundary conditions. They vary with the convection theory and are omitted in the following analysis. The resulting discrepancy with observation, to which we will refer, is not intolerable, and its study may in future help to resolve the uncertainties of the theory of convection.

At the boundaries $\mathrm{d}W/\mathrm{d}r$ and W are zero; therefore both models yield

$$U\Big|_{r=a} = -\frac{4\pi G\mu r}{g}\nabla^2 W\Big|_{r=a}.$$

Now U is expressed outside the Earth by the series

$$U = \frac{GM}{r}\left\{1+\sum_{n=2}^{\infty}(a/r)^n\sum_{m>0}^{m=n}(C_{nm}\cos m\phi + S_{nm}\sin m\phi)\,P_n^m(\theta)\right\},$$

where M is the Earth's mass, and the associated Legendre functions are defined by

$$P_n^m(x) = (1-x^2)^{\frac{1}{2}m}\frac{\mathrm{d}^m P_n(x)}{\mathrm{d}x^m}$$

Runcorn (1964*b*) shows that $\left.\frac{\mathrm{d}U}{\mathrm{d}\theta}\right|_{r=a}$ and $\left.\frac{1}{\sin\theta}\frac{\mathrm{d}U}{\mathrm{d}\phi}\right|_{r=a}$

are the radial gradients, at the surface of the convecting mantle, where $r = a$, of the horizontal components of velocity (v_N, v_E) in the northward and eastward directions. This is still true for the two cases of viscosity variation considered above. For the discontinuous model the result is obvious, for it is not necessary to specify the inner boundary of the convecting shell in the proof.

It is necessary again to use the assumptions that the crust is rigid and 50 to 100 km thick and that the boundary between the crust and the viscous mantle, in which thermal convection is possible, is sharp. At the surface of the convecting region of the mantle, the radial component of velocity must be zero.

Hence $$\left.\frac{\mathrm{d}^2(rW)}{\mathrm{d}r^2}\right|_{r=a} = r(\nabla^2 W)\Big|_{r=a}.$$

But $$\left.\frac{U}{r}\right|_{r=a} = k\nabla^2 W\Big|_{r=a} \quad \text{where} \quad k = -4\pi G\mu/g.$$

Thus $$\left.\frac{g}{4\pi G}\frac{1}{r}\frac{\mathrm{d}U}{\mathrm{d}\theta}\right|_{r=a} = \mu\left.\frac{\mathrm{d}(\nabla^2 W)}{\mathrm{d}\theta}\right|_{r=a} = \left.\left(\mu\frac{\mathrm{d}}{\mathrm{d}r}\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}\theta}\frac{\mathrm{d}(rW)}{\mathrm{d}r} + \frac{\mu}{r^2}\frac{\mathrm{d}}{\mathrm{d}\theta}\frac{\mathrm{d}(rW)}{\mathrm{d}r}\right)\right|_{r=a},$$

which is the viscosity times the vertical gradient of v_N at the surface, as the second term vanishes at the boundary.

Similarly, $$-\left.\frac{g}{4\pi G}\frac{1}{r\sin\theta}\frac{\mathrm{d}U}{\mathrm{d}\phi}\right|_{r=a}$$

is the viscosity times the vertical gradient of v_E at the surface.

Thus the stresses at the surface of the convecting shell are expressed in terms of the slopes of the geoid and are independent of the viscosity.

Figures 5*a* and *b* show the distribution of tractions applied to the crust by the convection currents, computed using Iszak's (1963) and Guier & Newton's determination of the coefficients C_{nm} and S_{nm} from the analysis of satellite orbits. Order of magnitude calculations show that these stresses are of the same order as those required to fracture the crust. As the geoid undulations are tens of metres and their wavelength thousands of kilometres, the stress is of the order of 10^6 dyn/cm^{-2}. If this is multiplied by the ratio of the cell dimension to the thickness of the crust (10^2) we obtain the tensile or compressive stress on the crust, i.e. 10^8 dyn cm^{-2}, sufficient to break it.

It will be seen that in the East Pacific, in the Atlantic, in the mid-Indian Ocean, South of Australia and in E. Africa, the stresses diverge. These are close to oceanic rises and known rift systems. The strong line of divergence in the Indian Ocean continues into central Asia, where Lake Baikal has been interpreted as part of a line of rifts (Beloussov 1960). It is possible that the discrepancy in positions is caused by the inadequacy of the gravity data. The spherical harmonic analysis of the topography of the globe shows that the harmonics higher than the fifth fall off markedly in strength. When the accuracy of measures of the lower harmonics of the gravity field is better, a more satisfactory comparison may be possible. On the other hand, the crust is inhomogeneous, so that the places where the ocean floor and the continents yield to the stresses may be offset from those to be expected were the crust a uniform shell.

Turning our attention to the zones of compression, indicated by strong convergence of arrows in figure 5*b*, these are the Western U.S., the Andes and the associated ocean trench, off the coast of South Africa, off the Tonga trench, the Japan trench, near the East Indies, and around Europe. All these are associated with mountain building or ocean trenches with the exception of Africa for which there is as yet no explanation.

The tractions on the Earth's crust show two features in accord with the palaeomagnetic data: the separation of the Americas from Europe and Africa and the northward movement of India and Australia.

Izsak's data which we have here used omit the zonal or axial harmonics as these are determined by a different method. It is now interesting to discuss the changes in figure 5*a* if these were included. The most important, apart from the second and fourth which are caused by the earth's rotation, is the third (O'Keefe 1959). This produces a pattern of velocities shown in figure 6. All, of course, are directed along lines of longitude, converging

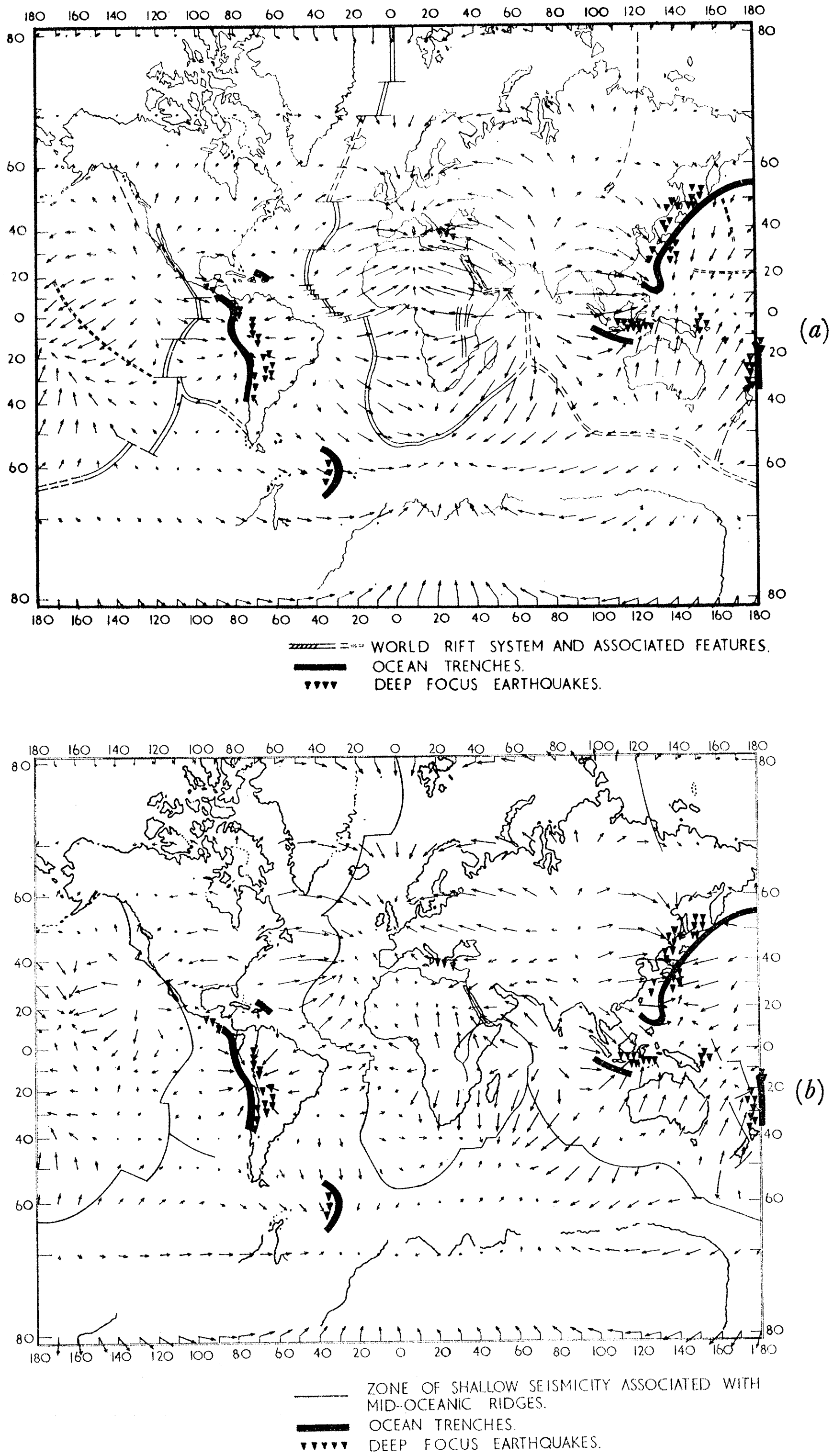

FIGURE 5. Tractions applied to crust on the convection current hypothesis derived from the harmonics of the geopotential through the eighth degree according to (*a*) Izsak (1963), (*b*) Guier & Newton (1965).

and diverging from lines of latitude at about 20 to 30° north and south of the equator. Inclusion of the higher harmonics will move these new zones of compression and extension somewhat. It has long been realized that the great mountain-building belts form a pattern of north–south chains, e.g. the Andes and a great east–west belt, e.g. the Alps–Himalayas. The same pattern is reflected in the zones of tension in the ocean floor; the great north–south ridges in the East Pacific, Atlantic and Indian Oceans and the east–west circum-Antarctic ridge. It may be conjectured that the inclusion of the axial gravity field in the above analysis will complete the zones of compression and tension predicted by the convection current hypothesis by adding an east–west belt of compression 20 to 30° north of the equator to correlate with the Himalayas and an east–west zone of tension in latitude 40 to 50° south of the equator corresponding to the circum-Antarctic ridge.

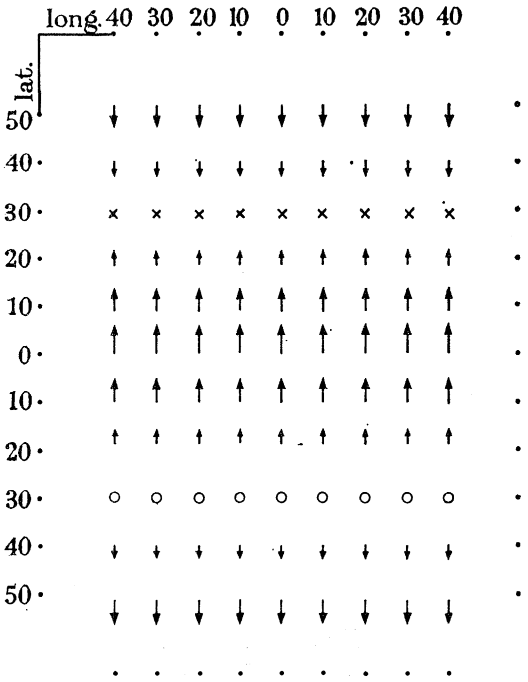

Figure 6. Tractions applied to crust by convection currents described by axial harmonics.

6. Changes in the convection currents in the mantle

In order to provide an explanation of continental drift, Runcorn (1963) argues that it is necessary to suppose that the pattern of convection currents in the Earth's mantle changed about 200 My ago. If the mantle has zero strength under stresses persisting over millions of years and has a Newtonian viscosity, Chandrasekhar's (1961) theory of convection in spherical shells under a radial gravitational field may be used. Chandrasekhar shows that instability in the marginal state occurs through a convection pattern described by a spherical harmonic, the degree of which depends on the ratio (η) of the radii of the inner and outer spherical boundaries. Vening Meinesz (1962) had argued that the spherical harmonic analysis of the present topography of the globe reflects the convection pattern in the Earth's mantle, as the continents would tend to lie above the descending currents. He found that the present positions of continents and oceans implied that the convection currents in the mantle had strong harmonics of third, fourth, and fifth degree, likely to be favoured by the present core size. The strength of the first six harmonics of the geopotential given by Izsak (1964) are shown in figure 7 together with those of the topography. Chandrasekhar's calculation showed that, as η for the Earth's mantle is at present 0·55, these harmonics are stronger than those through which the thermally induced instability would be expected to occur. We have seen that it is necessary to postulate that the convection currents in the mantle have changed. If the convection has changed from a simpler to a more complex mode, the strong fifth harmonic present suggests that this is the harmonic which present conditions in the earth tend to favour. Doubtless other factors affect the convection pattern besides the size of the core. However if the accretion theory of the origin of the Earth is accepted and it is supposed that the Earth's iron core has only separated

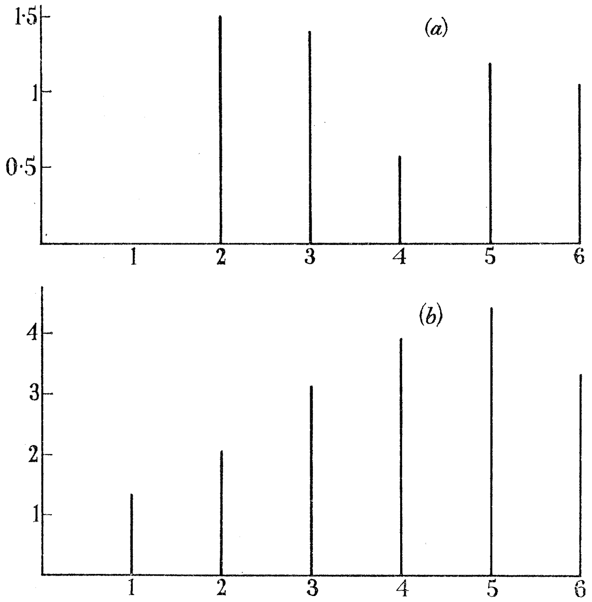

Figure 7. Comparison of strengths of harmonics of (*a*) geopotential up to sixth degree from Izsak (1964) with those of (*b*) the topography ($\times\sqrt{\{n(n+1)\}}$) (Vening Meinesz 1962).

gradually through the Earth's life, as originally suggested by Urey (1952), and that its radius is thus still increasing, a change in the number of convection cells in the mantle might recently have occurred. If this increase in the degree of the convection is the mechanism for the dispersal of the continents since the Palaeozoic, then the surprisingly recent time—compared with life of the Earth—during which it has occurred is given a rational explanation.

The ratio η of core radius to the Earth's radius at which the Rayleigh number of a given harmonic becomes less than that of the harmonic of next lower degree and therefore may be expected to develop in place of the latter can be calculated from Chandrasekhar's theory, but the values depend on the boundary conditions used. It is argued above that the appropriate ones for the Earth are a free inner boundary and a rigid outer one, for shearing stresses at the core-mantle boundary must vanish and the crust of the Earth is rigid. If these boundary conditions are used, Runcorn (1962) calculates, from Chandrasekhar's work, that the ratio of the radii of core and earth at which the second harmonic replaces the first harmonic as the mode through which instability occurs is 0·06. For the transition from second to third he obtains a value of η of 0·36, and for third to fourth 0·49. During these transitions the continents will undergo relative motion, involving stresses as the convection pattern changes to that of higher degree. The last such transition from fourth harmonic to the fifth is observed in the geological column as continental drift.

Runcorn (1962*b*) raised the question of whether there is any record in the earth's crust of the earlier transitions; these transitions would be expected to be periods of world-wide orogeny, which might involve extensive recrystallization of crustal material. Radioactive age determinations have largely been made on igneous and metamorphic rocks which have been formed in the deeper parts of the crust and are often associated with orogenic forces.

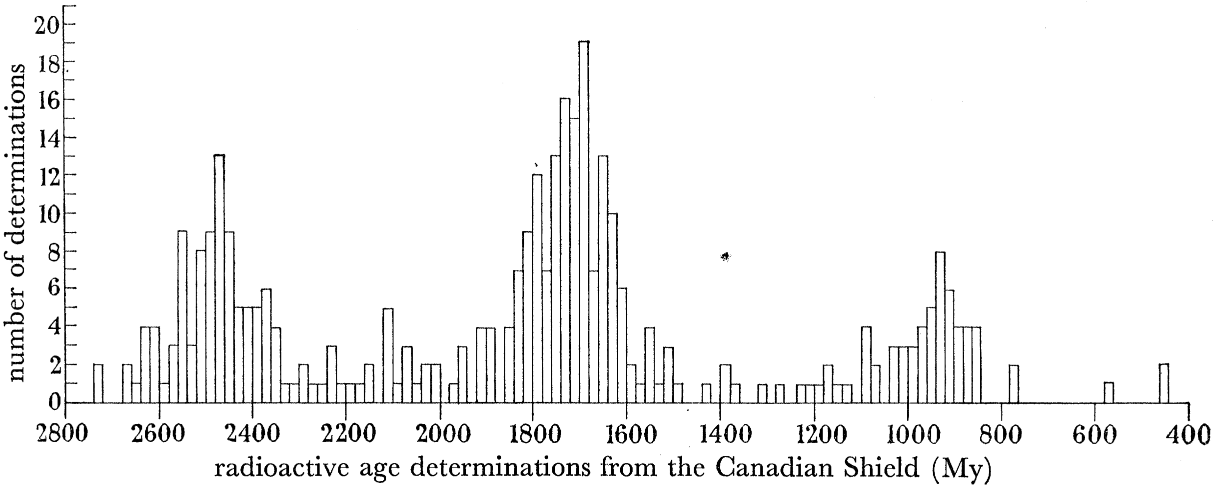

FIGURE 8. Histogram of radioactive ages from the Canadian Shield.

Surveys of the radioactive ages of the Precambrian shields (Gastil 1960) have shown that the ages obtained for such rocks appear to be grouped in peaks of about ±100 My width around the dates 1000, 1800, and 2600 My ago (see figure 8). The ages of Phanerozoic time form a broad spread covering much of the geological record since the middle Palaeozoic, and this appears to be associated with continental drift and the transition from a fourth to a fifth degree convection pattern in the mantle. It is natural to identify the 1000 My peak with the transition of the third to fourth degree convection pattern, the 1800 My peak with the transition from the second to third degree, and the 2600 My peak with the transition from the first to second. Gastil (1960) has reviewed the radioactive age dates and has shown that the peaks are present whether the ages are determined by the rubidium–strontium method, the lead method, or the potassium–argon method. He also shows that in spite of the poor coverage in some continents, the peaks appear to represent world-wide events. Davis & Tilton (1959) had also come to a similar conclusion that these peaks are real and are not simply due to deficiencies of sampling. The determination of the breadth of the peaks is difficult because of sampling problems but they are of the order of 200 My.

It is possible from this correlation to plot the radii of the core against these ages (figure 9). This shows that the core must have started its growth a little over 3000 My ago. This is reasonable on two grounds. First, if the earth was formed by accretion 4600 My ago, it would not necessarily reach a temperature, at which the creep processes required for convection were important, for some time. These depend on a factor exp (E/kT) where E is an activation energy, k Boltzmann's constant, and T the temperature, and it therefore may be supposed that the creep process rather suddenly became important as the earth heated up and only then would convection begin. The source of the heat is the uniform distribution of radioactivity. It may then be supposed that the convection would be maintained by the heat generated by radioactivity within the earth and by the release of potential energy due to the settling of iron into the core.

The law of growth of the core found by the above argument seems also to be consistent with a simple model suggested by Runcorn (1962*b*), i.e. that the rate of movement of iron into the core is proportional to the surface area of the core and to the mass of iron remaining in the mantle. Initially the radius will grow linearly with time as equal increases in radius represent increments of mass proportional to the surface area of the core. Eventually the curve will become asymptotic to the final radius (q) of the core when all the iron has left the mantle. Figure 9 shows the curve of the theoretical equation derived by Runcorn (1962*b*), which is

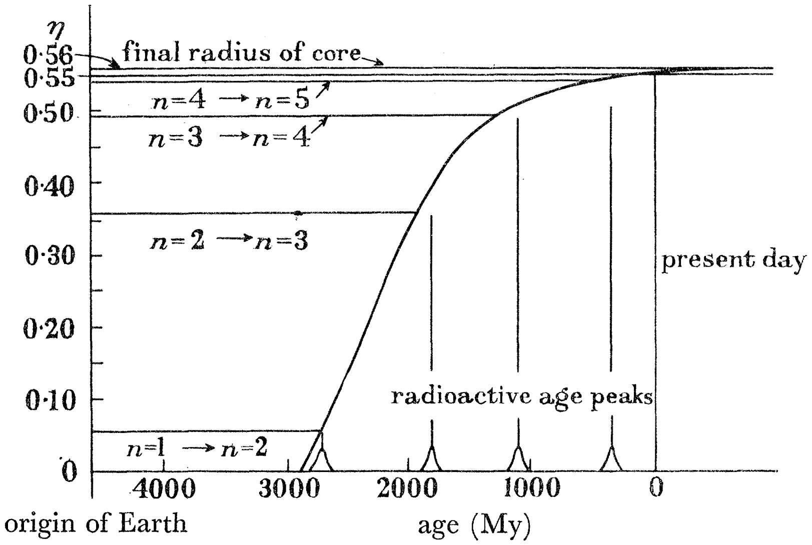

FIGURE 9. Diagram of growth of the Earth's core.

$$\ln\frac{\{(r/q)-1\}^2}{\{(r/q)^2+(r/q)+1\}}+2\surd3\tan^{-1}\left\{\frac{-2(r/q)-1}{\surd3}\right\}=Kt+c,$$

where K and c are constants and r the radius of the core at time t. Fitting by least squares gives $q = 0{\cdot}56$: thus about 6 % of the iron still remains in the mantle.

Two other lines of thought suggest that the convection currents may have been simpler and of larger scale in the earlier history of the Earth. The first is due to Hills (1947) who assumed that the present concentration of sial in one hemisphere resulted from a single convection cell (of first degree) sweeping acidic continental material together at one pole. This idea was attractive for, on Jeffreys's (1952) theory of the evolution of the Earth, the liquid sphere, condensed from a gas cloud, would naturally cool by convection after gravitational separation had rapidly formed the core and crust. Jeffreys & Bland (1951, 1952) showed, however, that Hills's single-cell convection would not form in the presence of a dense core of the present radius and that the more complicated convection pattern would not concentrate the continental material in a single hemisphere. The present theory removes this objection to Hill's idea.

The positions of the continents before the most recent continental displacements occurred can be inferred from palaeomagnetism, not exactly enough to justify a harmonic analysis but sufficiently to see that in such an analysis the lower harmonics would be more important than in the present topography of the globe. Runcorn (1963) shows that palaeomagnetic data from South America, Africa, India, Australia and Antarctica, indicate that these continents, in the mid-Mesozoic, were grouped closely near the South Pole. Creer, Irving & Runcorn (1956) from palaeomagnetic observations, and Opdyke & Runcorn (1960) from palaeo-wind observations, show that Europe and North America were mainly in the northern hemisphere, in lower latitudes than at present, at the end of the Palaeozoic. Such a continental distribution would be characterized by the $n = 4$ harmonic being much more important relative to the $n = 5$ harmonic than it is at present. One may therefore conclude that before continental drift took place the continents were positioned essentially by a convection pattern of the $n = 4$ type, as shown in figure 10 and that this gave way in the last 200 million years to convection of $n = 5$ type.

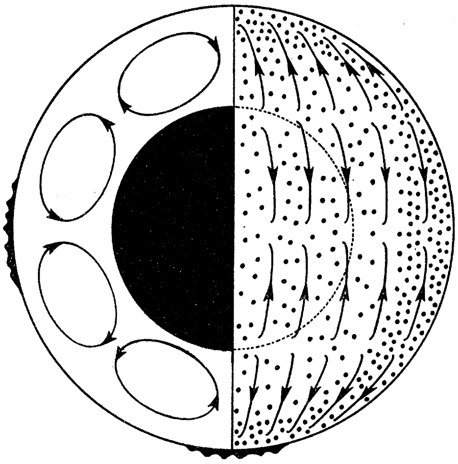

FIGURE 10. Fourth degree convection pattern.

7. QUANTITATIVE DISCUSSION OF THE GROWING CORE HYPOTHESIS

The hypothesis of a gradual growth in the Earth's core has two important consequences. First, it provides a source of energy continuously released since 3000 My ago. Unlike radioactivity this energy has been released at a rate which has increased during part of the Earth's life. Secondly, the moment of inertia has gradually diminished. Thus the slowing down of the earth by lunar tidal friction has been to some extent counteracted by the growth of the core. It is necessary now to evaluate these effects quantitatively.

We shall consider a whole series of Earth models, with different radii r_b of the core. In each model, iron is distributed in the mantle. We will assume that each model has the same external radius a. With the usual assumption about hydrostatic equilibrium

$$\mathrm{d}p/\mathrm{d}r = \rho g, \tag{7·1}$$

where p, ρ and g are the pressure, density and gravity at radius r. But

$$g = \frac{4\pi G}{r^2} \int_0^r \rho r^2 \,\mathrm{d}r \tag{7·2}$$

where G is the gravitational constant.

Now we know, from the seismological data, the relation of ρ and p for the core, which we will take as the equation of state for iron. Thus

$$\rho = F(p) \tag{7·3}$$

which is known for $r_b \geqslant r \geqslant 0$.

The dependence of ρ on p for the mantle presents a difficult problem and some approximation has to be made. Bullen (1963) points out the interesting fact that the incompressibility and its gradient are nearly continuous across the core-mantle boundary. Bullen therefore postulated that the incompressibility at the high pressures of the earth's deep interior is insensitive to composition (the compressibility-pressure hypothesis). No satisfactory theoretical basis for this exists but it will be accepted here as a useful working hypothesis. It clearly fails near the outside of the earth but in the upper few hundred kilometres of the earth the composition is so puzzling that any hypothesis would be equally open to objection.

Thus we take
$$\frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}p} = f(p) \quad (a \geqslant r \geqslant r_b), \tag{7·4}$$

$f(p)$ is known from seismology.

On this simplified model the surface density $\rho(a)$ of the earth will gradually decrease with time, as the iron separates to form the core, and r_b increases. As the external radius is taken to be nearly constant during these changes $g(a)$ is known and equal to the present value.

Suppose an arbitrary value of $\rho(a)$ is taken, greater than 3·3, then

$$\mathrm{d}p/\mathrm{d}r|_{r=a} = \rho(a)\, g(a). \tag{7·5}$$

Thus, with (7·5) as the boundary condition, (7·4) can be integrated to give the values of ρ and p down to the core boundary. Then, from (7·3), ρ_b just within the core is known and the integration can continue to the centre. By means of a digital computer it is possible to try various values of r_b so that the boundary conditions at the centre, $\mathrm{d}p/\mathrm{d}r = 0$ and $g = 0$, are satisfied. This then is a model Earth with a core smaller than the present and the rest of the iron distributed throughout the mantle, causing the surface density to exceed the present one. $F(p)$ and $f(p)$ are taken from Bullard (1958) (column 4 of table). The results of these calculations are given in figures 11 and 12.

Figure 11 gives the change in potential energy E of the earth with core radius and therefore with time

$$E = \int_0^a 4\pi\rho r^2 V \,\mathrm{d}r,$$

where V is the potential at radius r given by

$$\frac{G}{r}\int_{s=0}^{s=r} 4\pi s^2 \rho(s)\,\mathrm{d}s.$$

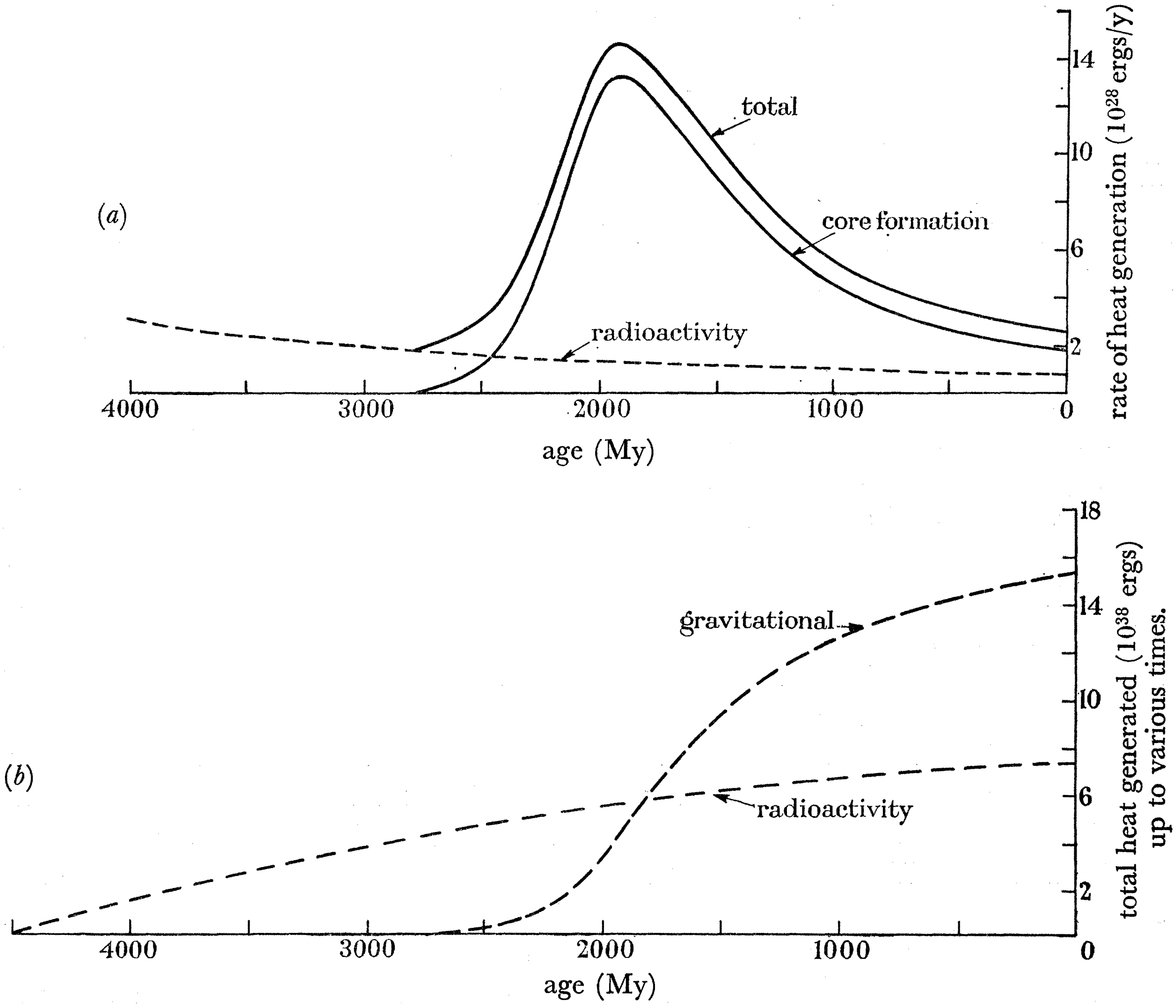

FIGURE 11. Comparison of energy released by radioactivity and by growth of the Earth's core.

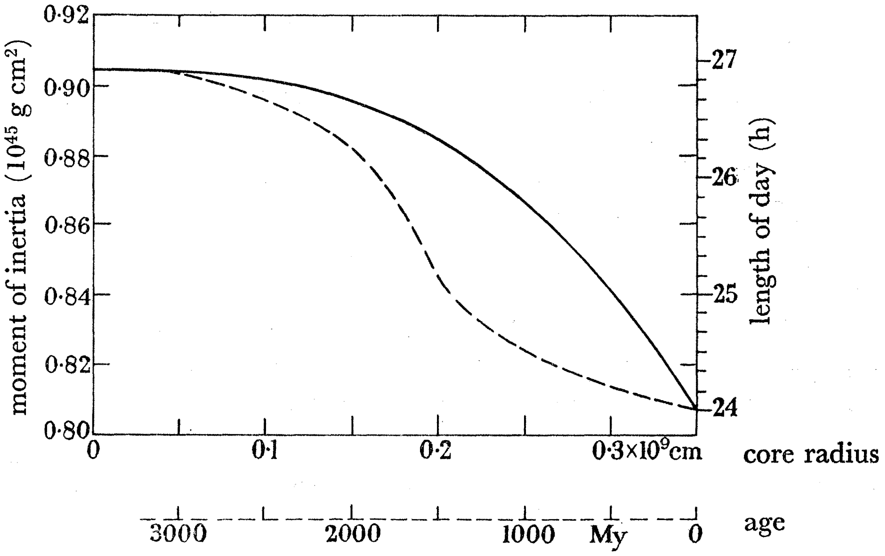

FIGURE 12. Changes in Earth's rotation due to growth of the Earth's core.

Figure 12 shows the change of moment of inertia I with core radius and time.

$$I = \int_0^a \tfrac{8}{5}\pi r^4 \rho \,\mathrm{d}r.$$

Munk & Davies (1964) have obtained a similar curve by a more approximate method.

The total energy released by the formation of the core up to the present is close to that given by Urey (1952) by a simplified calculation and is very much lower than that suggested by Stacey (1963) using an approximate method.

8. The accretion of the Earth

The separation of the Earth's iron core from the primeval Earth, a mixture of silicates and iron, presents no difficulty if the earth has at any time been molten. The denser iron would separate towards the centre in a very short time. However, Urey (1952) has given chemical reasons why the Earth could never have been molten. This suggests that the earth must have originated by a process of accretion. The initial temperatures in the earth on the accretion hypothesis could be very small, the surface temperature of 0 °C rising to about 600 °C at the centre as a result of adiabatic compression. While it has been suggested that the initial temperatures on the accretion hypothesis could be much greater if the gravitational energy released by the accreting particles could be retained, it seems more likely that the heat generated on impact at the surface of the growing planet would be radiated away. In this case the problem of how the core formed has to be solved. After accretion the radioactive elements of uranium, thorium and potassium would initially be distributed uniformly through the Earth. If, as Urey (1952) has suggested, it is supposed that the mantle of the earth has the same composition as chondritic meteorites, the amount of heat which has been released by radioactivity at different times in the earth's past can be calculated. Figure 11 shows curves calculated from the latest data of the radioactivity in meteorites given by Urey (1952). It can be shown from figure 11 that, even if none of this heat escaped, the earth would never have approached the melting point. However, Wasserburg, MacDonald & Hoyle (1964) have argued against the chondritic model and suggested that the radio-activity of the earth's interior is not likely to be even as great as that assumed above.

To overcome this difficulty it may be postulated that a large amount of heat was initially trapped within the earth making it possible for the melting point of iron to be reached and to suppose then that the denser iron managed to drain towards the centre between the silicate masses. To account for this initial heat it has been suggested that one of the short-lived isotopes, such as Al 24, could be responsible, but this supposes the accretion of the earth to have occurred within less than the half-life of this element, after the nuclear processes which generated it. On this theory the generation of the elements within the solar system was very rapidly followed by direct accretion into large masses.

It seems doubtful whether this could have happened without the intermediate step of accretion into small objects of roughly meteoric size. In recent years it has been found that stony meteorites possess a remanent magnetization. The study of this has shown that the magnetism was acquired by the same process of thermo-remanent magnetization which accounts for the magnetization of terrestrial igneous rocks (Stacey, Lovering & Parry 1961). It was naturally concluded that the magnetization of meteorites was acquired in a similar manner, i.e. by cooling on the surface of a planet possessing a general magnetic field. It has therefore been thought that the remanent magnetization of stony meteorites supports the view that meteorites originated from the breaking up of an existing planet. Yet the fact of meteoric magnetization really points to the opposite conclusion. For a planet to possess a magnetic field it must have a fluid, electrically conducting core. Further, for the amplifying effect of motions within the core to successfully counteract the natural free decay of the magnetic field, the core must have a minimum size. The planet will therefore have to be reasonably large and the temperature of most of its interior will be above the Curie point of the iron oxide minerals. In the case of the earth the Curie point is reached at depths of the order of 20 to 30 km. There can be little doubt, therefore, that only a minute proportion of this hypothetical planet would be cool enough to have acquired remanent magnetization. It is therefore impossible to explain the magnetization of stony meteorites in this way.

It is also unlikely that the magnetization could have been acquired during the few thousand million years since they first cooled. Although it is now known that interplanetary space contains magnetic fields of the order of 10^{-4} G, these are continually fluctuating, and this coupled with the low temperatures would not be likely to result in a magnetization which possesses the properties of thermoremanence. We are driven, therefore, to suppose that the magnetization was acquired during the initial cooling of the stony meteorites. That this weak magnetization has been retained for 4500 My need occasion no surprise, as many of the Precambrian sediments of the western United States which show strong consistent remanent magnetization are over 1200 My old (Runcorn 1964*a*). One concludes, therefore, that the meteorites were magnetized during the cooling which occurred at the time of origin of the solar system. The primeval dust cloud from which the sun and planets formed may have possessed an appreciable magnetic field, for without one it is not easy to explain why the angular momentum of the solar system now resides mainly in the planets (Alfven 1954). The planetesimals would be rotating about an axis fixed in space and it would therefore be possible for them to be magnetized by the component of the ambient magnetic field along this axis.

The conclusion is thus reached that the earth originated from a collection of small planetesimals, some stony and some iron, so that the possibility that the separation of the iron core has continued up to the present has to be considered.

It has been shown that a growing core may supply the essential link in the explanation of continental drift. The dispersal of the continents which once constituted Gondwanaland and Laurasia has been shown by palaeomagnetic measurements to have occurred in the last 200 My. The differences between Wegener's concepts and modern ideas of continental drift are considerable, but the earlier reasoning also put drift in the latter part of Phanerozoic time. Continental drift, therefore, must be recognized as a comparatively late event in the earth's evolution, but it is easier to understand if it is the latest of a series of periods of marked crustal movements of a world-wide character.

A search is therefore desirable as to whether there is evidence for growth of the Earth's core. Urey (1952) pointed out that there was in principle a method of determining whether the earth's core was growing at the present time from the astronomical evidence of the secular accelerations of the sun and moon, and Munk & Davis (1964) have shown that this evidence, derived from the ancient eclipses, and from Wells's (1963) work on corals does not exclude the moment of inertia changing as shown in figure 12.

The data from ancient eclipses seems of insufficient accuracy to permit of a decisive test but a more promising method is now possible through the determination of the lengths of the day and month from the study of corals (Runcorn 1964*c*).

The part of this paper in which the consequences of a cold origin of a planet are discussed is based on work done during a visit to the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under contract NAS 7-100. I am grateful to the Director and his colleagues for the facilities placed at my disposal. My thanks are due to Theodore J. Cullen of this laboratory for the computations of § 7. I thank Dr J. H. Parry and Mr A. Coode for help in the preparation of the manuscript. Dr L. Molyneux and Mrs N. Robinson helped with the computations of figure 5.

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