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Arrangement of convection in the Earth by lunar gravity

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> And here upon earth's noonward height
> To feel the always coming on
> The always rising of the night.
> Archibald MacLeish

Earth strain is found to have dependence on latitude. The possibility is explored that the external gravitational couple is a factor in tectonism. Evidence suggests that where extension is induced in a layer in which melting is limited by pressure, liquefaction and upwelling result.

It is then to be expected that the Earth's internal heat is dissipated by convection ordered (but not caused) by the tidal couple. Upwelling takes place in high latitudes and in the ocean basins and is marked by sea-floor spreading. Replacement at depth is effected in low latitudes, at the site of geoidal highs and deep-seated seismicity. An excess in the equatorial potential is associated with the excess of deformation in low latitudes. There then seems no reason to suppose that convection is confined to the upper mantle.

The effect at surface is that the lithosphere is displaced west, at an angular velocity greatest at the Equator and varying regionally. As a result this shell segments, and the segments rotate and interact.

1. Introduction

Information has been assembled as to the global distribution of strain.

Strain is found to have a dependence on latitude. The possibility is explored that the external gravitational couple is a factor in tectonism.

Sir George Darwin showed that in an Earth having uniform density and viscosity, distortion by the gravitational couple is insignificant. Data have become available as to the location in the Earth of defects in elasticity. Moreover, evidence has accumulated that segments of continental dimensions have been displaced intact. To illuminate the force system, an examination has been made of the deformation incurred by the ocean basins at the time of earlier pole positions.

Means have been considered by which the distortion expected might be observed.

2. Strain in the Earth

The incidence of strain in the Earth is shown by the shape of the geoid and the occurrence of earthquakes.

Strain state

Satellite geodesy has determined that the equatorial bulge is some tens of metres in excess of hydrostatic equilibrium. The bulge consists of equatorially-disposed regions of excess matter separated by regions in which the geoid is low. The regions of excess consist of a sector embracing Europe and part of Africa; the Americas, in particular tropical South America; and the western margin of the Pacific Ocean. The poles constitute regions of deficiency which penetrate to low latitudes in the Atlantic and central Pacific Oceans. A sector centred on the Indian Ocean is below equilibrium from pole to pole (Gaposchkin & Lambeck 1971).

Imposition of strain

Strain flux at the present day is a sample of the processes which have resulted in the accumulation of mass anomalies.

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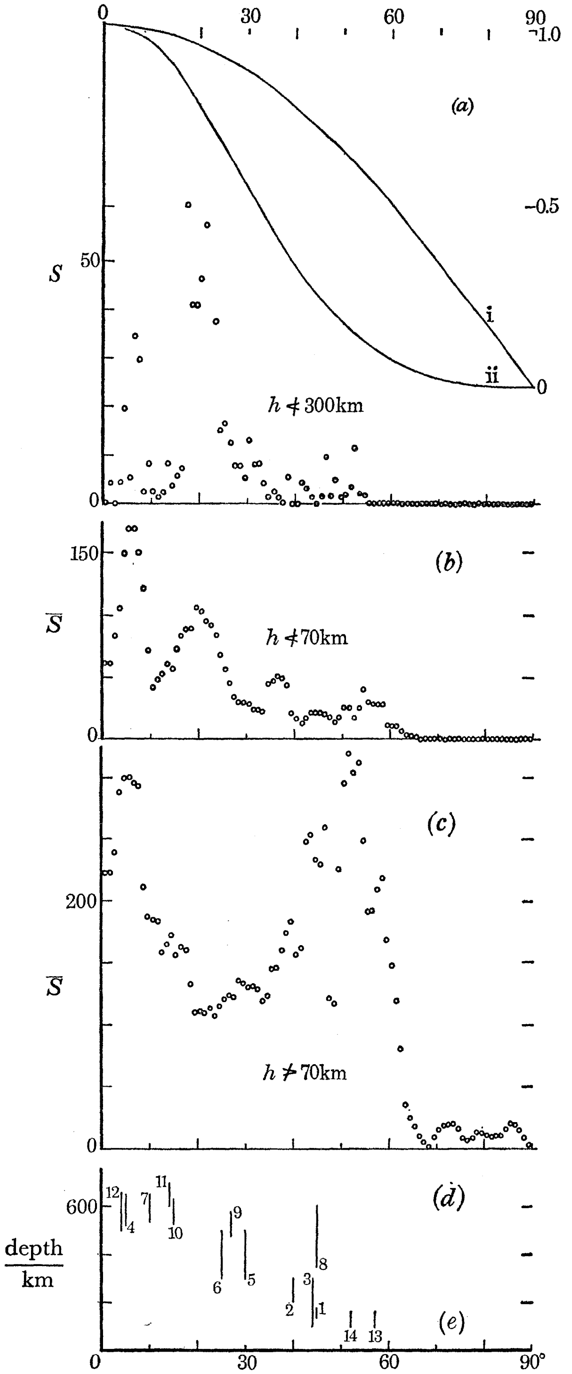

FIGURE 1. Comparison of the incidence of strain release as indicated by seismicity (*b*, *c*, *d*) with tidal forces (*a*; §4).

(*a*) Variation with latitude of: (i) force required to rotate the outer layer of the Earth intact about the layer beneath; (ii) force system engendered by the retarding torque.

(*b*) Incidence of deep seismicity in terms of *S*, the number of events per 10^7 km² for each degree of latitude in the interval 1961–9; focal depth not less than 300 km.

(*c*) Incidence of all sub-lithosphere seismicity during the same interval. $\bar{S}$ is the running average over five degrees of latitude, per 10^7 km²; focal depth, not less than 70 km.

(*d*) Incidence of lithosphere seismicity, for same interval, same units; focal depth, not more than 70 km.

(*e*) Depth of maximum seismic activity in regions of sub-lithosphere seismicity. The regions are: (1) Rumania; (2) Hindu Kush; (3) New Zealand; (4) Sunda; (5) Kermadec; (6) Isu-Bonin; (7) South America; (8) Kurile; (9) Tonga, south; (10) Tonga, north; (11) New Hebrides; (12) Philippines; (13) Scotia arc; (14) Aleutians. With the exception of (13) and (14), these are re-arranged in order of latitude from Isacks, Oliver & Sykes (1968, their figure 13).

Epicentral data kindly supplied by United States National Earthquake Information Center, Rockville, Maryland, from that agency's tape file of events detected by the World-Wide Standard Seismograph Net. Magnitude, not less than 5; total number of events, 10980.

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The flux of elastic energy is to some extent amenable to monitoring in terms of the incidence of seismicity. The World-Wide Standard Seismograph Network (Whitcomb 1971) detects events having characteristic periods of 30 s and less and a magnitude of 5 or greater. Earthquakes in this range of magnitude and their aftershocks account for more than 80 % of seismic energy release. Figure 1 illustrates the incidence of seismicity by latitude. In the interval in which W.W.S.S.N. has been operative, sublithosphere earthquakes have congregated in low latitudes and are absent near the poles. The incidence of lithosphere earthquakes is bimodal, having a peak at intermediate latitudes as well as near the Equator. A residual level in shallow seismicity persists to polar latitudes.

3. Secular tidal forces

The distribution of strain suggests, but does not prove, that a relation exists between tectonism and the Earth's rotation. Force systems have been suggested by which tectonism might be related to rotation, but the existence of most is speculative.

The form and magnitude of tidal torques can be established by astronomic observation, so that it seems worth comparing their reaction with observed aspects of tectonism.

To evaluate the effect of tidal friction, Sir George Darwin (1879*a*, *b*, *c*) made as mathematical model an Earth homogeneous as to density and viscosity. Darwin was aware that the Earth is not uniform, but pointed out that too little was known to model its elastic structure. Taylor (1919), Jeffreys (1929), and others, have shown that much of the mass asymmetry responsible for the tidal couple is water. The exterior solid shell varies in its properties from region to region, making it impossible to separate by tidal observation the angle by which its bulge leads the Moon and Sun.

With respect to the part of the torque attributable to the deep interior, the couple about the line of centres of the Earth and Moon may be represented (Tomaschek 1957) as

$$-N = \tfrac{8}{5}\pi Gm(r^4/R^3)u_r\rho \sin 2\epsilon,$$

in which G is the Newtonian constant; m the mass of the Moon; r the radius of the Earth; R the distance between centres; ρ the density of the matter in the inequilibrium bulge; u_r the height of the bulge; and ϵ the angle at the Earth's centre subtended by the bulge and the Moon.

The cotangent of the phase angle for small values is equivalent (Munk & MacDonald 1960) to the value of the elastic quality factor Q. The value of Q applicable to tidal frequencies in the lower mantle is not less than several hundred, and several times that in the outer solid layer including the zone of reduced seismic velocities (Lagus & Anderson 1968). In consequence the phase angle in the lower mantle cannot be greater than a few minutes of arc. u_r has been evaluated by Takeuchi (1950), using seismologic values of the elastic constants. The value of the gravitational couple in the lower mantle is then found (Bostrom, Sherif & Stockman 1973) to be not greater than 10^{18} N m (10^{21} dyn cm).

But the body comprising the lower mantle and core is being decelerated at essentially the same rate as the Earth as a whole, established by astronomical observation at surface stations, so that the acceleration is

$$A = L_{\mathrm{E}}/C_{\mathrm{E}} = L_{\mathrm{s+c}}/C_{\mathrm{s+c}}$$

and

$$L_{\mathrm{s+c}} = (L_{\mathrm{E}}\, C_{\mathrm{s+c}})/C_{\mathrm{E}}, \tag{1}$$

where L is the inertial couple, C the principal moment of inertia, and E, s and c denote respectively quantities attributable to the whole Earth, the lower mantle and the core. L_{E} is known

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astronomically (Munk & MacDonald 1960). The values of C can be established from seismologic values of the density, derived by Birch (1964).

Of the couple $L_{\mathrm{s+c}}$ necessary to decelerate the lower mantle and core, it is then apparent that not more than a fraction can be attributed to body forces.

Failing forces represented by a gravitational couple, the principal body of the Earth is decelerated by an east–west tangential force system $\tau_{\mathrm{s+c}}$ acting on its top, and from (1)

$$\tau_{\mathrm{s+c}} = L_{\mathrm{s+c}} - N_{\mathrm{s+c}}.$$

Using limiting values for the ratio of Q in the lower mantle to that in the upper (Lagus & Anderson 1968) $\tau_{\mathrm{s+c}}$ is found to have a value of not less than 3×10^{20} N m (3×10^{23} dyn cm), and tends to displace the hydrosphere and outer part of the solid Earth westward about the mantle.

The existence of $\tau_{\mathrm{s+c}}$ need not, *a priori*, lead to distortion. It might be argued that the material forming the outer layers of the Earth, although affected by convection, resists this force in perpetuity. Evidence as to whether it does must be sought elsewhere.

4. DISTORTION BY SECULAR FORCES

The composition of the system $\tau_{\mathrm{s+c}}$ is characteristic. It does not tend, for example, to lead to rotation intact of the lithosphere about the inner part of the Earth.

The couple $r\rho\ (\partial U_2/\partial\lambda)\ \mathrm{d}v$ (where U_2 is the tidal potential, v the volume and λ the longitude in respect to the Moon) acts on particles of rock and water forming an inequilibrium bulge which increases in height towards the Equator as $\sin^2\phi$, where ϕ is co-latitude. In consequence the tangential stress per unit area tending to displace the lithosphere east to west is

$$\tfrac{1}{4}\rho r^2\ (N/C_{\mathrm{e}})\ \sin^3\phi.$$

The variation of this function with latitude is shown as curve (ii) of figure 1*a*. It may be seen that the decelerating forces are more restricted than merely to the outer layer of the Earth. Within this layer they act principally in a band about the Equator.

In comparison, the shape of a force system required to produce rotation of a lithosphere intact about the shell beneath is shown as curve (i) in the same illustration. The body of the Earth is decelerated by forces acting on the lithosphere; principally the equatorial part of the lithosphere is coupled to lunar forces; the part in middle and high latitudes is decelerated by being fast to it. The difference between curves (i) and (ii) represents a shear acting in the vertical plane and maximum in intermediate latitudes. Within the low latitude belt the forces representing the retarding torque must be concentrated locally, by reason of regional variations in elasticity and in the shape of the geoid.

Former direction of forces

Figures 2 and 3 show the position of the continents at earlier times, plotted so as to compare their displacement with the direction of external torques. Mechanical considerations require that the rotational pole remains fixed with reference to inertial coordinates. The analysis of Slichter (1963) shows that the secular tilting torque can have displaced the rotational axis no more than 1° since Palaeozoic times. If it is taken that the rock magnetic record describes magnetic pole directions, and that the magnetic pole is associated with the pole of rotation, it must be accepted that successive portions of the lithosphere have occupied polar positions.

In the Pacific hemisphere the record is incomplete but consistent with an explanation that during the early Mesozoic the surface feature known as the Darwin rise (Hess 1962; Menard

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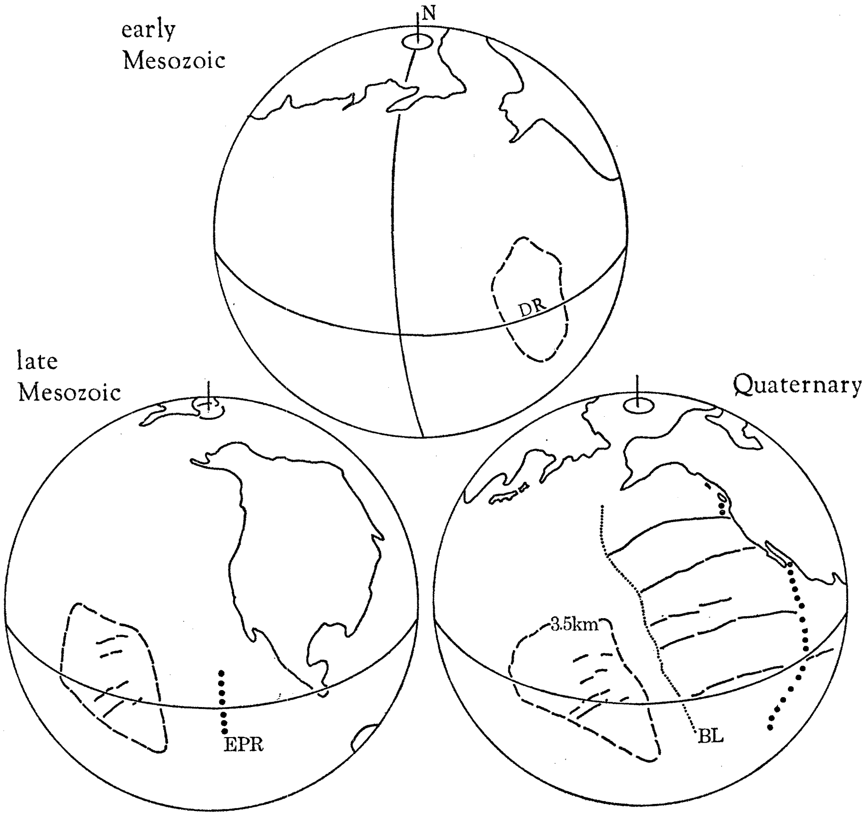

Figure 2. Deformation of the Pacific basin, from geophysical data and deep-sea drilling. The surface trace DR of the 'Darwin rise' (Menard 1964; Hess 1962) has been displaced west by subsequent extension of the sea floor about the east Pacific rise, EPR. The branch line, BL, defines the westward extent of Menard's fracture zones. The latter describe the spreading direction of the east Pacific rise and have repeatedly changed direction 20° clockwise since their incipience in the latter part of the Mesozoic (Menard & Atwater 1968, their figure 2; Rea 1970). In the same interval rock magnetism indicates that the magnetic pole has been displaced from northeastern Siberia (early Mesozoic) to Kamchatka, thence to the centre of the Arctic Ocean.

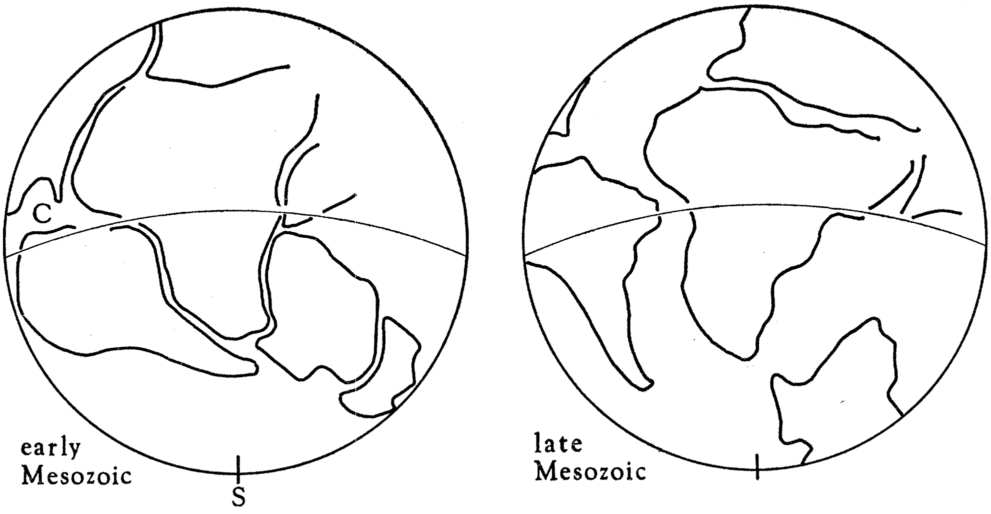

Figure 3. Fragmentation of Gondwanaland and development of the Atlantic Ocean with reference to the position of space-fixed poles and Equator. Except in the Caribbean (C) the sutures do not signify the presence of seaways in the early Mesozoic.

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1964) was located in the eastern Pacific Ocean. With shift of the rotational pole and initiation of the separation of North America from Laurasia the east Pacific rise came into existence in that region. Continuation of extension at the east Pacific rise, with continued shift of the pole, has resulted in the westward displacement of the lithosphere to its present position, and the repeated 20° clockwise rotation in spreading direction described by Menard & Atwater (1968).

Deformation in the other hemisphere is scarcely better recorded. The sea-floor magnetic pattern is more restricted, contradicts in the South Atlantic much of the geological record (Wright 1971), and in such critical regions as the southwest Indian Ocean is difficult to interpret (Veevers, Jones & Talent 1971). Onshore, rock magnetism does not provide a coherent record unless special solutions are accepted, such as the assembly of Antarctica from fragments (Creer 1967) and the joining of this continent to Australia followed by its separation. The rock-magnetism and palaeontological data are to some extent irreconcilable, in that it is not easy to accept the development of a tetrapod fauna at high latitudes (Colbert 1971). In the face of contradictory evidence most weight has been given in figure 3 to the palaeontological data, as being the hardest to disregard. We offer no new information as to whether India is integral to Laurasia, as suggested by stratigraphic evidence (Meyerhoff & Meyerhoff 1972) or has suffered long-distance drift.

Principal events in the fragmentation of Gondwanaland include the commencement of fragmentation at the Africa–Antarctica join and in the southern part of the North Atlantic Ocean (Dietz & Holden 1970; Smith & Hallam 1970; McElhinny 1970). These processes were initiated in the early Mesozoic. At that time both regions lay in low latitudes. One hundred million years later the opening of the North Atlantic was joined by the separation of South America from Africa. The régime change was accompanied by change in the location of the Equator, as the pole moved from a point in the South Pacific towards its present position. If a configuration of Gondwanaland is adopted in which Antarctica lay off the tip of Africa, the shift of the Equator must have been greater.

At this time the north pole was moving from northeast Siberia to Kamchatka, thence to its present position. As in all such discussions, 'motion of the pole' must be read to signify rearrangement of material relative to the space-fixed pole. The location of the pole of rotation is determined by the location of A', the axis of greatest nonhydrostatic moment (Goldreich & Toomre 1969). If the order of A' and B' in the inequality $A' > B' > C'$ reverses by increment, rapid pole shift must ensue. In the presence at the top of the mantle of a zone of incipient melting, pole shift must be accomplished by distortion of much complexity. Pole shift must thus have contributed to the break-up of Pangaea, and the displacement of such continents as Australia, but we find the record impossible to decipher.

At the present day in both hemispheres sea-floor spreading is predominantly east–west near the Equator, veering to north–south and diminishing in rate in high latitudes. Vectorially summed, its effect in the last 10 million years has been to displace the lithosphere west some 500 km (LePichon 1968, his figure 7; Bostrom 1971).

5. EFFECT OF EXTENSION IN AN ASTHENOSPHERE IN WHICH LIQUEFACTION IS LIMITED BY PRESSURE

In case tidal torques are responsible for the coherent quality of sea-floor spreading, in what follows enquiry is made as to what may be the coupling mechanism.

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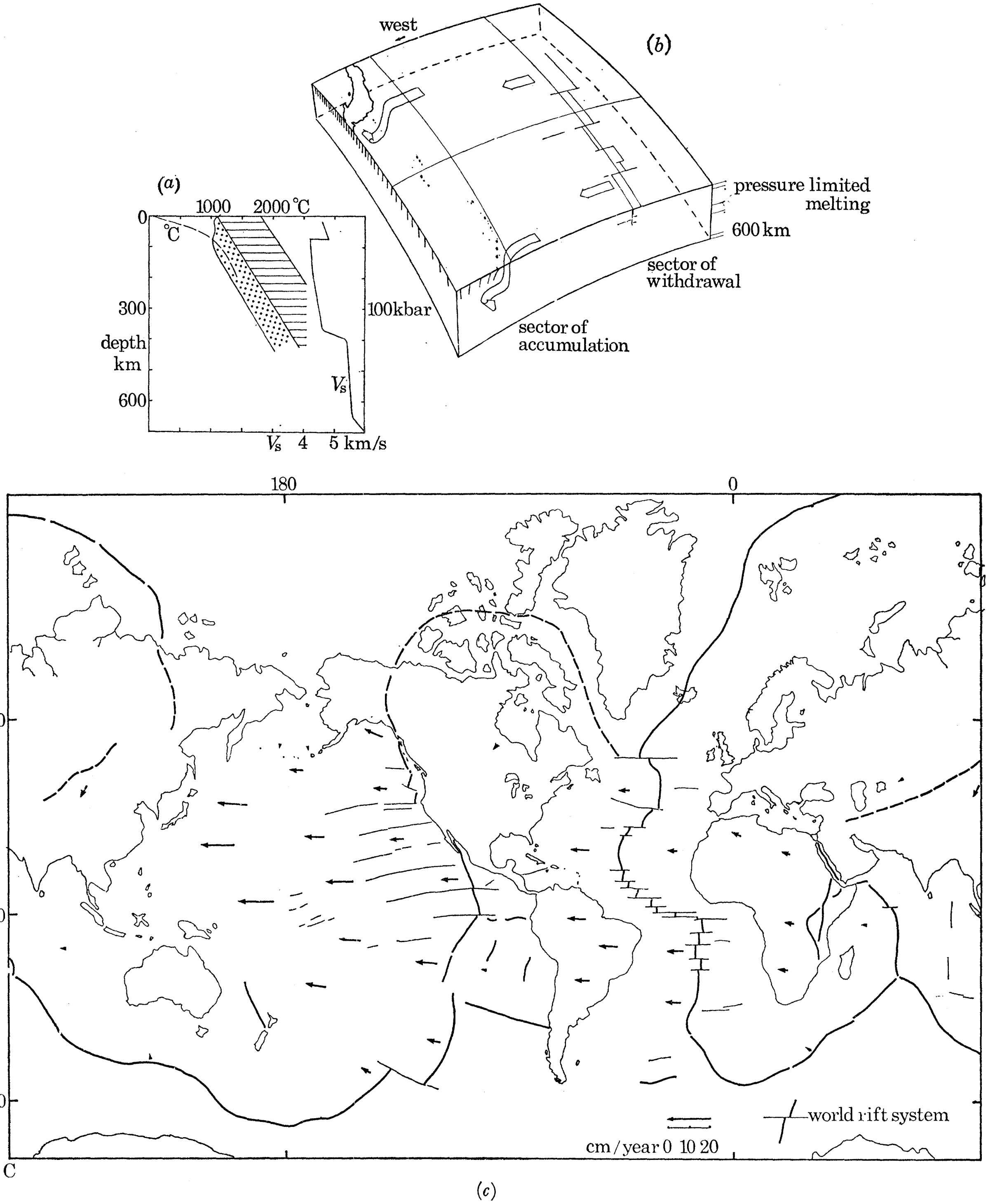

FIGURE 4. Response of a convective Earth to tidal traction.

(*a*) Asthenosphere based upon the peridotitic mantle of Wyllie (1971). The latter contains traces (0.1 %) of water. The isotherm intersects the region of partial melting, shown by dot ornament, at the depth at which wave velocities (Press 1971) drop sharply. Region of normal melting, hatched.

(*b*) Liquefaction and upwelling to be expected in zone of extension with complementary thickening and phase compression in sector of accumulation, as a result of westward displacement of lithosphere material. The vertical ornament near surface in sector of accumulation is intended to suggest addition of differentiate from depth to lithosphere, resulting in relaxational spreading of this region towards the ocean (§6).

(*c*) Displacement at the Earth's surface, in terms of the horizontal component in velocity. The arrangement suggested is one of many possible adopting a greater or less contribution by the retarding torque. The interpretation is based upon Menard's (1965) chart of the world-rift system; sea-floor spreading rates; the distribution of sub-lithosphere seismicity; and the form of the geoid as mapped by Gaposchkin & Lambeck (1971). Shortening of the vector arrows in the direction of their length implies that material balance is preserved by thickening; lengthening requires the existence of extension and upwelling. An implication in this model is that migration of the ridge crest (but symmetrical spread) is intrinsic to sea-floor extension, rather than being confined to the ridge peripheral to Antarctica.

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Arrangement of convection by tidal friction

The major part of the retarding torque is attributable to the seas and outer layer, so that both the force system and the resistance to it vary regionally. If displacement is significant, the lithosphere must segment and the segments be displaced at different rates. The effect to be expected in a model of the mantle is considered in figure 4*a* and *b*. The compositional restraints are those of Wyllie's (1971) periodotitic upper mantle. The temperature increase is selected so as to make the change to a partially molten phase coincide with the depth at which transverse wave velocities drop sharply in Press's representation (1971) of the low-velocity zone. The isotherm falls between those arrived at by Lubimova (1967) and by Clark & Ringwood (1964).

Initially material at depth is solid. If now the region finds itself between lithosphere segments suffering separation, not only does the surface suffer rifting but material formerly within the solidus is in a region of reduced pressure. It seems inevitable that partial-melting with separation of a melt fraction will take place, a process limited by the supply of heat. Upwelling of the melt fraction to fill the rift must be the consequence. If before the start of these events the mantle concerned was in a state of incipient convection, upwelling will be localized along the plane normal to extension.

The consequence of these processes in a sector of the lithosphere is shown in figure 4*b*. Extension in a region in which convection is marshalled by tidal forces must assume a coherent form. We take the liberty of identifying this with regularities exhibited by the system of oceanic rifts and fracture zones. The existence of convection is governed by old rules, in that it represents the most efficient agency of heat efflux from the Earth's interior. Its form is determined by tidal forces.

North–south secular force components

Slichter (1963) has shown that the component of the Earth's angular velocity normal to the orbital plane of the Moon decreases rapidly in comparison to the component within the plane. The result is tilting of the axis of spin towards increase in the obliquity. A difficulty is to push far enough back into geological time Slichter's 'rotation explosion', while not contravening the forces observed to act at present. The locus and effect within the Earth of extension components arising in consequence of regional non-uniformity of the lithosphere can be estimated with less uncertainty. A region in low latitudes from which material is being withdrawn faster than it is being replaced (as, for instance, the Indian Ocean) must be flanked to north and south by regions from which material flows in the direction of establishing hydrostatic equilibrium. The variation in the value of the torque tending to diminish rotation leads to east–west veering of the deformation as high latitudes are reached. The regional variation is superimposed, so that it seems no coincidence that the ocean–ridge system is well developed in the south Pacific and south Indian Ocean (figure 4*c*).

6. MASS DISPLACEMENT

In what follows, to explore the subject the assumption is made that the secular torques are effective in marshalling convection. What is the long-term result?

Regions of accumulation and deficit

Differential displacement of lithosphere segments is tantamount to a thickening of the Earth's outer layer, with accumulation of material, where the westward displacement rate slackens; and the inverse, the appearance of a region of deficit, where the velocity increases. Such regions

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may be grouped, so that the preponderance of extension in the African hemisphere is equivalent to its being the site of a net deficit, with corresponding acquisition elsewhere. Geologically this is described as the fragmentation of a Pangaean continent, and the encroachment of the Americas on the Pacific Ocean basin. It is unnecessary that uplimbs alternate with downlimbs; rift zones in the Atlantic, in East Africa and in the Indian Ocean may be contiguous without intervening zones of convergence.

A major uncertainty arises in the mechanism by which material is returned to depth. Return must take place in regions of accumulation, and it would be logical to suppose that these are represented by geoidal highs. The latter occur only outside high latitudes, and alone are the site of deep seismicity.

In the most general terms, in regions of accumulation a thickening of the surface layer must take place accompanied by the transition of minerals to their high-pressure form. Thickening may be accomplished by subduction into the asthenosphere of a slab of lithosphere, but evidence as to the existence of this is not yet overwhelming. Spreading and high heat efflux in sectors of accumulation such as the Sea of Japan (Karig 1971; Hilde & Wageman 1971) suggest that differentiate from depth is there added to the lithosphere. The addition results in gravitational relaxation of the intra-arc segment towards its periphery. The arcuate shape, deep-sea trench, shallow seismicity and Meinesz gravity strip are then not directly the expression of convection; but instead, of lithosphere deformation consequent upon the oceanward extension (figure 4*b*). Topography, the form of the free-air anomaly, and the convoluted distribution of hypocentres in eastern Indonesia and elsewhere point to the fact that in regions of high velocity gradient the flow is far from laminar.

In summary, the low-latitude geoidal highs marked by deep seismicity, in the main South America and the west Pacific margin, are regions of accumulation. Return of material to depth is there accomplished by thickening of the outer layer. Regions where the anelastic asthenosphere is most massive, namely the ocean basins, are marked by the most rapid abstraction of material, resulting in the appearance of geoidal lows and adjustment by upwelling.

Excess equatorial potential

If the retarding torque contributes to Earth deformation its effect must be zonal, because the force exerted per unit area increases exponentially towards the Equator (figure 1*a*). It is then to be expected that the potential at low latitudes will be greater than that at the poles, for the reason that a water body having waves possesses greater gravitational potential than it does in hydrostatic equilibrium. Otherwise put, the 'excess bulge' is the concomitant of the vertical component in the excess of deformation in low latitudes. The one-way shallow flow of material from the poles is represented by the ocean-ridge system in high latitudes.

Relieved of the implication by the excess equatorial potential that the Earth is so strong as to have preserved an earlier figure of rotation (Munk & MacDonald 1960), it seems logical to assume that convection is not confined to the upper mantle. Seismicity then ceases at 700 km because below this depth the mantle is too soft to accumulate elastic strain.

7. MEASUREMENT

To detect a coupling of tidal forces and convection requires observation of the displacement of surface segments and disbursement of the Earth's angular momentum.

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If the matter responsible for the geoidal high associated with the west Pacific Tertiary orogenic belt has accumulated in 6×10^7 years, the difference in velocity between the central and west Pacific segments is 10^{-8} radians/year. The strain in such a large area would be difficult to detect.

The potential in measuring tectonic motion by means of lunar laser ranging has been shown by Kaula *et al.* (1973). A technique having the advantage of being extant and referred to inertial coordinates is afforded by local time keeping. This provides a ready-made sample of the strains to be expected. Accuracy has been achieved (Markowitz 1970) by the introduction of the photographic zenith tube to observe rotation time (U.T.) and the caesium-beam clock representing atomic time (A.T.) with which to compare observations. The error in U.T.–A.T., based on observations at a global network collated at the Bureau International de L'Heure, is estimated to be 1.2 ms.

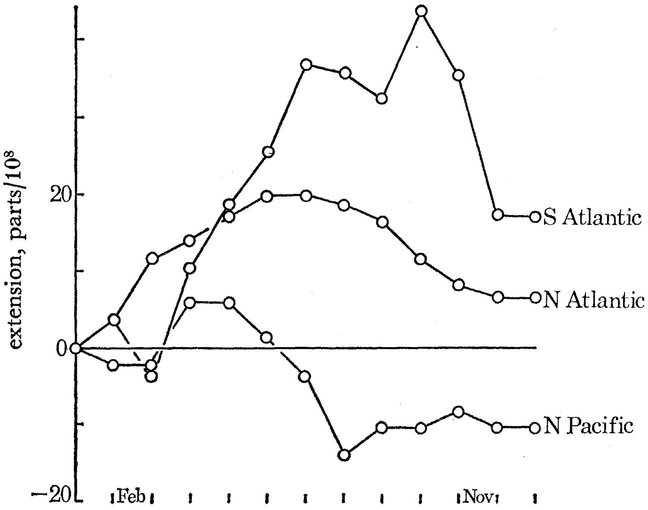

FIGURE 5. The east–west component of strain in the Atlantic and Pacific regions in the year 1960, derived from Pavlov's (1971) analysis of variations in local time. The Atlantic is believed on geophysical grounds to be affected by extension. The part of the Pacific here described embraces a sector of sea-floor extension, the east Pacific rise, and the sector of convergence east of Japan.

The data values represent the difference between local time in observatory groups for the months shown. Within any group time changes are simultaneous. The groups used were: for Europe, Greenwich, Hamburg, Neuchatel, Paris; for North America, Washington and Ottawa; for South America, Rio de Janeiro and Buenos Aires; in Japan, Tokyo and Misuzawa.

The decrease in Earth rotation due to tidal friction is modulated by the imposition of an annual fluctuation many times greater. The annual term (Munk & MacDonald 1960; Markowitz 1970) is explicable as transference of momentum and mass, represented by winds and by the winter air mass over Siberia.

Changes in local time are not globally simultaneous (Pavlov 1971), as they would be if the Earth were rigid. Differences representing strains between station groups embracing primary tectonic features are shown in figure 5. If observations covering a single year are significant, adjustment in atmospheric mass distribution is accompanied by elastic strain and by a residual greater than the expected error.

The unrecovered strain represents displacement larger than expected if extension is confined to the crest of the Mid-Atlantic Ridge. Unless an unidentified error is affecting stations by groups, it would appear that local time observations permit the measurement of displacement without establishing a surface connexion.

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8. Summary and conclusions

The imposition of strain is found to have a dependence on latitude.

To investigate this the action has been examined of the retarding torques. It appears that horizontal extension is induced in an asthenosphere in which melting is limited by pressure. This results in liquefaction and upwelling.

It is then to be expected that the planet's internally generated heat is dissipated by convection in a system arranged by the tidal couple. Upwelling takes place in high latitudes and in the ocean basins. Return to depth is effected in low latitudes, at sites marked by geoidal highs and deep-seated seismicity.

The effect at surface is that the lithosphere is displaced west, at a velocity greatest near the Equator and varying regionally. In consequence this shell segments and the segments interact.

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