GEOLOGIE EN MIJNBOUW VOLUME 51(6), p. 619–626 1972

POST-ARCHEOZOIC LARGE-SCALE CONVECTION IN THE EARTH'S MANTLE

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ABSTRACT

Static models of the lower mantle do not easily accommodate a cooling of the core on a terrestrial time scale. Moreover, merely shallow flows do not readily explain the present distribution of sial. Therefore, a still active, overall and occasionally reversing mantle convection is proposed that is consistent with the spasmodic character of orogenesis. This convection is compatible with modern estimates of pertinent parameters in a hydrodynamic theory of convection within spherical shells. It bears on the geomagnetic dynamo and helps to explain a correlation that has been suggested between changes in earthquake activity and in the earth's rotation. Apart from tidal dissipation within the mantle, a cooling of a radio-inactive core, on the order of 600°C during the last two and a half to three billion years, seems to be required to complete about a dozen successive mantle overturns.

INTRODUCTION

Present temperatures in the earth's core are probably not much higher than 3000°C (Verhoogen, 1961). On the other hand, the core appears to have formed catastrophically (Birch, 1965). Even while allowing for the geochemically imposed restraint that the mantle, as such, was never wholly melted, one must wonder how relatively static models of the lower mantle can account for a significant cooling of the core within a few aeons.

Vening Meinesz (1952) associated the present distribution of sial with a former continental drifting owing to a convection in the entire mantle. His conclusion was reiterated by Chandrasekhar (1961, Chapter VI) and Takeuchi (1966, fol. p. 101). Newly acquired data have led geoscientists to assume a modern continental drift which is the result of merely shallow mantle convection (Wilson, 1966). I will argue that such a system of superficial mantle currents is less plausible than a modern convection occupying the entire mantle.

Continuous mantle currents are difficult to reconcile with the spasmodic character of orogenesis and the occasional, small alterations of its world-wide pattern. Typifying overall convection, they may pose a problem with regard to a suspected lack of the mantle's chemical homogeneity, particularly, near the lower boundary (Press, 1968). I am led, then, to reconsider Griggs' (1939) proposal of a mantle exhibiting overall and intermittent flow. Clearly, such a mantle would still have to possess bulk densities that, in all regions, are sufficiently identical at comparable pressures and temperatures.

Convective mantle models may not readily explain the present near equality of continental and oceanic heat flows (MacDonald, 1964). But Zwart (1967) has emphasized that the thermal flux in continental mobile belts has experienced significant fluctuations during the Phanerozoic. It is, therefore, debatable whether the recent thermal equality is accidental or not. A diminished heat flow from the mantle, above descending currents which have been cooled during a long passage near the surface, need not be completely compensated by an increased flux owing to a concentration of sialic radioactivity. On

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the other hand, one has to assume a peculiar distribution of the main heat producing isotopes to account for the thermal equality in terms of a static model of the mantle.

PROBABLE DEPTH AND CHARACTER OF MANTLE CONVECTION

In geodesy, opposing views on the ultimate depths of the mantle currents have remained unresolved (cf. Runcorn 1966-a, Discussion). All the same, if merely shallow flows are to be presumed – together with the revived proposition to derive practically all diastrophic energy from continually respread radioactivity – then the present distribution of the continents becomes incomprehensible. Moreover, one would not be able to accept the orthodox geological statement that major orogenies are quasi world-wide and, more or less, cyclic (De Sitter 1956, p. 504). Specifically, one would fail to agree that Caledonian and Variscian diastrophisms can be distinguished from Mesozoic and Cenozoic ones. Naturally, the smaller the time and space scales, the more important the effects of lithospheric inhomogeneities become.

At this point, I want to mention a difficulty which is generally experienced in describing causal connections between the various phases of a diastrophic cycle (Shimer 1968, p. 213). The root of this problem may spring from the assumption that mantle convections are nonreversing. However, a habitually rejected geotectonic viewpoint seems lately to be accorded a more general approval as the result of geological field work under exceptionally favorable circumstances (Aubouin, 1965). This relates the geosynclinal and "post-tectonic" stages of an orogenic cycle to lithospheric tension, as opposed to the compression in the intermediate folding phase (cf. Holmes, 1965, p. 1176). Thus, in a mobile zone, fundamental changes of successive igneous phenomena ("granitic" batholiths versus "basaltic" lavas), in addition to small realignments of its tectonic features (including sedimentary basins as well as thrust sheets), become understandable from petrological and rockmechanical points of view. As a consequence of the alternating lateral stresses, there are reversing crustal movements like those that have been detailed in the Swiss Alps (Trümpy, 1960).

It seems to me that the main reversals are not accounted for by a mantle convection that is merely intermittent. Mysterious expansions and contractions on a global scale have been proposed to explain, for instance, the near congruity of the Mesozoic and Cenozoic belts of folding (cf. Bucher, 1933). However, a mathematical particularization of Griggs' geodynamic model could prove that, besides an intermittency of the mantle convection, reversing phases are possible within as well as between convection cycles. Here, one has to allow for the effects of a spherical geometry, and of an uneven surface distribution of the important heat producing isotopes (cf. Schuiling, 1969). I am inclined to assume that the Mesozoic and Cenozoic diastrophisms belong to, and are separated by a reversal in, the latest cycle of overall mantle convection. One might ascribe the current distribution of sial to a revolution of the mantle cells that lasted from the Jurassic until the latter part of the Tertiary. From the viewpoint of "plate" tectonics (Le Pichon, 1968), based on new observations and interpretations of seismic groupings (Isacks et al., 1968) and of magnetic anomalies over oceanic ridges (Vine, 1966), it appears (for reasons given below) that this latest mantle revolution could continue for a period on the order of five million years. The preceding convection cycle may be responsible for the less decipherable but, apparently, also nearly congruent global patterns of the Caledonian and Variscian deformations.

The palimpsest record of older orogenies is too obscure to be interpreted meaningfully. Even so, a tentative but repeatedly quoted histogram of Rb/Sr ages (Aldrich et al., 1960) indicates a diastrophic periodicity. Although the latter is irregular, I assume – as a first approximation – that the periods on the histogram last about half a billion years. Postulating in addition alternate surface expressions of the mantle upsets (cf. Zwart, 1967), I obtain major orogenic cycles of some 250 million years and, excluding the fundamentally different Archeozoic orogenies (Cumming et al., 1955), a conventional number of almost a dozen complete (180°) mantle revolutions in the last two and a half to three billion years. The geological data suggest that the revolutions themselves last, very roughly, 150 m.y. and that a period on the order of 100 m.y. is required to recharge the thermal convection motor after a complete turnover of the mantle cells.

PERTINENT ASPECTS OF HYDRODYNAMIC THEORY

The theory of cellular convection, in a liquid stratum heated from below (Rayleigh, 1916), has exposed the paramount importance of the layer's thickness. The superadiabatic temperature gradient can surpass, at any vertical interval, the minimum value for overall convection to an appreciable extent without causing a separate convecting in a sub-layer. Furthermore, local differences in, say, heat conduction, viscosity and content of thermal sources may still allow an overturning of the whole stratum.

Another theoretical finding, which can be applied to intermittent or reversing convection, relates horizontal (as well as vertical) cell dimensions to wave lengths of initiative perturbations. The latter, under idealized conditions, are determined by the thickness of the convecting layer. Thus, the fairly congruent global designs of, for instance, Mesozoic and Variscian folding (cf. Bucher 1933, Law 39) can be explained. These congruities show that local, incidental lateral temperature differences, at the surface or at the mantle's lower boundary (cf. Pekeris, 1936), are not very significant in the context of a general mantle convection. And, other considerations aside, they make it difficult to accept a change of the dominant harmonic – associated in the mathematical analysis with the mantle's main velocity field through which instability occurs – by a supposedly slow growth of the earth's core (cf. Runcorn, 1966-b). The spherical harmonic in question should not be derived from an analysis of tectonic features, such as mountain belts and oceanic rifts, since these are not first order effects of the implied convection.

Following Vening Meinesz (1952), I take the dominant harmonic term to be of the third order. (The predominant spherical harmonic pertaining to the present distribution of sial is, actually, of the first order. However, this first order term will not be discussed here as it is obviously related to a global convection which resulted in the catastrophic formation of the earth's core.) The dominance of the third order harmonic implies, on Chandrasekhar's (1961) theory of marginal convection in spherical shells, that both the mantle's lower and upper boundaries are free rather than rigid. Such a conclusion is hardly surprising when one considers how inviscid the fluid core is, and how thin the lithosphere, in relation to the entire mantle.

THE RAYLEIGH NUMBER CONCERNING THE ENTIRE MANTLE

In the presence of free boundaries, Chandrasekhar's (1961, Fig. 59) critical Rayleigh number – which must be exceeded to allow convection – has in a fluid mantle the value of 2×10^4, approximately. In order to simplify its use, this dimensionless quantity can be represented with some lack of rigor by $C_{f=3} = \alpha\beta \underline{g} r^4 (\kappa\nu)^{-1}$ (Chandrasekhar, 1970), where α is the coefficient of thermal expansion, β is an average superadiabatic temperature gradient, $\underline{g}$ is the centripetal acceleration, r is the earth's radius, κ is the thermal diffusivity, and ν is the kinematic viscosity. The physical quantities, denoted by Greek letters, vary to an imperfectly known extent through the mantle. As suggested above, this need not invalidate the proposed model. Turcotte and Oxburgh (1969) chose for the upper mantle $\alpha = 2 \times 10^{-5}$ °C^{-1}, $\beta = 5 \times 10^{-6}$ °C cm^{-1} and $\underline{g} = 980$ cm sec^{-2}, while κ may amount to about 0.03 cm^2 sec^{-1}. Provisionally employing these values, one learns that the absolute viscosity must exceed 10^{26} poises to prevent overall convection in a fluid mantle.

Without specifying the rheological situation, a critical Raleigh number for the actual mantle might be inferred from the convection structure. Late orogenic belts and oceanic ridges indicate a flow system – here interpreted as an overall convection – containing cells in the form of elongated rolls (rather than, say, cells with hexagonal outlines) (cf. Oxburgh and Turcotte, 1968). Under circumstances which apply to some extent to the mantle, rolls should be expected when the actual Rayleigh number is slightly larger than, but not exceeding three times, the critical value (Roberts, 1967). A numerical estimate of $C_{f=3}$, then, would be on the order of 3×10^4. Runcorn (1964) has stated that, here, Coriolis forces can be neglected. In this respect, magnetic forces can be disregarded as well. Besides, effects of the earth's rotation and of the geomagnetic field on the convection pattern at marginal stability are infinitesimal.

Nevertheless, cylindrical cell forms do not exclude ultimately large Rayleigh numbers. Therefore, one is free to adopt Anderson's (1966) estimate of the viscosity for the whole mantle. This value of 2.4×10^{22} poises results in a Rayleigh number which is rougly 3×10^3 times he supposedly critical value of the actual mantle. Turcotte and Oxburgh have developed a thermal boundary-layer model of convection which is adapted to similarly great Rayleigh numbers. Correspondingly, averaged velocities along the cell margins are, approximately, $0.2\ R^{2/3}\ \kappa d^{-1}$. Here, d is the layer's thickness. R is again the actual Rayleigh number. Only, now it is related to Rayleigh's (1916) critical value, R_c, which is 658. Consequently, the steady state velocities amount to about 10 cm per year. This results in a duration of some 100 m.y. for a 180° turnover of the mantle cell boundaries. The ensuing time scale is reasonably close to the one suggested above on tectonic evidence if one considers the inadequacy of a continued flow model, and the uncertainties concerning the involved parameters.

Aforementioned boundary layers, associated with high velocities, are not to be confused with their conventional counterparts which delimit flows of less than average speed. The latter develop only, in the presence of rigid walls, when the Reynolds number surpasses a value of about 130 according to Brodkey (1967, Chapter 14). With reference to any plausible mantle convection, the Reynolds number should be much too small to bring about the customary boundary situation. For the same reason, large-scale turbulence is even more out of the question.

IMPROBABILITY OF UBIQUITOUS SHALLOW CONVECTION

Superficial mantle convection cells are indicated on a map derived from satellite sensed gravity anomalies (Schwidersky, 1968). An average cellular diameter of close to 2000 km is portrayed. Boundaries show steep gradients implying a marginal state of convection; that is to say, R is not much larger than R_c. Applying Robert's theory of convection with internal heat generation after assuming a horizontal layer with two rigid boundaries, besides a plausible Rayleigh number of 1.1 times its critical value, one obtains a minimal thickness of 700 km for the convecting mantle stratum. The latter fits a zone of comparatively low viscosity that may be distinguished between depths of 40 and 700 km (cf. Turcotte and Oxburgh, 1969), thus reaching down to levels of the deepest earth quakes.

Provisional calculations show that a separate convection in a sub-layer of the deep mantle is improbable. In this respect, the theoretical situation concerning the upper mantle is less clear. With Anderson's relatively low value for a pertinent viscosity – while retaining above estimates for the other physical quantities that make up the Rayleigh number – the shallow convection would not be marginal. On the other hand, adopting the viscosities given by Turcotte and Oxburgh, one could confirm the steep gradients on the map in question. A maximal averaged velocity near the cell boundaries would be on the order of 1 cm per year. Its determination entails a formulated connection between the amplitudes of disturbances and all supracritical Rayleigh numbers (Chandrasekhar 1961, Appendix I).

The supposed marginal flow may still possess a thermal boundary layer (Roberts, 1967). The vertical extent of the latter at the upper border, expressed in units of d, is on the order of $(Rb^2 \log Rb^2)^{-1/6}$, where the number b has a value between 2 and 3. Thus, the base of the upper boundary stratum should be near the bottom of the seismic low-velocity zone. This accords with a suggestion proffered by Turcotte and Oxburgh. However, the upper boundary layer, associated with the envisaged convection in the entire mantle, would reach down to the same level, more or less.

In the complete absence of overall mantle flow, the shallow marginal currents could be quite credible, evolutionally. But, even if convections of various dimensions can coexist during a fraction of the longest relevant cycle, in the presence of mantle currents extending to the earth's core the small cells would have insufficient time to develop. In 100 m.y., a superadiabatic gradient would merely occur above a depth of some 150 km; too small a depth to permit a ubiquitous cellular flow, given the present bulk viscosities. Moreover, Runcorn (1966-a, Discussion) has warned that the calculation of eighth degree harmonics, needed to outline surface features with a minimum wave length of 3000 km, may be rather inaccurate. A more recently published map of geodetic datum shifts (Rapp, 1968) is not nearly as detailed.

ENERGY SOURCES FOR THE DEEP CONVECTION

A survey of plausible sources and sinks of energy discloses that radioactivity, homogeneously distributed, could not by itself have resulted in an overturning of the whole mantle. Within five billion years, a superadiabatic gradient would have developed only in the upper mantle. On the other hand, the required total temperature difference may be quite small. Taking Anderson's (1966) estimate for the overall mantle viscosity, and using the same values for α, g, r, κ and $C_{f=3}$ as heretofore, β amounts to 0.14°C per 1000 km. Subsequent to an overturning, previously superadiabatic temperatures become subadiabatic. On the proposed model, therefore, the differential heating should provide a gradient on the order of $2 \times \beta$, or 0.3°C for every 1000 km, over 100 m.y. As has been evaluated by Kaula (1966), lunar tide dissipation within the mantle produces at the present rate an appropriate gradient (except for the bottom 350 km) on the order of 1°C per 1000 km in 100 m.y.

To a depth of about 150 km, the superadiabatic temperature gradient, immediately prior to an overturning of the entire mantle, should be quite steep. After the upset, considerably more heating of this cooled layer would be necessary than tidal dissipation or reasonable amounts of radioactivity in the mantle itself could supply. Obviously, the rest of the required thermal energy should proceed from the earth's core. At least the order of its magnitude is obtained by assuming that the superadiabatic temperature increase of the stratum is approximately 700°C, on the average. This assumption is based on Gutenberg's (1951) adiabatic gradient – which happens to be reconcilable with the $\beta = 5 \times 10^{-6}$°C cm^{-1}, provisionally employed above. The volume of the layer would be almost 2.5×10^{25} cm^3, its density about 5.3 g cm^{-3} and its specific heat close to 10^7 ergs g^{-1} °C^{-1}. The required thermal energy, then, should be on the order of 10^{36} ergs. It follows that a considerable transport of energy from the core is called for. It amounts to, perhaps, 1.5×10^{36} ergs per 250 m.y. Precessional dissipation solely accounts for 3×10^{34} ergs every 1000 m.y. (Malkus, 1968). Verhoogen's (1961) gently cooling and radio-inactive core model exports not more than 1.5×10^{35} ergs each 250 m.y. An improbable core with Clayton's (1963) primordial abundances of the main heat producing isotopes could have generated the needed 1.5×10^{36} ergs, even in the last 250 m.y. However, a core possessing a negligible amount of U, Th and K should, according to Verhoogen's calculations, have experienced a rather credible decrease in temperature on the order of 600°C during the last two and a half to three billion years.

Around 350 km above the lower boundary of the mantle, the tidal dissipation is supposed to exhibit a maximum. Nevertheless, a slightly inverse gradient, if not negligible in the context of overall mantle convection, could be nullified in the more than usually conductive bottom layer because of higher temperatures in the earth's core.

IMPLICATIONS OF THE OVERALL MANTLE CONVECTION FOR THE EARTH'S ROTATION AND MAGNETISM

At present, the outer core should be cooling considerably and differentially. To clarify this point, let us assume a mantle convection and a sialic distribution which are completely characterized by a third order harmonic term. There could then be a circular "Afrasian" continent surrounded by a zone of "Atlantic", "Indian" and "Arctic" oceans. The latter would border an equally continuous zone that would include the "Americas", "Antarctica" and "Australia". And this continental zone would surround a (reduced) "Pacific" ocean.

With the mantle growing inwardly by accretions of solidified core material, the largest growth rates should occur below the centre of "Afrasia". They would, also, be above average underneath the ringed continental zone surrounding the "Pacific". The thicknesses of these ferreous accretions are necessarily limited by locally prevailing tensile strengths. Even without any mantle movements, therefore, the bottom of the mantle should disintegrate repeatedly at present; especially below the centre of "Afrasia". I associate such local disintegrations (and renewed accretions) with the excitations (and dampings) of Chandler wobbles. A rapidly intermittent flow of the entire mantle, on the other hand, may well be connected with a disintegration of the mantle bottom in a more general and axially symmetric manner. These general disintegrations I would relate to the, so called, decade fluctuations of the earth's rotation that are accompanied by variations of the magnetic drift (cf. Dicke, 1966). Schatzman (in: Marsden and Cameron, 1966) has correlated the changes in the length of day with an index of earthquake activity. It would appear that this correlation can not be explained satisfactorily without assuming the here envisaged movements of the whole mantle.

Presently, the core as a whole may be contracting at a rate which is significant in terms of the secular variation of the earth's rotation. The latter, in turn, bears on the problem concerning secular changes of the sea level.

Magnectic phenoma complicate the dynamic picture outlined above. Here, I will only mention that Hall currents in the mantle, and the lectro-magnetic coupling between core and mantle, should strongly depend on the thicknesses and areal extents of the ferreous accretions. Indeed, the juxtaposition of, say, a third order convection in the mantle and a second order convection in the fluid core leads to situations that are mostly axially asymmetric and, consequently, conducive to a proper functioning of the geomagnetic dynamo (Cf. Malkus, 1968).

CONCLUSIONS

A system of shallow mantle currents, as envisaged by many proponents of "plate" tectonics, would possess horizontal cell dimensions which are too small in relation to major tectonic features (cf. Roberts, 1967). Assertions to the contrary are based on a dubious interpretation of experimental models which are unrealistic (cf. VanderZee, 1951).

Because of tidal dissipation, the mantle as a whole may acquire a marginal state of convection within a period on the order of 100 m.y. Geologically plausible velocities and oscillations of the mantle flow can be accounted for by the superimposed effects of a cooled surface layer (and, perhaps, a heated bottom layer) that could be about 150 km thick. Forgoing the imitation of a spherical geometry, scale model investigations of, at least, the initial stages of the here envisioned convection cycle should be practicable (cf. VanderZee, 1949).

The geological and orogenic time scales, adopted here, are tentative ones. All the same, their order of magnitude appears to be correct and it should be feasible to narrow the periods in question by more elaborate calculations. The many boundary conditions that can be imposed on a geodynamic model, illustrating overall mantle convection, seem to offer satisfactory restraints on conjecture.

A geotectonically realistic convection in the entire mantle implies that bulk densities of mantle material are everywhere fairly identical at comparable pressures and temperatures. It argues, therefore, against the assumption that important seismic discontinuities often represent significant chemical changes. It favors Anderson's (1966) estimate of the mantle's overall viscosity, and it suggests that Kaula's (1966) model of tidal dissipation in the mantle is more realistic than others in which the dissipation is concentrated near the surface.

On a geological time scale, the mantle convection seems to be compatable with hydrodynamic theory. That is to say, the mantle as a whole is then seen to behave like a Newtonian liquid. On such a large time scale, an intermittency of the strong mantle currents should, therefore, result from interactions between various sinks and sources of energy rather than from a pseudoviscosity.

On a much smaller time scale, materials at the mantle bottom may possess tensile strengths which are of the same order of magnitude as the strengths manifested by the same kind of materials under laboratory conditions. Accordingly, and given a considerable cooling of the outer core at present, more or less axially symmetric accretions and disintegrations of the mantle bottom should occur which help to explain, for instance, decade fluctuations of the mantle's rotation, and Chandler wobbles. A convection occupying the entire mantle should, also, be taken into account when one considers geomagnetic dynamo models or an earthquake activity index.

A study of modern mantle convection must clarify its absence during the Archeozoic. This involves a reappraisal of the moon's origin. I intend to discuss these matters in a future paper.

ACKNOWLEDGMENTS

I am gratuful for the encouragement accorded to me by my colleagues; in particular, I.S. Parrish of Brunswick Tin Mines Ltd. And I am indebted to the staffs of the public library and secondary school in Elliot Lake, and to that of the locally situated, federal Mining Research Centre, for access to indispensable literature.

(Submitted July, 1971.
Revised November 27, 1971)

REFERENCES

Aldrich, L.T., Wetherill, G.W., Bass, M.N., Tilton, G.R. and Davis, G.L. (1960) – Mineral age measurements and earth history. Carnegie Inst. Washington Year Book 59, p. 208.

Anderson, D.L. (1966) – Earth viscosity. Science 151, p. 321.

Aubouin, J. (1965) – Geosynclines, Elsevier Publishing Co., Amsterdam.

Birch, F. (1965) – Speculations on the earth's thermal history. Geol. Soc. America Bull. 76, p. 133.

Brodkey, R.S. (1967) – The phenomena of fluid motions, Addison-Wesley Publishing Co. Reading, Mass.

Bucher, W.H. (1933) – The deformation of the earth's crust, Princeton University Press, Princeton, N.J.

Chandrasekhar, S. (1961) – Hydrodynamic and hydromagnetic stability, Oxford University Press, London.

____ (1970) – Private communication.

Clayton, D.D. (1963) – A calculation of the abundances of uranium and thorium from the primordial Pb^{206}/Pb^{207} ratio. J. Geophys. Res. 68, p. 3715.

Cumming, G.L., Wilson, J.T., Farquhar, R.M. and Russel, R.D. (1955) – Some dates and subdivisions of the Canadian Shield. Geol. Assn. Canada Proc. 7, Pt. 2, p. 27.

De Sitter, L.U. (1956) – Structural geology, McGraw-Hill Book Co., Inc., New York.

Dicke, R.H. (1966) – The secular acceleration of the earth's rotation and cosmology. In: The earth-moon system. Marsden, B.G. and Cameron, A.G.W., editors, Plenum Press, New York.

Griggs, D. (1939) – A theory of mountain-building. Am. J. Sci. 237, p. 611.

Gutenberg, B. (1951) – The cooling of the earth and the temperature. In: Internal constitution of the earth. Gutenberg, B., editor, Dover Publications, New York.

Holmes, A. (1965) – Principles of physical geology, Ronald Press Co., New York.

Isacks, B., Oliver, J. and Sykes, L.R. (1968) – Seismology and the new global tectonics. J. Geophys. Res. 73, p. 5855.

Kaula, W.A. (1966) – Thermal effects of tidal friction. In: The earth-moon system. Marsden, B.G. and Cameron, A.G.W., editors, Plenum Press, New York.

Le Pichon, X. (1968) – Sea-floor spreading and continental drift. J. Geophys. Res. 73, p. 3661.

MacDonald, G.J.F. (1964) – Dependence of the surface heat flow on the radioactivity of the earth. J. Geophys. Res. 69, p. 2933.

Malkus, W.V.R. (1968) – Precession of the earth as the cause of geomagnetism. Science 160, p. 259.

Marsden, B.G. and Cameron, A.G.W., (editors) (1966) – The earth-moon system, Plenum Press, New York.

Oxburgh, E.R. and Turcotte, D.L. (1968) – Mid-ocean ridges and geotherm distribution during mantle convection. J. Geophys. Res. 73, p. 2643.

Pekeris, C.L. (1936) – Thermal convection in the interior of the earth. Mon. Not. Roy. Ast. Soc., Geophys. Sup. 3, p. 343.

Press, F. (1968) – Density distribution in earth. Science 160, p. 1218.

Rapp, R.H. (1968) – Gravitational potential of the earth determined from a combination of satellite, observed and model anomalies. J. Geophys. Res. 73, p. 6555.

Rayleigh, Lord. (1916) – On convection currents in a horizontal layer of fluid, when the higher temperature is on the under side. Phil Mag. 32, p. 529.

Roberts, P.H. (1967) – Convection in horizontal layers with internal heat generation. J. Fluid Mech. 30, p. 33.

Runcorn, S.K. (1964) – Satellite gravity measurements and a laminar viscous flow model of the earth's mantle. J. Geophys. Res. 69, p. 4389.

____ (1966-a) – Satellite gravity observations and convection in the mantle. Geol. Surv. Can. Paper 66-14, p. 364.

____ (1966-b) – Change in the moment of inertia of the earth as a result of a growing core. In: The earth-moon system. Marsden, B.G. and Cameron, A.G.W., editors, Plenum Press, New York.

Schuiling, R.D. (1969) – A geothermal model of oceanization. Verh. Kon. Ned. Geol. Mijnb. Gen., Geol. Serie 26, p. 143.

Schwiderski, E.W. (1968) – Mantle convection and crustal tectonics inferred from a satellite's orbit. J. Geophys. Res. 73, p. 2828.

Shimer, J.A. (1968) – This changing earth, Harper and Row, New York.

Takeuchi, H. (1966) – Theory of the earth's interior, Blaisdell Publishing Co., Waltham, Mass.

Trümpy, R. (1960) – Paleotectonic evolution of the central and western Alps. Geol. Soc. America Bull. 71, p. 843.

Turcotte, D.L. and Oxburgh, E.R. (1969) – Convection in a mantle with variable physical properties. J. Geophys. Res. 74, p. 1458.

Van der Zee, T.J. (1949) – Het belang van de experimentele tektoniek voor de tektonische geologie. M. Sc. Thesis, Leyden University, Leiden, The Netherlands.

——— (1951) – Importance of the "tectonic" model theory. Geol. Mag. 88, p. 192.

Vening Meinesz, F.A. (1952) – The origin of continents and oceans. Geol. en Mijnb. 14, p. 373.

Verhoogen, J. (1961) – Heat balance of the earth's core. Geophys. J. 4, p. 276.

Vine, F.J. (1966) – Spreading of the ocean floor: New evidence. Science 154, p. 1405.

Wilson, J.T. (1966) – Did the Atlantic ocean close and then reopen? Nature 211, p. 676.

Zwart, H.J. (1967) – The duality of orogenic belts. Geol. en Mijnb. 46, p. 283.