Tectonophysics - Elsevier Publishing Company, Amsterdam
Printed in The Netherlands

Discussion

ON THE INTERPRETATION OF THE APPARENT FORM OF THE GEOID AND OF THE TERRESTRIAL HEAT FLOW

R.W. VAN BEMMELEN

Geological Institute, State University, Utrecht (The Netherlands)

(Received September 22, 1966)

SUMMARY

A comparison is made between the approach of the data on gravity and heat flow by the concepts of Wunderlich (1966) and the present author (Van Bemmelen, 1966).

Wunderlich's model of physical interpretation is based on an erroneous idea of the meaning of the form of the geoid, as determined by artificial satellites. The new model of the earth's evolution, presented by the author, offers a promising way of interpretation, which is based on physico-chemical principles.

WUNDERLICH'S INTERPRETATION OF GEOID ANOMALIES

The course of artificial satellites is largely determined by their energy of motion and the gravity field of the earth. Anomalies of the earth's gravity field cause anomalies in the form of the satellitic orbits. Geophysicists have developed a mathematical method to express the terrestrial gravity anomalies thus determined, as deviations of the geoid from the theoretical form of the spheroid. Stokes' formula:

$$N = \frac{a}{2\pi g} \int \Delta g f(\psi)\, \mathrm{d}\sigma$$

gives the value of the height of the geoid at a point on the geoid in terms of Δg over the entire earth (Garland, 1965, pp.38–42). Thus Kaula (1963) and Guier (1965) published maps of the anomalies of the height of the geoid, expressed in meters. These maps show extensive anomaly fields, with diameters of about 10,000 km and with maximum and minimum values up to some tens of meters only. The gradients of these bulges and depressions of the geoid are very low.

Bulges occur in the areas of the South Atlantic (+20 m), the North Atlantic and western Europe (+40 m) and the central Pacific Ocean (+ 40 m).

One of the two major geoid depressions has its centre (–60 m) in the northern part of the Indian Ocean and southern Asia (Tibet), and the centre of the other one (–40 m) coincides with the west coast area of the United States and the adjoining part of the Pacific Ocean.

These bulges and depressions of the geoid show no direct relations with the relief of the earth's surface, because they are virtually deviations from the rheological equilibrium inside the earth (Guier and Newton, 1965). However, in a recent paper in this journal, Wunderlich (1966) develops a hypothesis of thermal convection currents, which is based on the erroneous supposition that the deformations of the geoid are really superficial topographic phenomena. By circular reasoning the author then comes to the conclusion, that the culminations of the geoid coincide with positive gravity anomalies and the depressions with negative gravity anomalies: ". . . so wird man doch generell feststellen dürfen, dass sich Beulen der Geoidgestalt durch vergleichsweise hohe schwere, Dellen hingegen mehr durch Schweredefizit auszeichnen" (Wunderlich, 1966, p.191).

The map of the geoid anomalies in meters is then compared by Wunderlich with the map of the heat-flow contour lines published by Lee and Uyeda (1965). This map of the terrestrial heat flow shows fields of maxima and minima, which have about the same extent as the fields of the geoid deformations, but neither type of field coincides. If there is a genetic relation between both, this relation cannot be a direct one.

The author then proceeds rather arbitrarily, without any firm geophysical grounds, by supposing that the *contour lines* of the terrestrial heat flow are *flow lines* of systems of subcrustal convection currents, which rotate clockwise and anticlockwise (Wunderlich, 1966, p.194, fig.4). This procedure leads him to the remark, that the culminations of the geoid coincide with converging flow lines and that the depressions are to be found in those areas, where the flow lines diverge: ". . . so fallen die positiven Anomalien (Beulen) mit Bereichen der *Konvergenz* des Strömungsbildes zusammen, während die negativen Anomalien (Dellen des Geoids) dort auftreten, wo die Stromfäden *divergieren*" (Wunderlich, 1966, p.195).

First of all a closer inspection of fig.4 leads to the conclusion that in many places this statement is not confirmed by the facts. For instance, in the northeastern part of the Pacific Ocean, the converging "flow lines" coincide with a field of negative anomalies of the geoid; and in the central part of this ocean, diverging "flow lines" cover the area of a positive anomaly field of the geoid. Both situations are exactly in contrast to Wunderlich's statement, cited above.

But still more serious is the next sentence, in which the author remarks that the geoid deformations are *thus* caused by subcrustal flow processes: the damming up owing to converging flow lines results in an uplift, whereas the divergence of the flow lines pulls the geoid surface somewhat downwards: "In diesem Bilde werden die Anomalien des Geoids also verursacht durch subkrustale Strömungsvorgänge: *Staudruck in den Zonen der Gegeneinanderbewegung der Stromfäden bedingt Aufwölbung. Divergenz der Stromfäden hingegen ein leichtes Einziehen der Geoidfläche*" (Wunderlich, 1966, p.195).

This conclusion is evidently based on the erroneous notion, that the geoid anomalies, expressed in meters, are really deformations of the earth's *outer* form, whereas they are virtually the result of deviations from rheological equilibrium (gravitational anomalies) *inside* the earth.

Evidently the geophysical method of expressing the geodynamic instabilities, which exist inside the earth, as deformations of the *outer form* of the geoid is a cause of confusion among geologists who are not familiar with the mathematical and physical foundations of this method. They tend to accept the geoidal bulges and depressions as topographic features of the earth's form.

Therefore, the present author wants to indicate an alternative solution for the interpretation of the geoidal form of the earth. The important new geophysical data on the geoid anomalies and the terrestrial heat flow can be interpreted as the effect of deep-seated geodynamic and physico-chemical processes. In three previous papers, published in this journal, the concept of *mega-undations* has been developed (Van Bemmelen, 1964, 1965, 1966). According to this concept the extensive deformations of the geoid, as determined by the course of artificial satellites, are caused by active disturbances of the rheological equilibrium in the lower mantle.

Of course deviations from the rheological equilibrium may occur in all structural levels of the earth (called "Stockwerke" by Van Bemmelen, 1966). The gravitational anomalies occurring in the various levels have a combined effect on the orbits of the artificial satellites. But the more restricted and shallower fields of gravity anomalies, which cause undations of lesser categories of magnitude, have influences which are not (yet) discernable in the form of the satellitic orbits. The deep-seated gravity anomalies, situated in the lower mantle and causing mega-undations at the earth's surface, are chiefly responsible for the extensive fields of geoid deformations on Kaula's (1963) and Guier's (1965) maps. The low gradients of these anomaly fields indicate that they are caused by gravitational anomalies at great depth, probably in the lower mantle.

The active gravitational disturbances of the present time are situated underneath the youngest phase of the Indian Ocean Mega-Undation (*iIII* on fig.6 in Van Bemmelen, 1966, pp.111–112), and of the East Pacific Mega-Undation (*pIV* on fig.6). Buoyant masses in the lower mantle cause uplifts of the outer spheres (upper mantle and crust). They might explain the young-Cenozoic uplifts of the Himalayas and Tibet, and that of the Great Basin area of the west coast of the United States (respectively *iIII* and *pIV* on fig.6 in Van Bemmelen, 1966, pp.111–112).

These crests of active mega-undations coincide with the "depressions" of the geoid, but in reality they are areas of active uplift and gravitational spreading at and near to the earth's surface.

On the other hand, the older sections of mega-undations, such as the Darwin Rise in the central Pacific and the a0-aIII sections of the Atlantic Mega-Undations s.l., have already passed through the process of gravitational spreading. Moreover, the hotter and deeper spheres ("Stockwerke") which were exposed at the top of these mega-undations, as well as the juvenile suites of basalt magma which were segregated from their top, have had about 100–200 million years time for cooling. This cooling increases the mean density of the matter concerned, which results in a general tendency to sink down again. Consequently, the Darwin Rise and the Atlantic Mega-Undation (except its youngest phase, aIV, in the Arctic area) coincide with positive gravity anomalies; in other words, they cause the positive "bulges" of the geoid.

Thus the concept of mega-undations seems to provide a satisfactory model for the explanation of the geoid deformations.

HEAT-FLOW DATA

The available heat-flow data give, as yet, a very incomplete picture of their areal distribution on the world map. But the contour lines, drawn by Lee and Uyeda (1965) also appear to fit fairly well into this concept of mega-undations.

The terrestrial heat flow is the combined effect of many geodynamic and physico-chemical processes, such as:

(1) The reduction of depth and the actual exposure of deep-seated spheres ("Stockwerke") at the top of mega-undations. This "Atlantic type of oceanization" (see Van Bemmelen, 1966, p.114) causes steeper geothermal gradients and a higher heat flow.

(2) The increase of depth of the "Stockwerke" on the flanks of mega-undations, owing to their sideward spreading and the covering of the adjoining ocean by drifting crustal shields, causes a decrease of the geothermal gradient and a reduction of the heat flow.

(3) Endothermal and exothermal phase transitions of minerals in the outer mantle and at the base of the crust, caused by the geodynamic processes during the evolution of mega-undation, will influence the terrestrial heat flow.

(4) The segregation of juvenile basic magmas from upper mantle matter in the top part of mega-undations, as well as underneath the marginal geosynclinal belts in a later stage of evolution, their ascent as superheated basalts, causing the migmatization of the base of the overlying sialic crust resulting and the formation of silicic magma suites, followed by the intrusion of juvenile and palingenetic magmas into the crust and the ultimate phenomena of external volcanism - all these sequences of physico-chemical processes will have an effect on the terrestrial heat flow.

(5) The natural radio-active isotopes, concentrated in the upper (granitic) part of the sialic crust (and the sedimentary skin), also contribute to the heat flow. Their upward segregation in the course of the geological evolution and their present occurrence, for the greater part, in granites and sediments near to the surface seems to have led many geophysicists to an overestimation of their importance for the terrestrial heat balance.

(6) The exothermal serpentinization of peridotites, when they are exposed at the floor of newly formed oceans, owing to the spreading of the top parts of mega-undations, might be another, more superficial contribution to the terrestrial heat flow above actively spreading mega-undations (Schuiling, 1964). The oceanic heat flow is of the same magnitude as the continental heat flow; this observation has been used as an argument against continental drift. But Schuiling (1966) points out that, on the contrary, it might be used in favour of continental drift.

(7) The reversed process, namely the endothermal transformation of serpentine in anhydric orthosilicates, occurs when the sea floor is overridden by sialic crustal blocks. This heat consumption will reduce the heat flow to the surface, as has been found at the transition of the Japan Islands and the Japan Trench (Miyashiro, 1961; Horai et al., 1964). Moreover, the water vapours, liberated by the "Pacific-petal" movements of continental drift, will cause rising hydrothermal solutions and the high explosivity-index of the circumpacific volcanic belt.

(8) Deep faulting, such as the great transcurrent faults which accompany drift movements of continental and oceanic crustal units, enable

meteoric water to penetrate to considerable depths. This results in telethermal chemical processes, hot springs and other effects on the terrestrial heat flow.

It is evident, that the terrestrial heat flow is the combined effect of many geodynamic and physico-chemical processes. Heat is conducted and transported, heat is consumed by endothermal chemical or physico-chemical processes or it is produced by exothermal processes. Therefore, the ultimate heat flow at the surface is the result of many factors. Its interpretation should be based on a very careful analysis of the geological circumstances.

The following remarks (a–d) are but a tentative indication of the possible meaning of the supra-regional mega-fields of heat flow, distinguished by Lee and Uyeda (1965). The fact that these fields have an extent of the same order of magnitude as the geoid deformations might indicate that there is some genetic relation between them. The present geoid deformations coincide, according to the present author, with the active top parts of mega-undations. So the mega-fields of heat flow may also be related to the geodynamic and physico-chemical processes which occur during the evolution of the mega-undations.

(a) The low heat flow in the areas of the South and North Atlantic Oceans might be explained by the greater age of the a0–aIII phases of the Atlantic Mega-Undation s.l. The part of the upper mantle, exposed during the Atlantic type of oceanization, have already cooled considerably in the course of about 100 million years. The same can be said of the field of low heat flow in the Indian Ocean, which coincides with the older phases of the Indian Ocean Mega-Undation s.l. (*i0–iII* on fig.6 of Van Bemmelen, 1966), and that in the central Pacific, which coincides with the fossil Darwin Rise.

(b) On the other hand, the field of high heat flow, which coincides with the Afro–Arabic Mega-Undation (*Afr.II*) and the central African Mega-Undation (*Afr.III*), might result from intrusive dike swarms of relatively superheated basalt magma intruded into the overlying sialic crust, and the associated penetrative process of oceanization of the mediterranean type (see Van Bemmelen, 1966, p.114).

(c) The field of high heat flow in the area of the East Pacific Mega-Undation s.l. might be explained by the exposure in young Cenozoic time of deeper strata of the upper mantle, the segregation and ascent of superheated basalt magma, and the exothermal serpentinization of peridotites exposed to the sea water.

(d) The field of relatively high heat flow in the area of eastern Australia and the Coral and Tasman Seas might be the result of active physico-chemical processes, which cause a Mediterranean type of oceanization and the outward rafting of sialic units (such as Figi Islands).

CONCLUSION

In conclusion, it can be said that the new geophysical facts, provided by the data on the form of the geoid and on terrestrial heat flow probably can be interpreted by means of the concept of *mega-undations* (Van Bemmelen, 1964, 1965, 1966), whereas they are not explained by the model of *thermal convection currents* which rise from the base of the mantle up to the base of the crust, as advanced by Wunderlich (1966).

REFERENCES

Garland, G.D., 1965. The Earth's Shape and Gravity. Pergamon, Oxford, 183 pp.

Guier, W.H., 1965. Recent progress in satellite geodesy. John Hopkins Univ., Appl. Phys. Lab., Preprint, 24 pp.

Guier, W.H. and Newton, R.R., 1965. The earth's gravity field as deduced from the Doppler tracking of five satellites. J. Geophys. Res., 70(18): 4613–4626.

Horai, K., Uyeda, S. and Rikitake, T., 1964. Terrestrial heat flow in Japan. Bull. Volcanol., 27: 191–193.

Kaula, W.M., 1963. Determination of the earth's gravitational field. Rev. Geophys., 1: 507–551.

Kaula, W.M., 1966. Tesseral harmonics of the earth's gravitational field from camera tracking of satellites. J. Geophys. Res., 71(18): 4377–4388.

Lee, W.H.K. and Uyeda, S., 1965. Review of heat-flow data. Geophys. Monograph., 8: 87–190.

Miyashiro, A., 1961. Evolution of metamorphic belts. J. Petrol., 2(3): 277–311.

Schuiling, R.D., 1964. Serpentinization as a possible cause of high heat-flow values in and near the oceanic ridges. Nature, 201(4921): 807–808.

Schuiling, R.D., 1966. Continental drift and oceanic heat flow. Nature, 210(5040): 1027–1028.

Van Bemmelen, R.W., 1964. The evolution of the Atlantic Mega-Undation. Tectonophysics, 1(5): 385–430.

Van Bemmelen, R.W., 1965. The evolution of the Indian Ocean Mega-Undation. Tectonophysics, 2(1): 29–57.

Van Bemmelen, R.W., 1966. On mega-undations: a new model for the earth's evolution. Tectonophysics, 3(2): 83–127.

Wunderlich, H.G., 1966. Wärmefluss, höhen Anomalien des Geoids und Geotektonik in Abhängigkeit von Fluktuationen des tiefen Erdmantels. Tectonophysics, 3(3): 187–207.