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Terrestrial Heat Flow

Virtually all processes that occur within the earth are dependent on both temperature and pressure. If we are to apply to the real world the many laboratory measurements of the behavior of earth materials as functions of pressure and temperature, it is essential that we have the best possible information on the variation with depth of both these parameters. The pressure-depth relation can be specified within quite narrow limits from what we know about the earth's moment of inertia, gravity field, and densities, and from the travel paths of elastic waves from earthquakes and underground explosions. Unfortunately, we are unable to predict the temperature at a given depth with nearly the same accuracy as we can the pressure.

The geotherm (temperature *versus* depth within the earth) is a function of surface temperature and surface heat flux and of the subsurface variation of both radioactive heat productivity and the coefficient of heat transfer. The last two can be measured on the surface, but their variation with depth is dependent on our assumptions as to the chemical composition and physical properties of the deep interior. Of the first two, the surface temperature is well known and its relatively small range of variation makes its effect on the geotherm quite small below depths of a few kilometers. Thus the only directly measurable quantity relating to the variation of temperature with depth is the surface heat flow.

The study of terrestrial heat flow is in its infancy relative to many other geophysical disciplines. The first reliable measurements were performed just over thirty years ago, and over 90 % of the existing data have been obtained during the past decade. There are presently about four thousand data, less than one thousand of which were measured on land, and measurements are now being made at the rate of about one thousand per annum.

Fortunately, timely and thorough review articles have accompanied the great increase in the volume of data during the past five years. Lee and Uyeda[1] tabulated and reviewed virtually all of the data available up to the end of 1964. Their tabulation has been updated recently by Simmons and Horai.[2] Lee and Uyeda[1] included a statistical analysis of the data and a summary of major findings for both continents and oceans. Both Lee[3] and Horai and Simmons[4] have made more recent statistical analyses on a global scale based on three

thousand or more data. Useful regional summaries were given by Lubimova and Polyak[5] for Eurasia and by Verma and Narain[6] for India. Langseth and Von Herzen[7] have assembled a thoughtful and comprehensive review of oceanic heat flow and its tectonic implications.

As the recent surge of data collection has progressed, heat-flow studies have reached the "working hypothesis" stage of interpretation. This report presents what I consider to be the major working hypotheses in approximately the order of their enunciation. I make no attempt to rank them in order of importance because they are interrelated and their relative impact will vary with the individual problem to which a given hypothesis is being applied. I do not claim originality for all unacknowledged ideas expressed below, but the available space does not permit exhaustive documentation. I gratefully acknowledge the comments and suggestions of Arthur H. Lachenbruch and W. H. K. Lee, but accept full responsibility for errors of fact and reasoning.

The working hypotheses are as follows:

1. *Continental and oceanic heat flow are approximately equal.* Before the first successful oceanic measurements in the early 1950s, it seemed reasonable to expect that heat flow from the ocean floor would be lower than that on continents by a factor of two or more. This expectation was based on the assumption that the mantle beneath the two regions was essentially the same and that a substantial fraction of the observed continental flux was produced by the decay of radioactive elements in the crust. The first few oceanic values were in the same range as continental heat flow, and the thousands of measurements to date bear out the early results. The spatial distribution of determinations is still uneven, and the exactness of the equality as well as the magnitude of the mean heat flow from each unit depends somewhat on how the averaging is done.[3,4,7] Nevertheless, the mean heat flows are approximately equal whereas the crustal contributions are not, and so we must conclude that the mantle beneath oceans differs in some fundamental way from that beneath continents. This conclusion must be reconciled with the abundant evidence favoring the hypotheses of sea-floor spreading and continental drift. Among the consequences are:

(a) "Oceanic" mantle is converted to "continental" mantle along the leading edge of a continental plate forming new continental crust by fractional melting (with upward differentiation of radioactive elements and probably some degree of combination with continental detritus). Island arcs appear to be surface expressions of this process.

(b) The difference in heat productivity between continents and oceans occurs in the upper few tens of kilometers of the crust and mantle. As first suggested by Bullard,[8] the amount of radioactivity beneath continents and oceans is equal, but the continents are "top heavy" with respect to radioactive elements. Thus, for moving plates, the entire thickness that is distinctively continental or oceanic must be rafted over material that is essentially homogeneous (laterally) in radioactivity.

(c) The presumption of large mass movements implies that heat is produced by friction along sliding surfaces. With rigid plates, frictional heating may be caused by movement along a gravity gradient which, in turn, is caused by thermal processes occurring at depth within the earth.

2. *Distinct heat-flow provinces exist.* In the early days it seemed that the earth's mean heat flow was something over one unit (μcal cm^{-2} sec^{-1}) and this figure was used in estimating the geotherm. In the mid-to-late 1950s Howard[9] and Kraskovski[10] independently stated that heat flow from old Precambrian shields was lower than that from younger areas. Lee and Uyeda[1] refined this obversation by defining three broad classes of post-Precambrian thermal region. As for oceans, Lee and Uyeda[1] noted that ridges, basins and possibly trenches formed distinctive heat-flow provinces. Since 1965 a large number of heat-flow provinces have been recognized both on continents and in oceans.

The boundaries of most major heat-flow provinces appear to correspond to those of major physiographic and tectonic provinces. Thus the Basin and Range is a high heat-flow province, and the Canadian shield, a province of low heat flow. A province that transcends physiographic boundaries is the "Cordilleran thermal anomaly zone". As defined by Blackwell,[11] this includes the Basin and Range, parts of the Northern Rocky Mountains, and possibly the Columbia Plateau. The recognition of distinct provinces allows a regional approach to the interpretation of heat-flow data as opposed to a purely local interpretation or the first order continent *versus* ocean division. Investigation of the nature of the transition between regions of contrasting heat flow can place quite narrow constraints on the distribution of radioactive elements with depth or the deep thermal structure conductivity structure of the crust.

3. *For the granitic intrusive rocks of a given heat-flow province, heat flow and near surface heat production are closely related.* Specifically, the relation is linear with

$$q = q^* + DA_0 \quad (1$$

where q and A_0 are observed heat flow and surface heat production, and q^* and D are constants (within a given province) having the dimensions of heat flow and depth. This relation was first discovered for the Appalachians by Birch *et al.*,[12] but the Appalachian parameters have since been found to apply in the stable continental region between the Appalachians and the Rocky Mountains[13] and the linear relation has been observed in both the

Basin and Range and Sierra Nevada provinces.[13,14] For the provinces defined to date, D ranges from 7 to 10 km and q^* from 0.4 in the Sierra to 1.4 in the Basin and Range. The simplest interpretation of the observed relation is that the heat production A_0 at any point within a province extends to a depth D and that the intercept q^* is the heat flowing from below that depth. q^* for any province is a combination of the heat flow from the mantle and the lower crust (below depth D) for which the mean heat production is laterally homogeneous. Lachenbruch[14] pointed out that this interpretation requires that all plutons be the same thickness and suggested an alternative interpretation in which radioactive material is distributed as a function of depth, z, within plutons (in a gross way) according to

$$A(z) = A_0 e^{-z/D} \quad (2)$$

This relation is the only one that fits Eq. (1) and allows for differences in thickness of plutons. In particular it allows differential erosion among the plutons of a given province. In this case q^* is still equivalent to the heat flow from the lower crust and mantle. For either of the above interpretations, it is convenient to regard q^* as an upper limit to the mantle heat flow. Establishing q^* for a province, in effect, strips off the zone of variability in the upper crust and gives us another geophysical window on the earth's deep interior. The large difference between q^* for the Sierra Nevada and for the Basin and Range places severe constraints on models for the crust and upper mantle in this region. Furthermore, the abruptness of the transition[15] implies that it occurs at shallow depth or is the result of thermal transients. The hypothesis implicit in Eq. (1) is the most recent of the major working hypotheses in heat flow, and many more observations are required either to establish its generality or to amend it. Recent advances and improvements in gamma-ray spectrometric techniques for the determination of radioelement abundances combined with a high degree of interest in obtaining "q, A_0 pairs" among heat-flow groups assure us that abundant data are forthcoming.

The three working hypotheses outlined above by no means complete the list of useful heat-flow studies, and I will devote the space that remains to outlining other investigations of general importance.

Heat flow and the "New Global Tectonics"

The thermal consequences of sea-floor spreading and plate tectonics have been discussed in detail in many publications, the most recent of which include articles by McKenzie,[16] Sleep,[17] Turcotte and Oxburgh,[18] and Lee.[3] Heat-flow results are generally compatible with the new tectonics in that heat-flow is high along ridges, low near trenches and low to normal and generally uniform in deep ocean basins. Uyeda and his colleagues have made a thorough study of heat flow across the Japanese arc,[19] and together with scientists from Scripps Institution of Oceanography, are extending the study to neighboring arcs. Their findings are generally consistent with the hypothesis that the oceanic crust is being thrust beneath the arcs.

In applying heat-flow results to a spreading ocean floor, it is essential to take account of the rather long time constants involved in thermal processes occurring at depth. To illustrate, a 5-km thick slab of basalt has a thermal time constant of about 10^6 years. Thus, a thermal event at the base of an oceanic crust spreading laterally at the rate of, say, 5 cm per year will be observed at the surface some 50 km away from its point of origin. A continuing thermal event originating 10^6 years ago will be "smeared" over several tens of kilometers. Thus, we should expect to see no sharp heat-flow peaks in areas of lateral movement, unless the heat has been carried very close to the surface by a rising magma column or some other form of vertical mass movement. This can be expected to occur near the crests of ridges and in regions where volcanism is observed.

Heat-flow variations across major fault zones.

When movement occurs along a fault, energy is released, the amount depending on the stress, the effective area of contact, and the strain rates. For steady creep, most of the energy is partitioned between heating and granulation along the sliding surfaces, while for earthquakes a small portion of the energy is released as seismic waves.

Brune, Henyey, and Roy[20,21] have measured heat-flow profiles across several major strike-slip faults in central and southern California. In most cases they found no measurable anomalies associated with the faults themselves, and the maximum anomaly measured was $0.3\,\mu\text{cal cm}^{-2}\,\text{sec}^{-1}$. Using reasonable values for slip rate and fault depth, over plausible ranges of vertical stress distributions, they concluded that the steady state or initial shear stresses along the faults are no greater than a few hundred bars. Stresses of a kilobar or more along these faults could have resulted in significant heat-flow anomalies.

In summary, the results of recent heat-flow studies have been very important in the development of our present concepts of the internal constitution of the earth. We can expect to see the blank spaces in oceans filled in very rapidly in the near future. On the continents, where we must drill boreholes to measure heat flow, results will continue to accumulate, but at a slower rate than for the oceans. By far the majority of continental heat-flow data have been obtained from boreholes or excavations intended for other purposes. On behalf of all my colleagues, I gratefully acknowledge the cooperation of the mining and oil industries and agencies of various governments without which few of the existing data could have been obtained. Even though most continental data have come from holes drilled for exploration or public works, it should be noted that many of the key data in recent important discoveries have been obtained by drilling specifically for heat flow.[12,13,14] Continued support for heat-flow drilling in critical areas, such as continental margins and transition zones between provinces of contrasting heat flow, will undoubtedly lead to more important discoveries.

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References

1. W. H. K. Lee and S. Uyeda, in *Terrestrial Heat Flow*, edited by W. H. K. Lee (Geophys. Monograph 8, Am. Geophys. Union, Washington, D.C., 1965), p. 87.
2. G. Simmons and K. Korai, J. Geophys. Res. **73**, 6608 (1968).
3. W. H. K. Lee, Phys. Earth and Planet. Interiors. In press (1970).
4. K. Horai and G. Simmons, Earth Planetary Sci. Letters **6**, 386 (1969).
5. E. A. Lubimova and B. G. Polyak, in *The Earth's Crust and Upper Mantle*, edited by P. J. Hart (Geophys. Monograph **13**, Am. Geophys. Union, Washington D.C., 1969) p. 82.
6. R. K. Verma and H. Narain, in *The Crust and Upper Mantle of the Pacific Area*, edited by L. Knopoff *et al.* (Geophys. Monograph **12**, Am. Geophys. Union, Washington, D.C., 1968) p. 22.
7. M. G. Langseth, Jr. and R. P. Von Herzen, in *The Sea* **4** edited by A. E. Maxwell (Interscience, New York. In press, 1970).
8. E. C. Bullard, Nature **170**, 200 (1952).
9. J. C. Jaeger and R. F. Thyer, Geophys. J. **3**, 450 (1960).
10. S. A. Kraskovski, Isv. Akad. Nauk SSSR ser. Geofiz. 247 (1961).
11. D. D. Blackwell, J. Geophys. Res. **74**, 992 (1969).
12. F. Birch, R. F. Roy, and E. R. Decker, in *Studies of Appalachian Geology: Northern and Maritime*, edited by E-an Zen *et al.* (Interscience, New York, 1968) p. 437.
13. R. F. Roy, D. D. Blackwell, and F. Birch, Earth Planetary Sci. Letters **5**, 1 (1968).
14. A. H. Lachenbruch, J. Geophys. Res. **73**, 6977 (1968).
15. R. F. Roy, E. R. Decker, D. D. Blackwell, and F. Birch, J. Geophys. Res. **73**, 5207 (1968).
16. D. P. McKenzie, Geophys. J. **18**, 1 (1969).
17. N. H. Sleep, J. Geophys. Res. **74**, 542 (1969).
18. D. L. Turcotte and E. R. Oxburgh, J. Geophys. Res. **74**, 1458 (1969).
19. S. Uyeda and V. Vacquier, in *The Crust and Upper Mantle of the Pacific Area*, edited by L. Knopoff *et al.* (Geophys. Monograph **12**, Am. Geophys. Union, Washington, D.C., 1968) p. 349.
20. J. N. Brune, T. L. Henyey, and R. F. Roy, J. Geophys. Res. **74**, 3821 (1969).
21. T. L. Henyey, *Heat Flow near Major Strike-Slip Faults in Central and Southern California*, Ph.D. Thesis (California Institute of Technology, Pasadena, California, 1968).