Thermal Constraints on the Distribution of Long-Lived Radioactive Elements in the Earth

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Phil. Trans. R. Soc. Lond. A 1979 **291**, 269-275
doi: 10.1098/rsta.1979.0025

Phil. Trans. R. Soc. Lond. A. **291**, 269–275 (1979)
Printed in Great Britain

Thermal constraints on the distribution of long-lived radioactive elements in the Earth

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Geochemical data show that radioactive heat production in the crust plus upper mantle (which is defined seismically to terminate at a depth of 415 km) cannot account for the heat escaping from the Earth. Deeper sources must be invoked, and a number of qualitative models of the variation of radioactive heat generation with depth are suggested. Preferred models involve a narrow zone of high heat production about halfway between the crust and the core.

Introduction

The thermal budget of the Earth is largely determined by the amounts and the distributions of the long-lived radionuclides in its interior. In this paper we examine a number of models of the distribution of uranium, thorium and potassium in the Earth, and compare the heat that they predict to be generated in the Earth's interior with the heat that is observed to escape through the surface. One result of such modelling might be the setting of constraints on planetary history.

The constraining rôle of terrestrial heat flow

Our knowledge of the physical and chemical properties of the Earth decreases as we look ever deeper into its interior. At the surface we mainly see the chemically processed rocks typical of the crust, with some material derived more or less directly from the mantle. In addition, we know the heat flow over much of the Earth's surface. These are the data that we shall use to attempt to constrain the properties of the deeper parts of the Earth.

Within a few hundred kilometres of the Earth's surface, the processes responsible for sea floor spreading and plate tectonics dominate the thermal régime. The depth through which they operate is conjectural, but the bottom of the geologically active region is commonly considered to coincide with one of the seismic steps in the mantle at depths of about 400 or 700 km. Whatever the depth of the active layer, the convective motions act as a thermostat, fixing the temperatures, for the following reason. There are a variety of physical mechanisms by which the largely solid mantle may undergo the deformations required by plate tectonics. All of these have in common the property that they are extremely sensitive to temperature. A moderate increase in temperature markedly decreases the resistance to deformation. Hence if we were somehow to increase the heat supplied to the base of the active layer, the principal effect would be to speed up the motions. Only a minor increase in temperature would result. Conversely, a decrease in heat supply would mainly slow the motions and give little cooling.

The consequence of this thermostatic effect of upper mantle activity that is most interesting for our purposes is that virtually all of the heat generated within the active layer, or supplied to it from beneath, must appear at the surface within a geologically short time. The convective motions, with temperature-dependent velocities, ensure a balance between heat flow and heat supply.

An estimate of the amount of heat being generated in the crust and upper mantle, based largely on chemical analyses of material available to us at the Earth's surface, is given in table 1, which is taken from an earlier discussion (Clark & Turekian 1977). Our model of the continental crust is based on the concept of heat flow provinces in its simplest interpretation (Roy, Blackwell & Decker 1972), and our calculations are based on the well studied example of the eastern United States (Birch, Roy & Decker 1968). The model assumes a thin layer with vertically constant but laterally variable heat generation, resting on a substrate through which a constant amount of heat is flowing. Thus the substrate includes the lower crust and the upper mantle. The mean heat generation of the upper layer is taken from measurements of radioactivity which were made for the purpose of correlating heat flow with heat generation (Birch *et al.* 1968). The estimate of heat generation in the lower crust is taken from measurements of the radioactivity of granulite-facies rocks from the Adirondack Mountains of northeastern New York State made by Clark & Roy (unpublished results).

Table 1. Heat generation in the crust and upper mantle

	heat generation fW g^{-1} (fcal g^{-1} s^{-1})	total heat generation TW (Tcal s^{-1})
continental crust ($M = 16 \times 10^{21}$ kg)		
0–7.5 km (1)	1550 (371)	8.37 (2.00)
7.5–40 km (2)	289 (69)	
oceanic crust ($M = 7 \times 10^{21}$ kg)		
0–2 km (3)	460 (110)	1.00 (0.24)
2–7 km (4)	21 (5)	
upper mantle (to depth of 415 km) ($M = 64 \times 10^{22}$ kg)		
ocean-ridge basalt (4)	21 (5)	13.4 (3.2)
pyrolite model of Clark & Ringwood (5)	21 (5)	13.4 (3.2)
ultramafic nodules, Western Victoria, Australia (6)	7.41 (1.77)	4.6 (1.1)
oceanic peridotite nodules (7)	3.56 (0.85)	2.1 (0.5)
continental peridotite nodules (7)	14.4 (3.45)	9.2 (2.2)

	heat loss TW (Tcal s^{-1})
heat lost by heat flow	
average of world wide measurements (8)	32.0 (7.65)
corrected for ocean ridge effects (9)	42.7 (10.2)

Notes: (1) representative value from Birch, Roy & Decker (1968); (2) unpublished data by Clark & Roy, also Birch, Roy & Decker (1968); (3) 2 parts U/10^6; Th/U = 4, 1.5% K; (4) Tatsumoto, Hedge & Engel (1965); (5) Clark & Ringwood (1964); (6) Green, Morgan & Heier (1968); (7) Wakita *et al.* (1967); (8) Lee & Uyeda (1965); (9) Williams & Von Herzen (1974).

The oceanic crust is assumed to consist of an upper layer 2 km thick comprising sediments with minor lavas (layers 1 and 2 of seismologists). Heat generation is calculated from typical values of the radioactivity of these materials. The lower layer (layer 3), 5 km thick, is assumed to be ocean-ridge basalt, with a radioactive element concentration like those given by Tatsumoto, Hedge & Engel (1965). The oceanic crust makes a relatively minor contribution to the overall heat balance, and hence no great precision is needed in these figures.

Five models of heat generation in the upper mantle are given in table 1, based on samples of probable mantle origin. In these calculations we have assumed that the lower boundary of the upper mantle is at a depth of 415 km, corresponding to the base of the first seismic step (Anderson & Kovach 1969; see also Anderson & Hart 1976). This depth was chosen for convenience and, as we shall see, should not necessarily be identified with the base of the convectively active layer. Our first model is based on the assumption that the upper mantle has the same content of radioactive elements as ocean-ridge basalts. This assumption represents the upper extreme in heat production in the upper mantle because it is observed that uranium, and by inference thorium and potassium, are strongly concentrated in the liquid relative to residual solids in a partial melting process (Kleeman, Green, & Lovering 1969). On the basis of this observation, the source material would be expected to be less radioactive than the ocean-ridge basalts themselves. The particular pyrolite model of Clark & Ringwood (1964), which is based on a mixture of 'average' basalt and dunite, coincidentally leads to the same value of heat generation as the ocean-ridge basalt model. The other models are based on suites of ultramafic nodules brought up by basaltic lavas. Model 3 is based on nodules from south-eastern Australia and models 4 and 5 are respectively oceanic and continental representatives of a worldwide suite of nodules. The last 3 models contain markedly less radioactivity than the first 2.

Two estimates of the heat lost from the Earth by conduction through the surface are also given in table 1. The lower estimate is a worldwide average of reported values of heat flow compiled by Lee & Uyeda (1965). Subsequently several authors have recognized that measurements of heat flow near centres of sea floor spreading record only conducted heat, whereas a substantial amount of heat is carried to the surface by circulating interstitial fluids in such regions. References to early papers on this subject are given by Williams, Von Herzen, Sclater & Anderson (1974). Williams & Von Herzen (1974) have derived the higher value of heat loss given in table 1 by evaluating the contribution of circulating fluids with the help of models that are partly empirical and partly theoretical. The higher value of heat loss, as given by Williams & Von Herzen, appears to be the more reliable, despite the inevitable uncertainties in the models upon which it is based. Most of our subsequent discussion is based on this value; it should be emphasized, however, that substantial discrepancies between heat loss and heat generation still remain, even if the older, lower estimate of the heat loss is adopted.

It is immediately obvious from table 1 that the crust and upper mantle, as normally defined seismically, cannot supply the observed heat. Clark & Ringwood (1964) found the same discrepancy, based on their specific pyrolite model, despite the fact that they estimated crustal radioactivity from entirely different considerations. Wakita *et al.* (1967) emphasized that upper mantle models based on their measurements on nodules, are incapable of providing the observed heat, and O'Nions, Evensen, Hamilton & Carter (1977) have reached the same conclusion in a recent summary of available data.

POSSIBLE SOURCES OF THE EXTRA HEAT

We obviously must look to deeper levels in the Earth to supply the balance of the heat flow. There are several ways in which this might be done, and it is useful to begin by considering the heat generation arising from a radioactive shell extending from the top of the mantle to various depths in the Earth. Results are given in figure 1; in constructing the figure it was assumed that the crust contributes 9.37 TW† (2.24 Tcal/s), in accordance with table 1, that no heat is

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† The prefix T represents a factor of 10^{12} and f a factor of 10^{-15}.

generated at depths below the base of the radioactive zone, and that all of the heat produced in it is able to escape. A clear constraint on heat generation in the mantle is brought out by figure 1. If the mean heat generation is much less than 8.4 fW g^{-1} (2 fcal g^{-1} s^{-1}), then the observed heat flow (Williams – Von Herzen value) cannot be supplied, even if the whole mantle has this level of radioactivity. Values of heat generation ranging up to 21 fW g^{-1} (5 fcal g^{-1} s^{-1}), which is the highest value given in table 1, still require thicknesses of 700–1000 km or more for the radioactive zone.

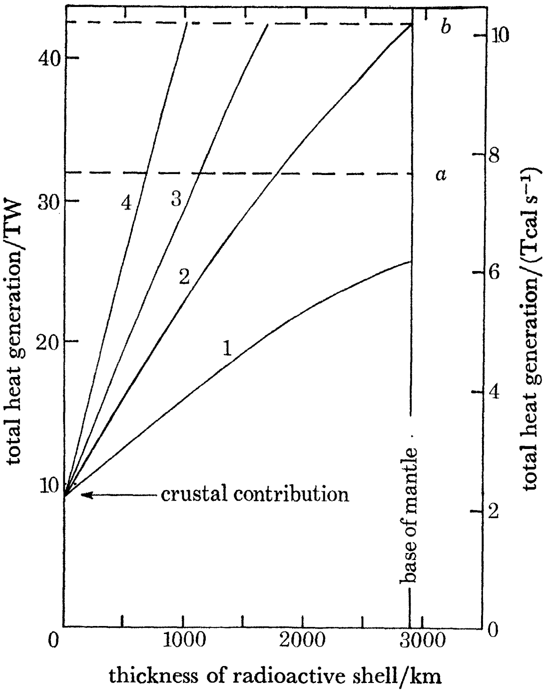

FIGURE 1. Total heat generation plotted against thickness for shells in the upper mantle with uniform internal heat generation. Curves 1 to 4 refer to heat generations of 4.2, 8.4, 12.5 and 21 fW g^{-1} (1, 2, 3 and 5 fcal g^{-1} s^{-1}) respectively. Lines *a* and *b* represent surficial heat flows of 32.0 and 42.6 TW (7.65 and 10.2 Tcal s^{-1}).

The key to the understanding of permissible distributions of the heat sources within the Earth lies in the nature of two modes of heat transfer: convection and conduction (possibly including radiation). Convection requires bulk transport of material for heat transfer and, as such, admits the possibility of geochemical differentiation during the transport process. The most important effect, for our purposes, is the potential for redistributing the heat producing elements over time. Conduction, a less efficient method of heat transport, is the dominant mode expected in layers of the Earth that are too rigid to permit convective circulation. Thus the assumptions in constructing figure 1 can be rephrased: the layer in which the heat is produced and supplied to the surface is a radioactively homogeneous convective layer, and the layer below is rigid with no heat supply to the convective layer above.

The case in which the deep mantle is rigid, so that heat must be transferred by conductive (and radiative) processes, has been discussed previously (Clark & Turekian 1977). It was found that heat generated by radioactivity in the core, or by radioactivity distributed *uniformly* through the lower mantle, was almost entirely trapped in the rigid layer, and little heat escaped into the upper mantle. Cooling of the lower mantle and core could supply significant heat flow provided that the thermal conductivity of the lower mantle is high enough. It must be at least 0.21 W cm^{-1} K^{-1} (0.050 cal cm^{-1} s^{-1} K^{-1}), which is ten times the value commonly inferred for crustal rocks. But if the flux observed at the surface is to be supplied in this way, the conditions of high conductivity in the lower mantle and high radioactive heat generation (appropriate to ocean-ridge basalts) in the upper mantle (to a depth of 415 km) must be met simultaneously.

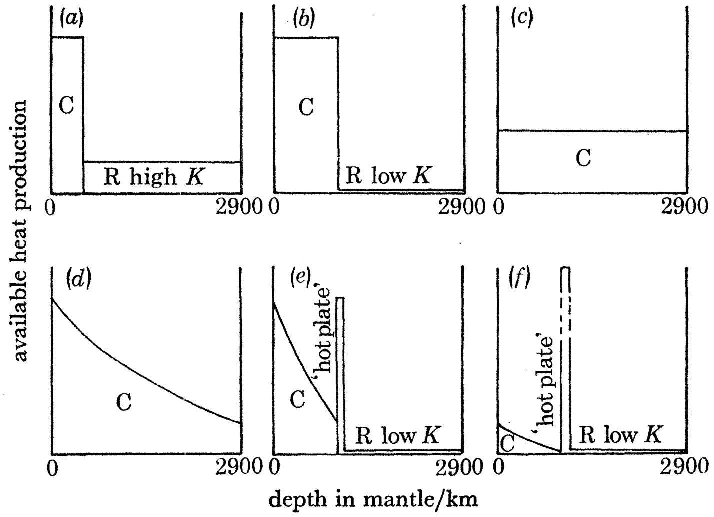

FIGURE 2. Cartoons of possible configurations of heat generation in the Earth. Cases (*a*–*f*) are described in the text. C, convective; R, rigid; *K*, thermal conductivity.

Figure 1 shows that if we assume that the heat generated by ocean-ridge basalt is typical of upper mantle material, a convectively active layer extending to a depth of 1000 km would supply the observed heat flow without recourse to deeper heat sources. Clearly this is not a unique solution, especially as it assumes homogeneous heat production in the active layer. This would imply that despite convective cycling on a time scale of the order of 10^8 years, there was no significant concentration of U, Th and K towards the uppermost part of the mantle.

Alternative configurations of heat generation, capable of accounting for the observed heat flux, are shown in the form of cartoons in figure 2. Each case that we have illustrated has special requirements that must be subjected to geochemical and geophysical tests.

Figure 2*a* represents an upper mantle of homogeneous ocean-ridge basalt (or 'pyrolite' of table 1), extending to a depth of 415 km and supplying heat by convection. The rigid lower mantle is assumed to supply heat by conduction with a thermal conductivity an order of magnitude greater than found in crustal rocks.

Figure 2*b* represents an upper mantle of homogeneous ocean-ridge basalt extending to a depth of 1000 km, overlying a rigid lower mantle supplying no heat.

Figure 2*c* represents the homogeneous distribution throughout the entire mantle. The material must produce 8.4 fW g^{-1} (2 fcal g^{-1} s^{-1}) which is within the range of mantle-derived materials of table 1. The mantle must be convective, in order to permit the escape of radiogenic heat, but no upwards concentration of heat sources is allowed.

The possibility of having the radioactive heat sources permanently locked in a fully convective layer, as required by figures 2*a*, *b* and *c*, encounters the objection that such motions would be expected to expel the radioactive elements. Potassium, if it were ever introduced at depth in the Earth at all, might be trapped in a high-pressure hollandite structure (Ringwood, Reid & Wadsley 1967), but no such haven appears to exist for uranium and thorium. Pervasive convection would in all probability sweep the deep mantle free of radioactivity, and if such a convective pattern exists, a mechanism for reinjecting the radioactivity must be devised. Alternatively, convection in the deep mantle may be localized in space and time, so that parts remain undifferentiated. The rheological properties of the deep mantle must then be compatible with this convective pattern and must permit the retention of a substantial fraction of the radioactive heat sources (see also O'Nions *et al.* 1977).

This objection is met in figure 2*d* by allowing redistribution of the heat sources in a fully convective mantle. Exponentially distributed heat generation ranging from the ocean-ridge basalt value at the top of the mantle, to the oceanic peridotite value at the core–mantle boundary yields a half depth of about 1000 km. The exponential distribution could be the result of pervasive convection of an originally homogeneous mantle, but if the time scale of a convective cycle is about 10^8 years, there have been about 45 cycles since the Earth was formed. Under such conditions a virtually quantitative transport of the radioactive elements into a surficial layer should have occurred. This is clearly not supported by the analytical data upon which table 1 is based and implies either that our geochemical reasoning is in error or that this model does not adequately represent the state of things.

Figure 2*e* restricts the convectively active layer arbitrarily to the top 1000 km of the mantle and imposes the condition that the heat production decreases exponentially from the high ocean-ridge basalt value at the crust-mantle boundary to the oceanic peridotite value at 1000 km. Under these conditions, two-thirds of the heat derived from the mantle is supplied by the convective layer, and the remaining one-third from below. If the thermal conductivity is low below 1000 km, the required heat must be produced in a thin rigid slab just below the convective zone. This is one of several possibilities suggested by the data and has been mentioned in our earlier paper (Clark & Turekian 1977). Essentially this layer acts like a 'hot plate' from which heat is transferred without transfer of the heat-producing elements. An attractive feature of this model is that it provides a heat source to drive upper mantle convection. Figure 2*f* illustrates the case of lower heat generation in the active layer, which then requires greater heat production at the level of the 'hot plate'.

This research has been supported by the U.S. National Science Foundation (S.P.C.) and the National Aeronautics and Space Administration (K.K.T.).

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