PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# Heat Flow and Differences in Lithospheric Thickness [and Discussion]

E. R. Oxburgh and Kingsley Dunham

*Phil. Trans. R. Soc. Lond. A* 1981 **301**, 337-346
doi: 10.1098/rsta.1981.0115

*Phil. Trans. R. Soc. Lond.* A **301**, 337–346 (1981)
*Printed in Great Britain*



# Heat flow and differences in lithospheric thickness

By E. R. Oxburgh, F.R.S.
*Department of Earth Sciences, University of Cambridge,*
*Downing Street, Cambridge, CB2 3EQ, U.K.*

Observations of surface heat flow may be used to constrain the thickness of the lithosphere only in those regions that have approached conductive equilibrium, presumably the oldest continental and oceanic areas. A model is set up to investigate lithospheric thickness differences between old oceans and old continents. The main variable parameters are the surface heat flow, the mean heat production within the continents, and the vertical distribution of the continental heat production. There need be no thickness difference between an old continental region, with a heat flow of 40 mW $m^{-2}$ and a uniform crustal heat production of 0.5 μW $m^{-3}$, and an old oceanic region. Both these values are close to average for old shield areas. Lower surface heat flow, higher mean heat production or exponental distribution of the same heat sources imply a thicker continental lithosphere. In some places old continental lithosphere is probably thicker than that under oceans.

## Introduction

In some respects the question of the thickness of the continental lithosphere may be regarded as equivalent to that of the number of angels able to stand on the point of a needle. From two points of view, however, it is very important.

First the mantle material, which is mechanically coupled to continental crust and moves along with it during plate motions, forms a geochemical reservoir (in the sense of O'Nions & Hamilton, this symposium). Knowledge of its volume and the processes by which material may be added to it or removed from it, and their relative rates, is required for an understanding of the crust–mantle chemical system. It is of particular interest to know the extent to which continental volcanism represents partial melting of the lithosphere and how much, if any, of this volcanism is derived from the underlying circulating part of the mantle (Oxburgh & Parmentier 1978).

Secondly, the thickness of the lithosphere has important implications for a variety of surface tectonic processes, such as the development of sedimentary basins, the formation of rifts, and the lithospheric mass balance in regions of continental convergence such as the Alps and Himalayas.

In this paper we consider the extent to which measurements of surface heat flow may be used to constrain the thickness of the lithosphere. We note that this problem has recently been considered by other workers, in particular Pollack & Chapman (1977), Crough & Thompson (1976), and England & Richardson (1980).

The most favourable situation for using heat flow observations to understand the properties of the lithosphere must be in very old regions, i.e. those that have experienced long periods of tectonic stability and in which an approach to conductive equilibrium may be supposed. In the sections that follow we examine the question of whether heat-flow observations provide grounds for believing that there are differences in lithospheric thickness between old oceanic and old continental regions.

## The model

The argument is sometimes offered that because, within observational error, the average heat flow values from old oceanic areas and old continental regions are the same there is no reason to expect significant differences between the lithospheric thickness of the two areas.

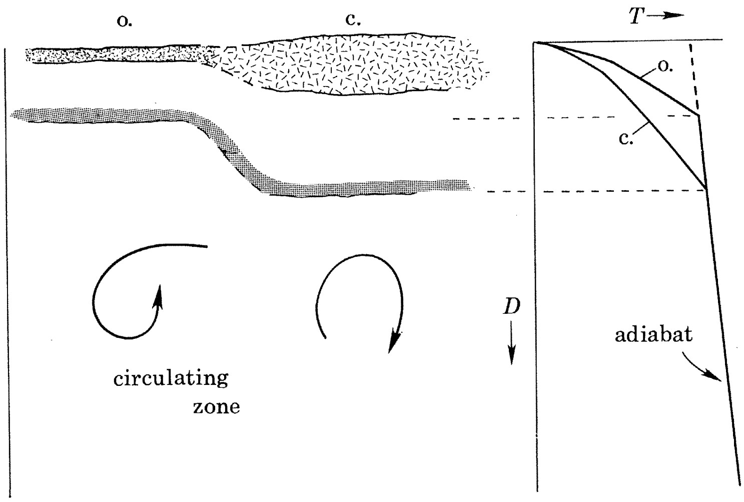


Figure 1. Sketch to show the model considered. Left side: o., oceanic region; c., continental region. Dark stipple to mark the base of the lithosphere, here arbitrarily shown thicker under the continent. Beneath the lithosphere there is a 'well stirred' circulating zone within which the thermal gradient is close to adiabatic. Right side: schematic temperature profiles through the two lithospheric structures shown to left. Both profiles meet the sublithospheric adiabat, but at different depths.

This statement carries the implications, probably reasonable, that the thickness of the lithosphere is largely determined by the temperature distribution within it, and that at some depth its ductility becomes so low that it is too weak to resist the shear stresses associated with plate motions and there is a transition from mantle material that is mechanically coupled to the plate to that which is involved in the larger-scale fluid motions of the underlying mantle. The statement need, however, be true only if the surface heat flow measured in both kinds of area is generated in the same way. The most important difference between them lies in the relative contributions of intraplate radiogenic heat production to the surface heat flow.

We examine this difference by means of a simple model, which is illustrated in figure 1. It is assumed that within upper parts of the circulating zone beneath the plates the gradient of temperature is close to adiabatic; this should be a good approximation if this region is characterized by vigorous small-scale unsteady convection. This means that if plates are of different thickness the temperature at their lower surface will vary, but along one adiabat.

Further, if the surface heat flow is prescribed, and one point on the adiabat is known, the thickness of a plate is determinable from a knowledge of its thermal properties and the distribution of radiogenic heat production within it. In practice, although no fixed point on the adiabat is known, it is still possible to examine variation in lithospheric thickness without determining absolute thicknesses. We adopt this approach here because temperatures beneath plates are uncertain by several hundreds of degrees, even in oceanic areas, where there is some confidence that the thermal structure of the plate is understood.

We regard the plates as moving over a body of well stirred fluid. Their upper surfaces are at approximately constant temperature, buffered by the ocean–atmosphere system. Their lower surfaces are close to constant temperature too, except in so far as there will be an adiabatic temperature difference associated with any difference in plate thickness. Such approximations cannot provide a satisfactory general model for the thermal structure of plates, but they are adequate for a comparison of the older parts of plates.

Provided that we are concerned only with thermal regimes that are steady or very slowly changing, the lateral variation in heat flow measured at the surface depends on plate thermal properties, the abundance of heat-producing elements within the plates, and plate thickness. In the discussion that follows we use observations to constrain the surface heat flow, make the dubious assumption that the thermal properties of crust and upper-mantle rocks are adequately known, and examine the interdependence of intraplate heat production and plate thickness.

For the reasons given earlier, we shall be concerned with a comparison of old continental and old oceanic plate areas. Viewing the problem in a qualitative way, more of the surface flux in continental regions is expected to be provided by intraplate heat sources, and these will largely be located in the continental crust forming the upper part of the plate. For any given surface heat flux, the greater the fraction of that flux originating within the plate, the lower will be the conductive component of the flux coming from below. That conductive component is approximately proportional to the thermal gradient in the lower part of the plate and, in so far as the lower plate boundary temperature is fixed, except for adiabatic variation the most likely cause of variation in the gradient is variation in plate thickness. To summarize, in a comparison of two old plate areas with similar surface heat flow, that with the higher intraplate heat production might be expected to be thicker. We show below that although this is often the case it is not always so, and that the vertical distribution of the heat production is important too.

## Heat production in oceanic lithosphere

Oceanic lithosphere is believed to have a threefold compositional layering that results from the extraction of partial melts from the uppermost mantle at mid-ocean ridges (Oxburgh & Parmentier 1978). Analyses of fresh basaltic glasses dredged near ridge crests provide the best estimates of concentrations of heat-producing elements in the oceanic crust (see, for example, Cohen *et al.* 1980). On the assumptions that such basaltic liquids represent 10–20 % melts of the underlying mantle material from which they were formed and that there was virtually complete fractionation of K, U and Th into the melt, it is possible to arrive at the distribution of heat-producing elements for the oceanic lithosphere shown in table 1. Although all values used are uncertain by a factor of 3, it is clear that intraplate heat production makes a negligible contribution to oceanic heat flow.

Virtually all the heat lost through an old oceanic plate is conducted from below and the gradient of temperature will be close to a steady state conduction profile.

## Results

In this section are presented the results of numerical calculations for temperature distribution in the lithosphere, with a range of values for heat production distributed uniformly and non-uniformly within the crust. Thermal conductivity is allowed to vary with temperature and





PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

TABLE 1. MODEL PARAMETERS

*old oceanic plate:* $q_0 = 40$ mW m$^{-1}$

| layer thickness/km | | $a$ | $b$ | $k$/(W m K) | $A$/(μW m$^{-3}$) |
|---|---|---|---|---|---|
| crust | 8 | | | 2.0 | 0.13 |
| upper mantle | 32 | 0.15 | $2\times10^{-4}$ | | 0† |
| | 40 | 0.15 | $2\times10^{-4}$ | | 0.05 |

*old continental plate:* $q_0$ range 40–20 mW m$^{-2}$

| | $a$ | $b$ | $A$/(μW m$^{-3}$) | $A_0$/(μW m$^{-3}$) | $D$/km |
|---|---|---|---|---|---|
| continental crust to 35 km | 0.37 | $2.69\times10^{-4}$ | 0.173–0.8 | 0.69–3.2 | 8.5 |
| 35 km, to base of plate | 0.15 | $2\times10^{-4}$ | 0.05 | — | — |

$q_0$, surface heat flow (mW m$^{-2}$)
$k$, thermal conductivity (W m K)
$A$, $A_0$, mean, and surface, radiogenic heat production (μW m$^{-3}$)
$D$, exponential depth constant for decrement of heat production with depth; so, $A_z = A_0\,e^{-z/D}$, where $z$ is depth of interest
$a$, $b$, $c$, $d$, constants in the conductivity equation:

$$k = \frac{1}{a+bT} + c\Delta T + dz,$$

where $c$ is taken as $1.6\times10^{-3}$, $\Delta T$ is the amount by which the temperature exceeds that at which radioactive heat transfer becomes significant, $d$ is taken as $1.7\times10^{-5}$ and $z$ is depth (see Cull 1976)

The conductivity of the continental crust is that measured on garnet and pyroxene granulites. That for the oceanic crust is based on the author's measurements on basaltic flows and intrusives in the 2 km Reydarfjordur borehole, Iceland, and Cull's (1976) demonstration that $k$ for the Laki basalt is nearly independent of temperature up to 500 °C.

† Depleted zone of Oxburgh & Parmentier (1978).

pressure, and with bulk composition. As shown below lithospheric differences are derived from temperature profiles. The results are summarized in figure 2 and table 2.

Figure 2 shows differences in lithosphere thickness between continental regions with different characteristics and a 'standard' old oceanic lithosphere, which is taken to be 80 km thick; a temperature is calculated for a depth of 80 km according to the oceanic parameters of table 1 and then the depth is calculated at which the temperature under the continental area being considered matches that under the standard ocean after allowance has been made for adiabatic effects. The difference between the depth and 80 km is plotted as $\Delta h$. A family of curves is shown for $\Delta h$ as a function total crustal heat production. The scales at the top of the diagram

TABLE 2. TEMPERATURES (°C) AT THE BASE OF OLD CONTINENTAL CRUST 35 km THICK

| heat flow | $A$/(μW m$^{-3}$) | | | | $A_0$/(μW m$^{-3}$) | | | |
|---|---|---|---|---|---|---|---|---|
| mW m$^{-2}$ | 0.17† | 0.25† | 0.4† | 0.8† | 0.69‡ | 1‡ | 1.6‡ | 3.2‡ |
| 40 | 595 | 575 | 530 | 420 | 570 | 539 | 474 | 307 |
| 35 | 510 | 490 | 450 | 335 | 485 | 455 | 390 | 230 |
| 30 | 425 | 405 | 365 | 260 | 405 | 370 | 310 | 155 |
| 25 | 345 | 305 | 285 | | 320 | 290 | 230 | |
| 20 | 265 | 245 | 210 | | 245 | 215 | 155 | |

$A$, Uniform heat production.
$A_0$, Surface values for exponentially decreasing heat production; $D$ = 8.75 km. Total crustal heat production is the same for corresponding points in the two halves of the table.

are for crustal heat production that decreases exponentially with depth, and those at the bottom for uniform concentration throughout the crust; for the same total heat production a uniform distribution of sources permits a thinner lithosphere than does an exponential distribution. The model suggests that a stable continental region with uniform heat production and a heat flow lower than 30 mW $m^{-3}$ should have a lithosphere that is thicker than that under an old ocean. On the other hand, for heat flow values between 30 and 40 mW $m^{-2}$, the thickness may be either greater or less than that of an old ocean depending on the crustal heat production.

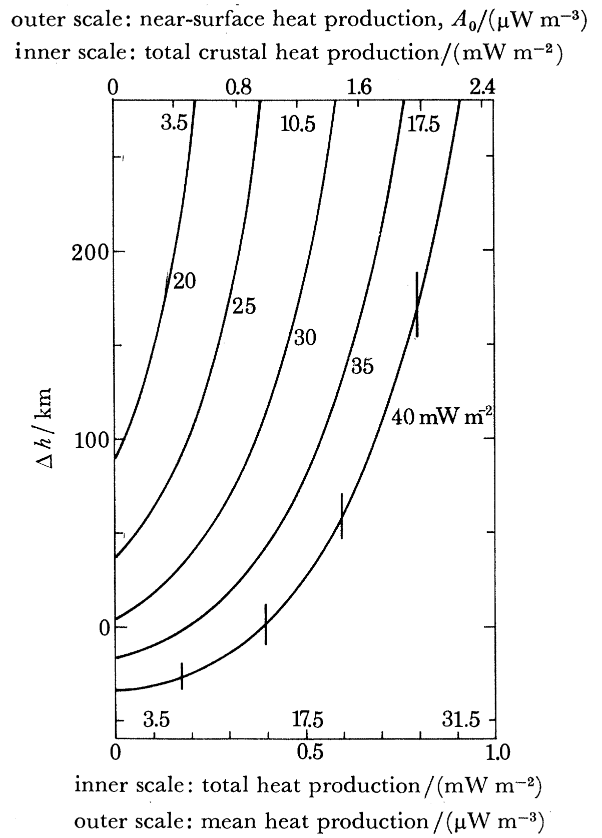


FIGURE 2. Dependence of $\Delta h$, difference in lithospheric thickness between old oceanic and old continental areas, on heat flow (values given on curves) and continental radiogenic heat production. Abcissae: lower scales give values for heat production for a uniform distribution of sources in 35 km crust; upper scales are for exponential distribution of sources with exponential constant, $D$ = 8.75 km. Vertical lines on the curve for a heat flow of 40 mW $m^{-2}$ show the effect of allowing for an error of $\pm$ 10 % on the thermal conductivity of the continental crust.

In the following section we examine more closely the problem of continental radiogenic heat production and its bearing on the interpretation of figure 2. It should be noted that the results presented in terms of $\Delta h$ are not very sensitive to the actual thickness of the 'standard' old oceanic lithosphere and even if the latter were 50 % thicker than the model value chosen the $\Delta h$ values would not be greatly affected.

Table 2 is not directly relevant to the main argument but is a side product of the calculations and shows the range of temperature expected at the base of an old continental crust for various values of heat flow and crustal heat production.




PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

## Crustal heat production in old continental crust

Nearly all known regions of old continental crust have surface exposures of high-grade regionally metamorphosed schists and gneisses within which other lithologies appear to be of relatively insignificant volume. There have been relatively few studies of regional heat production in such areas, but that of Bunker *et al.* (1975) is a notable exception. Their average value for the western Australian shield is 3.37 μW $m^{-3}$, with values ranging from 8.43 to 0.93 μW $m^{-3}$. A similar study in Rhodesian Craton gave an average of 0.88 μW $m^{-3}$ (Oxford Heat Flow Group, unpublished data).

Both these studies involved analyses, by γ-ray spectrometry, for U, Th and K. Unfortunately the analytical errors associated with the measurement of low concentrations (e.g. typically in rocks with bulk heat production < 0.25 μW $m^{-3}$) are rather large.

A second source of information on heat production in ancient terrains comes from analyses of uranium made during U–Pb geochronological studies. Two studies are of particular interest, that of the Lewisian basement of northwest Scotland by Moorbath *et al.* (1969) and that on the Precambrian of west Greenland at Isua (Moorbath *et al.* 1975). Unfortunately in neither are analyses of Th and K available. For the Lewisian the U concentrations are among the lowest ever recorded and average 0.28 mg/kg, with a range from 0.03 to 1.18 mg/kg. At Isua values range from 1.259 to 0.468 mg/kg, with an average of 0.698 mg/kg. In many cases, however, an incompatibility is observed between the present $^{238}U/^{204}Pb$ ratio, the age and the measured $^{206}Pb/^{204}Pb$; this seems to result from a relatively recent loss of U from the system. Moorbath *et al.* (1975) show that this is so at Isua, where the recent Pb losses are up to about 40 %. They suggest that these are attributable to near-surface ground-water movements. For the Lewisian, recalculation of the authors' values shows that there are cases both of apparent recent gain and loss of U and that the mean U content of the sample suite analysed is not significantly affected by such corrections.

Taking average values for Th/U of 4 and U/K of $10^{-4}$ (Clark 1966), rough estimates of heat production can be made, giving about 0.5 μW $m^{-3}$ (0.7 if corrected for recent U losses) for Isua, and about 0.2 μW $m^{-3}$ for the Lewisian. Such values should, however, be treated with great caution both because of the uncertainty in the uranium values and because of the natural range of variation of U/Th and U/K ratios observed in nature. There is some suggestion from the recorded mineral parageneses of the rocks analysed, many of which carry feldspars, mica and amphibole, that the K values estimated in this way are too low.

These and some other observations of heat production in old shield areas are given in table 3. They show that there is variation of more than an order of magnitude. Properly controlled, statistically valid estimates, however, are not available. It does seem, though, that high-grade metamorphic rocks exposed at the surface in such regions rarely, if ever, become so depleted in heat-producing elements that their heat production falls below 0.2 μW $m^{-3}$.

We now consider the variation of radiogenic heat production with depth in the crust. It is evident in many young granitic terrains that near-surface concentration of heat production cannot persist very far with depth, otherwise the total crustal heat production would exceed the surface heat flow. Studies of heat flow and near-surface heat production led several groups of workers (Birch *et al.* 1968; Hyndman *et al.* 1968; Lachenbruch 1968) to the conclusion that heat production must be strongly fractionated upwards in the crust. Lachenbruch also showed that the surface observations could be satified by an exponential decrease in heat production with depth. His approach has subsequently been adopted by many others and the exponential depth constant (i.e. the depth above which about two-thirds of the heat production occurs) varies between 4 and 15 km, with an average about 8.5 km. Direct observational evidence of a decrease in heat production with depth in the crust is available from several sources. Lachenbruch & Bunker (1971) showed a decrease downwards in a borehole 2 km deep in the Canadian Shield. Hawkesworth (1974) found a similar phenomenon in a study of the East Alpine basement. In both cases the observations contained a great deal of scatter and it was not possible to establish the relation between decrement and depth. Hart (1978) has studied the variation of heat production with depth through a 14 km crustal section exposed on the flanks of the Vredefort dome in South Africa. He finds a downward decrease in the upper part of the section, but in the lower part heat production shows no further decrease and in fact increases over one section of several kilometres. The lowest values of heat production measured by Hart are about 0.97 μW m$^{-3}$.

Table 3. Heat production, $A$, in old shield areas/(μW m$^{-3}$)

| | average $A$ | lowest $A$ | comment | source |
|---|---|---|---|---|
| Rhodesian shield | 0.88 | 0.19 | 26 samples | Oxford Heat Flow Group, unpublished data |
| western Australia | 3.37 | 0.93 | 36 Archean granitic rocks | Bunker *et al.* (1975) |
| | 0.90 | — | average greenstone | Lambert & Heier (1967) |
| | 2.64 | — | average shield | Lambert & Heir (1967) |
| Greenland Isua | 0.5 | — | 8 samples; only U analyses available | Moorbath *et al.* (1975) |
| Scotland, Lewisian | 0.2 | — | 37 samples; only U analyses available | Moorbath *et al.* (1969) |
| Musgrave Range, SW Australia | 0.47 | — | granulites | Lambert & Heier (1967) |
| north Norway | 0.77 | — | granulites | Heier & Thoreson (1970) |
| post-Archaean lower crust | 0.17 | — | estimates from various sources; Th content/(mg kg) = 4 U content/(mg/kg) | Taylor (1978) |
| average 20 km lower crust | 0.26 | — | estimate based largely on W Australia | Hyndman *et al.* (1968) |

Perhaps the main conclusion of this section should be that knowledge of heat production in the lower crust is still inadequate. It is clear from studies of young terrains that heat production must fall with depth. In some areas this decrease may be exponential, but apparent exponential depth constants deduced by conventional methods may be unreliable (England & Richardson 1980; England *et al.* 1980), and in some areas the exponential model is certainly inappropriate (Richardson & Oxburgh 1979). In any case, there is no evidence that heat production typically or systematically continues to decrease with depth in deeply eroded high-grade metamorphic terrains. A subjective estimate for heat production in old continental crust is 0.5 μW m$^{-3}$; in some areas it may be as low as 0.2 μW m$^{-3}$, but it cannot fall significantly below that unless the continental rocks involved are different from all those at present thought plausible for the lower crust. An upper bound to mean crustal heat production in such areas is harder to establish; we here take it to be 1 μW m$^{-3}$.

## Heat flow in old continental areas

Heat-flow values measured in old continental areas have recently been reviewed by Sclater *et al.* (1980). They range from over 100 to less than 20 mW $m^{-2}$, with an average around 40 mW $m^{-2}$. Even if heat-flow measurements are made to the most rigorous experimental standards, it is never possible to know to what extent any single measurement is affected by circumstances peculiar to the observation site (e.g. non-one-dimensional heat transfer, deep slow water movements). For that reason it would be desirable to average such values over areas with dimensions at least of the same order as the thickness of the crust; in this way it should be possible to suppress the effects of local site peculiarities and to establish real regional variations in heat flow. Unfortunately the density of measurements for most of the world is far too low for this approach to be applied and in nearly all cases one is left in uncertainty as to what significance to attach to any particular value.

A similar problem arises when attempts are made to correlate heat flow and near-surface heat production; locally heat production is heterogeneous on the scale of variation of the surface geology in the region where the measurement of heat flow was made.

The model indicates that there should be a correlation between heat flow and heat production in old continental regions and that a significant part of the variation in heat flow in such areas may be attributable to variation in crustal heat production. There is some indication that this is so (Rao & Jessup 1975). It can be readily established from figure 2 that a quasi-linear relation should in many cases exist between heat flow and heat production in such areas and that the relationship holds regardless of whether the variation in heat flow is at constant, or varying, $\Delta h$, and regardless of whether the distribution of heat production with depth is constant or exponential. In these cases, however, there is no simple interpretation of the slope of the regression line or the intercept at zero heat production (see, for example, Rao & Jessup 1975).

## Discussion

The model suggests that, if heat flow in old continental areas is 40 mW $m^{-2}$ or higher on a regional scale, there is no case on heat-flow grounds for suggesting any significant difference in thickness between continental and oceanic lithosphere unless average crustal heat production is higher than the old-continental average proposed above, 0.5 μW $m^{-3}$. If, however, extensive old regions with heat flows consistently lower than 40 mW $m^{-2}$ are established the case for an unusually thick continental lithosphere in that area is plausible, unless the mean crustal heat production is exceptionally low. If 0.2 μW $m^{-3}$ is taken as the lower limit for mean crustal heat production, any regionally significant heat flow of less than 35 mW $m^{-2}$ implies a lithosphere that is thicker than the oceanic standard. Such an area may possibly exist in central and west central southern Africa (Chapman & Pollack 1974).

It should be noted that for any given total crustal heat production an exponential distribution of heat sources will imply a lower subcrustal temperature (table 2), and thus a thicker lithosphere than does a uniform depth distribution of the same heat sources.

So far there has been no discussion of the uncertainties in thermal conductivity. The model has been set up in such a way as to minimize their effect on the results. Even so the conclusions are particularly sensitive to the conductivity assigned to the continental crust. The uncertainties arise not only from the dearth of relevant measurements but also from petrological uncertainties on the gross mineralogy of the crust down to 35 km. To give some idea of the consequences of under- or over-estimating mean crustal conductivity by 10%, bars are shown in figure 2 indicating the differences at different values of heat production for the 40 mW $m^{-2}$ curve.

There has also been no discussion of the processes by which the lithosphere has developed. The results presented here suggest that the lithosphere is probably variable in thickness and in some places is significantly thicker than is old oceanic lithosphere. Furthermore, the 'lithosphere' for which results are presented here, which was defined in the introduction, is certainly different from the 'lithosphere' the thickness of which is estimated from surface flexural parameters.

The results do not offer any means of distinguishing between the alternative means proposed for the generation of continental lithosphere (see, for example, Jordan 1978; Oxburgh & Parmentier 1978; Pollack & Chapman 1977) and any argument for local increases in thickness must also satisfy other geophysical constraints (see, for example, Turcotte & McAdoo 1979).

## Conclusion

We conclude that:

(1) mean heat production in old continental areas is likely to average about 0.5 μW $m^{-3}$ and that it is unlikely anywhere to average less than 0.2 μW $m^{-3}$;

(2) an old continental area with such an average heat production and characterized by a regional heat flow of 40 mW $m^{-2}$, close to the old continental average, should be underlain by lithosphere *ca.* 10–20 km thicker than the lithosphere under old oceans;

(3) old continental areas with regional heat flows in the range 30–40 mW $m^{-2}$ need not have thicker than average lithosphere beneath them, but in that case their mean crustal heat production must be close to the lower limit observed;

(4) old continental areas with regional heat flows lower than 30 mW $m^{-2}$ are likely to have thicker than average lithospheres; how much thicker depends on crustal heat production.

Discussions of various aspects of this problem with P. C. England and R. K. O'Nions are gratefully acknowledged. This work arises from measurements carried out under a N.E.R.C. Research Grant for heat flow studies.

## References (Oxburgh)

Birch, F., Roy, R. F. & Decker, E. R. 1968 In *Studies of Appalachian geology, northern and maritime.* (ed. E-an Zen, W. S. White, J. B. Hadley & J. B. Thompson Jr), ch. 33, p. 475.

Bunker, C. M., Bush, C. A., Munroe, R. J. & Sass, J. H. 1975 *U.S. Dept Interior, Geol. Surv. open-File Rep.* 75–393.

Chapman D. S. & Pollack, H. N. 1974 *Nature, Lond.* **250**, 477–478.

Clark, S. P. 1966 *Mem. geol. Soc. Am.*, no. 97.

Cohen, R. S., Evensen, N. M., Hamilton, P. J. & O'Nions, R. K. 1980 *Nature, Lond.* **283**, 149–153.

Crough, S. T. & Thompson, G. A. 1976 *J. geophys. Res.* **81**, 4857–4862.

Cull, J. P. 1975 D.Phil. thesis, Oxford University.

England, P. C. & Richardson, S. W. 1980 *Geophys. Jl R. astr. Soc.* **62**, 421–437.

England, P. C., Oxburgh, E. R. & Richardson, S. W. 1980 *Geophys. Jl R. astr. Soc.* **62**, 439–455.

Fountain, D. M. 1976 Italy; a cross section of the continental crust – new evidence from seismic velocities of rock samples. *Tectonophysics* **33**, 145–166.

Hart, R. J. 1978 Ph.D. thesis, University of Witwatersrand.

Hawkesworth, C. J. 1974 *Nature, Lond.* **249**, 435–436.

Hawkesworth, C. J., Moorbath, S., O'Nions, R. K. & Wilson, J. F. 1975 *Earth planet Sci. Lett.* **25**, 251–262.

Heier, K. S. & Thoresen, K. 1970 *Geochim. cosmochim. Acta* **35**, 89–99.

Hyndman, R. D., Lambert, I. B., Heier, K. S., Jaeger, J. C. & Ringwood, A. E. 1968 *Phys. Earth planet. Interiors* **1**, 129–135.





PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Jordan, T. H. 1978 *Nature, Lond.* **274**, 554–548.
Lachenbruch, A. H. 1968 *J. geophys. Res.* **73**, 6977–6989.
Lachenbruch, A. H. & Bunker, C. M. 1971 *J. geophys. Res.* **76**, 3852–3860.
Lambert, I. B. & Heier, K. S. 1967 *Geochim. cosmochim. Acta* **31**, 377–390.
Moorbath, S., O'Nions, R. K. & Pankhurst, R. J. 1975 *Earth planet. Sci. Lett.* **27**, 229–239.
Moorbath, S., Welke, H. & Gale, N. H. 1969 *Earth planet. Sci. Lett.* **6**, 245–256.
Oxburgh, E. R. & Parmentier, E. M. 1978 *Phil. Trans. R. Soc. Lond.* A **288**, 415–429.
Pollack, N. H. & Chapman, D. S. 1977 *Tectonophysics* **38**, 279–296.
Rao, R. U. M. & Jessop, A. M. 1975 *Can. J. Earth Sci.* **12**, 347–360.
Richardson, S. W. & Oxburgh, E. R. 1979 *Nature, Lond.*, **282**, 565–567.
Sclater, J. G., Jaupart, C. & Galson, D. 1980 *Rev. Geophys. Space Phys.* **18**, 269–311.
Taylor, S. R. 1979 In *The Earth, its origin structure and evolution*, pp. 353–376. London and New York: Academic Press.
Turcotte, D. L. & McAdoo, D. C. 1979 *J. geophys. Res.* **84**, 2381–2387.

## *Discussion*

SIR KINGSLEY DUNHAM, F.R.S. (*Charleycroft, Quarryheads Lane, Durham DH*1 3*DY, U.K.*). What picture had the author in his mind of the partition of radioactive minerals between the crust and the mantle? It can not be supposed that the whole radioactive mineral content of the earth is now concentrated into the outer crust, otherwise mantle convection would presumably have ceased and our planet would soon be as dead as the moon.

E. R. OXBURGH. There is no suggestion that all the Earth's heat-producing elements are located in the crust. On the other hand they may be sufficiently concentrated there that their abundance and distribution significantly affect the crustal thermal gradient. The abundance of heat-producing elements in the mantle is sufficiently low that it does not greatly affect the calculation of local conductive thermal gradients within the lower lithosphere. Nevertheless, this small contribution was taken into account.