Heat flow in a metamorphic crust

from Peter J. Smith

In investigations which attempt to relate the Earth's heat flow to crustal structure and composition, it has been usual to view the crust in terms of homogeneous igneous rocks. Thus, for example, when Roy *et al.* (*Earth planet. Sci. Lett.*, **5**, 1; 1968) demonstrated the correlation betwen geothermal flux and surface heat production, they made it clear that their measurements and analysis applied specifically to intrusive granitic bodies. But as Smithson and Decker (*Earth planet. Sci. Lett.*, **22**, 215; 1974) point out, although crustal models involving homogeneous igneous rocks have the merit of simplicity they may be a poor general representation of the real Earth. Fifty years ago, Clarke and Washington (*Prof. Pap. U.S. geol. Surv.*, **127**; 1924) could plausibly argue that 95% of crustal rocks are igneous; but modern work is more likely to stress the importance, and even the predominance, of metamorphic rocks with characteristic heterogeneities.

Evidence for the modern view is extensive. The W nd River Mountains of Wyoming, for example, are a broad anticlinal uplift with a core of Precambrian rocks largely comprising migmatite. Borehole data suggest that in places such rock is at least 4 km thick, in addition to which denser metasedimentary rocks such as mica schists, garnet schists and metagraywacke may be found at structurally higher levels. Again, a profile through the Ivrea zone of the Alps has been interpreted in terms of an upper crust comprising metamorphic rocks such as mica schist, a middle crust which is granitic in the form of migmatite and granitic gneiss, and a lower crust consisting of dehydrated mafic metamorphic rocks and diorites. Migmatites underlying other metamorphic rock types are also found in Canada, east Greenland, southern Norway and central Europe. Indeed, Barth and Reitan (in *The Precambrian*, Interscience; 1963) have estimated that as much as 93% of the exposed southern Norwegian Precambrian may be metamorphic—a figure which corresponds well with Wilson's picture (in the same volume) of the Canadian Shield as a region of metamorphic rocks "in which areas of granite and other igneous rocks are interspersed".

But where does all this (and much more) leave the analysis of terrestrial heat flow in terms of simple igneous and homogeneous structures? The answer is, of course, a rather poor approximation to the truth, but an approximation which can nevertheless be built on to give a picture closer to reality. Smithson and Decker build by proposing the following three-zone model of stable continental crust:

- The upper zone consists largely of metamorphic rocks of intermediate composition with a mean density in the range 2.75–2.80 g cm^{-3} and seismic P wave velocities ranging from 6.2 to 6.5 km s^{-1}. Geological relationships and gravity interpretations suggest that this surface zone could be 5–12 km thick, although Smithson and Decker use a thickness of 8 km. The metamorphic rocks actually comprise mica schists, metagraywackes (biotite gneiss and quartzo-feldspathic gneiss), greenstones and amphibolites. According to Shaw (*Geochim. cosmochim. Acta*, **31**, 1111; 1961), the mean heat production within the Canadian Shield is 4 heat generation units (h.g.u.); and it is known that intrusive granites generally have a higher heat production. The intervening metamorphic rocks of the upper zone must therefore have a heat production lower than 4 h.g.u. The estimate made by Smithson and Decker is 3 h.g.u., based on a mixture of mica schists, metagraywacke and mafic rocks.
- The middle zone is also 8 km thick and comprises rocks which are less dense and more granitic than those of the zone above. This is the migmatite zone and consists largely of granitic gneiss and augen gneiss intermixed and interlayed with biotite-rich gneiss and amphibolite lenses. The mean density of this very heterogeneous region is about 2.72 g cm^{-3}, P wave velocities lie in the range 6.0–6.3 km s^{-1} and the highly variable heat production has a probable average of about 5 h.g.u.
- The lower zone, 18 km thick, is composed of dense rocks (2.80–3.00 g cm^{-3}) with high seismic velocities (6.5–7.0 km s^{-1}). Both field and laboratory studies show that at likely pressures and temperatures in the lower crust mafic rocks would be recrystallised as metamorphic rocks in the amphibolite, granulite or eclogite facies, although the last of these is unlikely. Smithson and Decker argue that granulite facies rocks actually comprise the bulk of the lower crust, although they expect pockets of amphibolite to coexist with them. Heat production is estimated to be 0.5–.5 h.g.u.

Having proposed this more "realistic" model, however, Smithson and Decker are at pains to emphasise that the zones should not be interpreted as discrete layers. The zones are heterogeneous and grade into each other irregularly, so that even the quoted thicknesses cannot be regarded as universal. Average values tend to conceal considerable diversity in both the horizontal and vertical directions. Thus the model is a generalisation which may apply in the specific form given only in relatively few localities.

Notwithstanding these restrictions, if the surface heat flow for stable continental areas is taken to be 1.2 heat flow units (h.f.u.) in accordance with the suggestion from Blackwell (in *The Structure and Physical Properties of the Earth's Crust*, American Geophysical Union, 1971), the model predicts a heat flow contribution of 0.3–0.5 h.f.u. from the upper mantle. The upper limit of this range then leads to temperatures of 130° C at a depth of 8 km, 407° C for the Moho at 34 km, and 538° C at 54 km in the upper mantle—temperatures which are comparable with, but slightly lower than, those obtained by Blackwell from other models. The controversial point to arise here is the claim by Smithson and Decker that such low temperatures rule out the possibility of a universal seismic low-velocity zone produced in the crust by thermal effects. A low-velocity zone may arise in places in the upper or middle crust because of variations in composition, but it would be unlikely to exist over an area of even continental extent.

In search of a meaning

from a Correspondent

The first plenary meeting of the International Society for Research on Aggression, whose objects are as much educational as scientific, was held in Toronto on August 17 and 18. The constitution of the society refers to "the destructive and constructive aspects of aggression", but does not define aggression: and in fact definition was the most prominent theme of the meeting, which was attended by fifty or so researchers (about one-fifth of the total membership) from fields as various as anthropology, psychiatry, and experimental psychology.

On the question of definition, K. Lagerspetz (Swedish University, Turku) pointed out that although most definitions include the delivery of noxious stimulation to another organism, this does not always apply in psychiatry or the social sciences. She asked whether, nonetheless, unifying concepts exist for all the fields of behaviour to which the term 'aggressive' is applied. In her view the notion of an 'aggressive drive' is not useful; and is critical of the frustration hypothesis and analyses in terms of learning and inhibitions.

Adopting an historical perspective, J. P. Scott (Bowling Green State University, Ohio) suggested 'disaggregation', or disruption of normal social patterns, as a general concomitant of anti-social violence in both human and animal societies.

The pluralism advocated by Lagerspetz was echoed in a discussion on classification and definition. K. E. Moyer (Carnegie-Mellon University,