Global dynamics and the temperatures of metamorphism

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The problem of the heat of metamorphism has been recognized for a long time. Neither normal heat flow from the mantle nor radioactive heating seem able to account fully for the structure in space and in time of the thermal fields of metamorphism. The heat derived from magmas is the manifestation of a heat transfer mechanism; anatectic crustal magmas do not at all address the fundamental problem of the source of the energy influx associated with metamorphism. The association of dynamothermal (regional) metamorphism with orogenic belts at convergent plate boundaries is, however, clear. May deformation, with conversion of mechanical energy to heat play a role in the origin and structure of the thermal fields of metamorphic/orogenic belts?

Field-based studies have found specific temperature profiles to be best explained when strain-heating is included in the analysis. Computational models based on stress, strain rates, and consequent strain-heating, have demonstrated the possibility of at least local and perhaps wide-spread temperature increase owing to deformation.

A different approach uses estimates given by Verhoogen (1980), in particular the global rate of energy input into orogenic fold belts. By coupling this estimate to estimates of volumes of Cenozoic fold mountains average specific energy input rates can be made. Some of the energy goes into energy sinks such as endothermic reactions, energy stored by dislocations, unrelieved elastic strain, and heat carried away by water of dehydration reactions.

Simple computation models based on one-dimensional heat flow with uniform heating throughout a given depth interval used two approaches: the first fills all energy sinks first and then allows the input energy to be converted to heat, and the second fills sinks and generates heat gradually throughout a 10 million year metamorphic/orogenic event. Calculations were performed distributing the strain-heating over a 70 km thick orogenic crust and then distributing the strain-heating over a 150 km thick deformation of crust and upper mantle.

Using low, medium, and high values of heat transfer (conductivity) for the 70 km model the calculated maximum temperatures reached at 39 km depth are: first approach, 446°, 297°, and 223°C; second approach, 430°, 287°, and 215°C. For the 150 km model the calculated maximum temperatures occur over a broad depth range (50 to 100 km) and are: first approach, 172°, 114°, and 86°C; second approach, 83°, 55°, and 41°C.

The energy involved is only a small fraction of the global energy flux, but the dynamics of the lithosphere may cause a portion of that energy to focus on a small part, the orogenic belts, at any one time with the apparent result that strain-heating makes a non-negligible contribution to the temperatures of regional metamorphism.

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The problem of the heat of metamorphism – how the appropriate amount of heat reaches the right place at the right time – has been recognized for a long time (Fyfe et. al., 1958). Normal (conducted) heat flow from the mantle into the crust appears to be inadequate even if metamorphic reactions were not dominantly endothermic. The rate of radioactive heating may hardly be enough to fill the endothermic reaction sink (Verhoogen, 1980), and furthermore, the distribution of radioactive heat sources does not account well for the observed structure of the thermal fields of metamorphism. The heat derived from magmas is largely the manifestation of a heat transfer mechanism; anatectic magmas do not at all address the fundamental problem of the source of the energy influx which must, throughout much of the crust, have produced temperatures 100°C to 200°C, or even more, above what one would normally expect to prevail at any given depth (Verhoogen, 1980). Crustal thickening (England and Thompson, 1984; Thompson and England, 1984) may account for some aspects of the P-T-t paths of regional metamorphism, but is strained to account fully for the complexity of multiple phases of metamorphism and temperature oscillations.

Worldwide we observe that more recent orogenic belts have higher heat flow than do old cratons (Morgan, 1984). Griffin and O'Reilly (1987) show geotherms from cratonic western Australia and active southeastern Australia that differ by about 470°C at a depth of 30 km, for whatever complex of reasons.

Heat flow, radioactivity, heat transfer by magmas and crustal thickening all play a part, but none is sufficient nor do they, even when taken together, seems to be able to account fully for the magnitude and the structure of the energy influxes and resulting thermal field in metamorphic/orogenic belts. It seem that we need to identify an additional heat source, especially one that is non-uniform – even discountinuous – in space and in time.

We recognize the association of dynamothermal (regional) metamorphism with orogenic belts at convergent plate boundaries. We observe that deformation is concentrated in these belts. We know an exceptional heat input is found there. Exceptional deformation and exceptional heat input coincide. Is that coincidence in space and time purely fortuitous? Or may deformation of the crumpled leading edge of the overriding plate, with conversion of mechanical energy to heat, play a role in the origin and structure of the thermal fields found in metamorphic/orogenic belts?

Several field-based site related studies have concluded that specific temperature profiles could be explained when strain-heating was included in the analysis (e.g. Ambrose, 1936; Graham and England, 1976; Scholz et. al. 1979).

Another approach, based on analyses of models of stress, strain, strainrates, and consequent heat production to estimate temperature increases, has been tried and shown to be capable of producing at least local and perhaps quite widespread significant strain-heating (e.g. Reitan, 1968a, 1968b, 1969; Brun and Cobbold, 1980; Fleitout and Froidevaux, 1980; Wan et. al., 1986).

A different approach is to make use of estimates given by Verhoogen (1980) on the global energy requirements of geological phenomena. While many of these estimates must be recognized to be first approximations or even informed guesses (Verhoogen, pers. comm. 1987) it is nevertheless of interest to take them as guidelines and explore their consequences. Such follow-up inquiry may show there to be value in efforts to refine those estimates.

We recognize that the dynamics of the lithosphere result in a small part of the global heat budget being focused, as conversion of mechanical energy to heat, on a small part of the lithosphere at convergent plate boundaries. We may ask, what is the large scale thermal response of a given overall estimated amount of energy accumulating during deformation of the crumpled leading edge of the overriding plate where orogeny and metamorphism occur?

What follows is an attempt to evaluate the strain-heating implied by an estimate given by Verhoogen (1980) of the global rate of energy imput into orogenic fold belts, so as to assess the potential of strain-heating as one component of the complex of energy inputs contributing to the thermal fields of metamorphic terranes.

Among Verhoogen's (1980) global estimates is that of the strain energy rate in belts of deformation, including an estimate of that not converted to seismic energy. In one place (Verhoogen, 1980, p. 13) the estimate is stated to be ". . . somewhat larger than 1 x 10^{12}W. . .". Elsewhere (p. 8) the figure 7 x 10^{11}W may be deduced from the text. For calculations to produce heating profiles I have used 1 x 10^{12}W. (The calculated temperature at any depth is a direct function of the rate of heating (Reitan, 1969); to the extent the energy input rate is too high the temperature should be scaled down accordingly. Verhoogen (pers. comm. 1987) has indicated that he thinks his earlier estimate may be too high.)

Into what volume is this energy being put? Wyllie (1976) estimates that 2.8 % of Earth surface is underlain by Cenozoic fold mountains. Assuming 70 km for a thickened crust in orogenic belts, a volume of ca. 1 x 10^{24} cm^3 is obtained for Cenozoic crust involved in fold belt deformation. If the duration of an orogenic/metamorphic episode is taken to be 10 million years (Fyfe et. al., 1958), then about 15 % of the Cenozoic fold belt volume, 1.5 x 10^{23} cm^3, is being deformed at any one time. It follows that the total energy input rate (i.e. 1 x 10^{12}W) divided by the volume being deformed at any one time (i.e. 1.5 x 10^{23} cm^3) gives a specific energy input rate, Q_T = 6.7 x 10^{-12}W cm^{-3} = 1.6^{-12} cal $cm^{-3}sec^{-1}$, and a total energy input over a 10 million year orogenic/metamorphic episode, $E_T = Q_Tt$ = 4.8 x 10^{12} cal cm^{-3}.

Not all this energy is simply converted to heat. There are energy sinks. What are they and how large are they?

Endothermic reactions of metamorphism have been estimated (Fyfe et. al., 1958; Verhoogen, 1980) to require 50 cal gm^{-1} or roughly 150 cal cm^{-3}, an average rate of energy consumption over 10 million years of about 5 x 10^{-13} cal $cm^{-3}sec^{-1}$. The energy stored by dislocations (Reitan 1977, 1979) can hardly exceed 1 cal gm^{-1} (3 cal cm^{-3}), representing an average rate of 0.1 x 10^{-13} cal $cm^{-3}sec^{-1}$. Unrelieved elastic strain energy held in the rocks is of the same order of magnitude as that of dislocations or less (Reitan, 1977, 1979).

Water released by dehydration reactions carries away heat with it. From Wood and Walther (1986) a mass ratio for average pelite of water of dehydration: rock of 1:25 is obtained. As some of the heat carried away by water from its point of release is simply transferred to cooler regions higher up, it seems ample to attribute heat carried away to an average increment of heating of water of 200 degrees, or about 8 cal gm^{-1} (25 cal cm^{-3}), an average rate of heat extraction throughout 10 million years of 0.8×10^{-13} cal $cm^{-3}sec^{-1}$.

For computational purposes, as a first approximation, either of two approaches may be used. The first approach allows all energy sinks to be filled first after which internal heating of the deformation volume occurs at the full rate, Q_T, but over a reduced time interval, t_R. The second approach allows all energy sinks to be filled gradually over the 10 million year time interval; the sum of the skin-filling rates, $Q_S = 0.6 \times 10^{-12}$ cal $cm^{-3}sec^{-1}$, is subtracted from Q_T to give a reduced rate of heating, Q_R, maintained over the full 10 million year time interval, t_T.

The computation model is a one-dimensional heat-flow model with uniform heating, Q, throughout a depth interval, a to b, for a time period, t. The temperature increase, T, is computed for any depth, z, with T=0 at z=0 (see Reitan, 1969). Thermal diffusivity is taken as 1.3×10^{-2} cm^2sec^{-1} (based on thermal conductivity of 8×10^{-3} cal $sec^{-1}cm^{-1}deg^{-1}$ [Turcotte and Schubert, 1982; Kirby, 1983]). As both mass movement of magma and of water transfer heat more rapidly than thermal conductivity would alone, enhanced heat transfer is approximated by substituting successively 12×10^{-3} cal $sec^{-1}cm^{-1}deg^{-1}$ and 16×10^{-3}cal $sec^{-1}cm^{-1}deg^{-1}$ for the base conductivity value. Calculations were performed distributing the strain-heating over a thickened orogenic belt crust of 70 km. According to the first approach (fill all sinks first) the computed maximum temperature increases over any pre-existing geotherm at the end of 10 million years occur at 39 km depth and for the three different conductivity values are 446°, 297°, and 223°C. According to the second approach (fill all sinks gradually) the maximum temperature increases are 430°, 287°, and 215°C.

As deformation may involve the upper mantle, too, the computations may be made with the uniform heating rate distributed over a thickness of 150 km. Of course, by increasing the deformed volume the magnitudes of the energy sinks, all of which are volume dependent, are correspondingly increased.

The same two approaches and variables were used except that b, the bottom of the zone of uniform heating, is at a depth of 150 km. Using the first approach 7.8 million years pass during which sinks are filled before any conversion of energy to heat begins, because the specific rate of energy input is much reduced and the total size of the sinks is much enlarged. For the three "effective" conductivities the maximum temperatures are found over broad plateaus (from roughly 30 to 120 km depth) and reach 172°, 114°, and 86°C. The second approach, in which all of the sinks throughout the 150 km depth are filled gradually by the much reduced specific energy input rate, produces temperature increases, again over quite broad plateaus (from about 60 to 95 km depth), of 83°, 55°, and 41°C.

Even the least of these models indicates that strain-heating is a significant component of the set of contributors to the temperatures found in orogenic/metamorphic belts. Strain-heating appears not to be simply a factor exclusively restricted to local phenomena. The work done in deforming rocks is largely dissipated as heat and appears to make a significant overall contribution to the magnitude and complex structure of the thermal fields in deformed belts.

The energy involved is truly only a small fraction of the global energy flux, but the dynamics of the lithosphere cause a portion of that energy flux to be focused on only a small fraction of the crust at any one time, resulting in a non-negligible effect on the temperatures reached in the crust during dynamothermal metamorphism.

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