THERMAL IMPLICATIONS OF METAMORPHISM IN GREENSTONE BELTS AND THE HOT ASTHENOSPHERE-THICK CONTINENTAL LITHOSPHERE PARADOX; Paul Morgan, Department Geosciences, Purdue University, West Lafayette, IN 47907.

From considerations of secular cooling of the Earth and the slow decay of radiogenic heat sources in the Earth with time, the conclusion that global heat loss must have been higher in the Archean than at present seems inescapable. The mechanism by which this additional heat was lost and the implications of higher heat loss for crustal temperatures are fundamental unknowns in our current understanding of Archean tectonics and geological processes. Higher heat loss implies that the average global geothermal gradient was higher in the Archean than at present, and the restriction of ultramafic komatiites to the Archean and other considerations suggests that the average temperature of the mantle was several hundred degrees hotter during the Archean than today (1). In contrast, there is little petrologic evidence that the conditions of metamorphism or crustal thickness (including maximum crustal thickness under mountains) were different in Archean continental crust from the Phanerozoic record (see 1). Additionally, Archean ages have recently been determined for inclusions in diamonds from Cretaceous kimberlites in South Africa (2), indicating temperatures of 900 to 1300 degC at depths of 150 to 215 km (45 to 65 kbar) in the Archean mantle (3), again implying relatively low geothermal gradients at least locally in the Archean. In this contribution the thermal implications of metamorphism are examined, with special reference to greenstone belts, and a new thermal model of the continental lithosphere is suggested which is consistent with thick continental lithosphere and high asthenosphere temperatures in the Archean.

High-grade metamorphism is common in Archean terrains (4, 5), and includes some greenstone belts, such as in the Yilgarn block of SW Australia (6). High metamorphic temperatures (700 degC or more) and often high metamorphic pressures (5 to 10 kbar or greater) are indicated by the mineral assemblages in these terranes, and they are underlain in most cases by continental crust of normal thickness (7, 8). Conductive thermal relaxation models have been proposed to predict the thermal conditions of metamorphism in the crust following tectonic activity such as underthrusting (e.g., 9-11). As demonstrated by Ashwal and Morgan (7), however, simple thermal relaxation of thickened crust cannot reasonably produce the high temperatures required by granulite metamorphism with a thick section of crust (30 km or more) below the shallowest depth of granulite metamorphism without requiring the lower part of the crust to be supersolidus. Basically the temperature range for granulite metamorphism is so close to estimates of the crustal solidus for reasonable crustal compositions (e.g., 12), that a positive geothermal gradient below the shallowest depth of granulite metamorphism causes the geotherm to intersect the solidus above the Moho. Ashwal and Morgan (7) conclude that unless granulite metamorphism occurs only near the base of the crust and the thick section of crust now below the exposed granulites was added after metamorphism, major crustal magmatic activity is associated with granulite metamorphism. Such extreme thermal conditions are not required by lower grades of metamorphism, but any metamorphic gradients which indicate a high geotherm suggest the upward transport of heat by magma unless the crust is thin.

If it is accepted that magmatic heat transport is an essential component of the crustal thermal regime during the peak thermal conditions recorded by the metamorphic mineral assemblages in the crust (at least where high geothermal gradients are indicated), then maximum temperatures recorded in these systems were buffered by the solidus. The occurrence of young granulites at the top of sections of normal thickness crustal sections similarly indicates that modern maximum geothermal gradients are buffered by the solidus. A similar conclusion is indicated by heat flow data from areas of recent tectonism in which high heat flow must result from magmatic heating of the crust (e.g., 13). Maximum temperatures at shallow depth are buffered by the boiling point curve at hydrostatic or lithostatic pressures, below which maximum temperatures are buffered by the crustal solidus. As these maximum crustal temperatures are commonly encountered in areas of active tectonism and magmatism today, it is impossible for maximum temperatures recorded by Archean metamorphic assemblages to have been higher than modern maximum temperature conditions unless the solidus was different. Thus, in this buffered system, higher heat loss in the Archean is not expected to be recorded by metamorphic assemblages indicating higher geothermal gradients than peak modern conditions, although these peak crustal thermal conditions may have been more widespread in the Archean than at present.

The occurrence of high-grade (granulite) metamorphism in Archean greenstone belts suggests that either the high-grade areas were produced near the base of the crust and subsequently the crust has been thickened below the high-grade terranes, and/or magmatism was an important process during the high-grade metamorphism. The intimate association of plutons with the greenstone belts in "granite-greenstone" terranes suggests the importance of magmatism during this high grade metamorphism, and is consistent with models which suggest basal melting of stacked simatic thrust sheets during the evolution of at least some greenstone belts (14-16).

Perhaps the most paradoxical indicator of Archean thermal conditions with respect to higher global heat loss is the relatively low Archean geothermal gradients indicated by the formation of diamonds of Archean age. The diamond stability field is consistent with geotherms predicted for modern shield areas with thick (150 km or greater) lithosphere (e.g., 13). Meyer (3) has suggested that diamonds were formed in the asthenosphere which in turn suggests that perhaps the higher temperatures deduced for the Archean mantle from the occurrence of komatiitic lavas were not universal. A more common interpretation of the diamond data is that they indicate the existence of thick "keels" of subcontinental lithosphere below at least some areas during the Archean (1, 16). However, as the lithosphere is intimately related to the thermal boundary of upper mantle convection, it would be expected that this boundary layer and the lithosphere would have been thinner during the Archean with higher global heat loss and mantle temperatures. A possible solution to this paradox may be found in the intrinsic heat production of continental lithosphere.

There are two basic variable parameters that control the stable thickness of the continental thermal boundary layer (lithosphere), the heat production within the layer and the heat input to its base (13, 17). The layer thins if heat input to its base increases, and thickens if the heat input decreases. This heat input depends upon the temperature difference between the lower portion of the stable boundary layer and the underlying convection cell, or more specifically the temperature gradient in the lowest portion of the layer. As this gradient decreases to zero, the heat input to the base of the lithosphere decreases to zero (negative gradients are not permissible in a stable thermal boundary layer). The thickness of stable continental lithosphere with zero heat input at its base is independent of the global heat loss, assuming that the heat can be lost elsewhere (oceanic and other continental lithosphere), and this may possibly be a mechanism for maintaining thick continental lithosphere at a time of high global heat loss and high average mantle temperatures.

The condition for zero heat flux into the base of the stable continental lithosphere is that the temperature increase within the lithosphere due to its intrinsic radiogenic heat production creates a geotherm that is asymptotic to the asthenosphere isotherm (or adiabat with an adiabatic basal heat flux). For thick lithosphere this condition requires a small but significant component of heat production in the mantle lithosphere, and an example of such a heat production distribution and geotherm are given in Figure 1. This condition has the interesting property that thicker lithosphere is indicated for higher asthenosphere temperatures for similar heat production distributions. If heat production distributions of this type are realistic it is unlikely that they are accidental (see also 18), and the concentration of radiogenic heat production into the lithosphere by metasomatism and crustal building processes may be related to the stabilization of continental lithosphere.

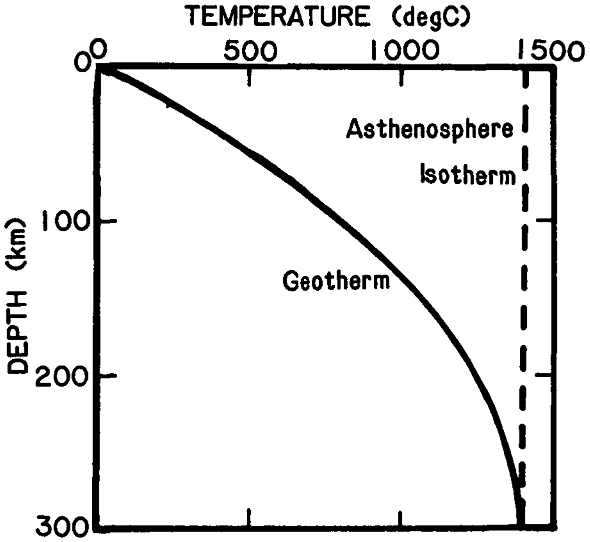

Figure 1. Example of continental lithosphere geotherm asymptotic with asthenosphere isotherm as a result of its intrinsic radiogenic heat generation. A two component crustal heat generation model is assumed for this geotherm: An upper crustal component decreasing exponentially with depth from 2.7 µW/m**3 at the surface with a depth scale length of 7 km, and an additional uniform component of 0.09 µW/m**3 (geotherm model modified from 19).

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