GREENSTONE BELT TECTONICS - THERMAL CONSTRAINTS: M.J. Bickle (Dept Earth Sciences, University of Cambridge, Cambridge CB2 3EQ, U.K.) and E.G. Nisbet (Dept Geological Sciences, University of Saskatchewan, S7N OWO, Canada).

Archaean rocks provide a unique record of the early stages of evolution of a planet. Their interpretation is frustrated by the probable unrepresentative nature of the preserved crust and by the well known ambiguities of tectonic geological synthesis. Broad constraints can be placed on the tectonic processes in the early earth from global scale modelling of thermal and chemical evolution of the earth and its hydrosphere and atmosphere. The Archaean record is the main test of such models. It is the purpose of this contribution to outline what general model constraints are available on the global tectonic setting within which Archaean crust evolved, and what direct evidence the Archaean record provides on particularly the thermal state of the early earth.

The distinct tectonic style of Archaean granite-greenstone terrains undoubtedly reflects secular variation in the earth's tectonic processes as a result of chemical and thermal evolution. Since tectonic processes are a direct manifestation of heat loss processes in the earth, changes in the earth's thermal state are likely to be primarily responsible for changes in tectonic style. However, the geological record of tectonic processes is also influenced by the state of chemical evolution of the solid earth and its hydrosphere and atmosphere. As discussed below the basic volcanic dominated nature of greenstone belts is probably as much a consequence of higher mantle temperatures as any specific tectonic setting. Until proved otherwise we must assume that 'greenstone belts' formed in as wide a range of tectonic environments as modern sedimentary sequences. Care must be taken to distinguish features which are due to a specific tectonic environment from those indicative of general tectonic processes in the Archaean earth.

Global Thermal Histories

Calculations of global thermal evolution are based on derivations of relationships between internal temperature and heat loss. Given such a relationship and the present temperature and radiogenic heat producing element distribution within the earth it is possible to calculate temperature distributions in the past with the assumption that the heat loss processes (convection) varied only in rate throughout earth history. Most current models are formulated to satisfy the cosmochemical constraint that present day radiogenic heat production produces about half of the total heat loss and that the earth was hot soon after accretion [e.g. 1]. The main area of uncertainty intrinsic in the modelling is the treatment of convection in a fluid of temperature sensitive and non-Newtonian viscosity. One set of models, the 'parameterised' convection calculations, derives a relationship between internal temperature and heat loss by computing heat loss as a function of viscosity for a series of models run with internally constant but differing viscosities and assuming some form for the viscosity temperature dependence. Implicit in such modelling is the assumption that convection in a variable viscosity fluid can be approximated by a constant viscosity appropriate to a characteristic temperature within the system. However, as first demonstrated by McKenzie and Weiss [2] the assumptions of parametrical convection calculations are not appropriate to convection in variable viscosity fluids. Christensen [3] points out

2. All the models predict that higher internal temperatures result in thinner, higher thermal gradient boundary layers (Plates)[1,3]. Further constraints must come from Archaean geology, which provides evidence on two critical parameters, upper mantle temperatures and continental lithospheric thermal gradients.

1. Mantle Temperatures

The presence in Archaean greenstone belts of komatiitic lavas more magnesian than any younger lava is one of the few distinctive features of the Archaean and prime evidence that mantle temperatures were higher. To quantify the difference we need to know (1) the eruption temperature of komatiites and (2) the relationship between komatiite eruption temperatures and mantle temperatures. The first question has provoked surprisingly little discussion given its significance [e.g. 5,6]. Liquidus temperatures of komatiitic lavas are proportional to MgO content but this may be increased by olivine accumulation. Glassy, near phenocryst free lavas [7], and relict forsterite-rich olivine compositions have been taken to indicate liquids at least as magnesian as 27-30% MgO [5] although this is disputed [6]. Alternatively excess H_2O or alkalis have been suggested as fluxes lowering liquidus temperatures [e.g.8]. The latter is potentially testable through the temperature dependence of Ni olivine:liquid partition coefficients although such systematic tests have not been made. Even so eruption temperatures of ~1500°C (25% MgO) to ~1600°C (30% MgO) are 100-200°C hotter than any more recent lava.

The relationship between komatiite temperature and mantle temperature is more problematic. Adiabatically upwelling mantle cools along substantially higher thermal gradients (higher dT/dP) above the solidus as a result of the latent heat of melting (Fig. 2). If komatiites represent ~50% melts at high

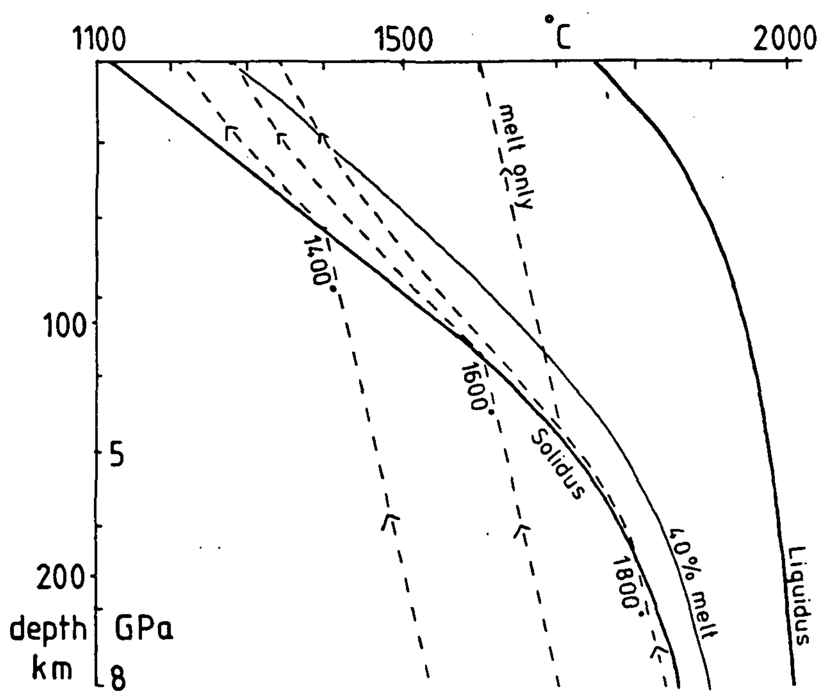

Figure 2. Mantle liquidus and solidus and adiabatic ascent paths calculated with the assumption that melt and solid do not segregate on ascent, after McKenzie and Bickle [23].

level with an olivine residue then a 1600°C komatiite must be derived from a mantle in excess of 2000°C from depths >300km where we are essentially ignorant of mantle solidus-liquidus temepratures. Such temepratures substantially exceed the upper bound of mantle temperatures derived from global thermal modelling. Alternatively it has been suggested that eutectic melts at high pressure shift to komatiite compositions [9]. Available phase equilibrium data suggests this might be in the region 50-100 kbar [Fig.3]. If so komatiites might be derived from mantle temperatures of 1800°C-1900°C, a potential temperature of 1700-1800°C, and 400-500°C hotter than present day average mantle. If komatiites are derived from anomalously hot upwelling convective instabilities the potential temperatures of such regions are 200°C-300°C hotter than mantle in present day thermal plumes.

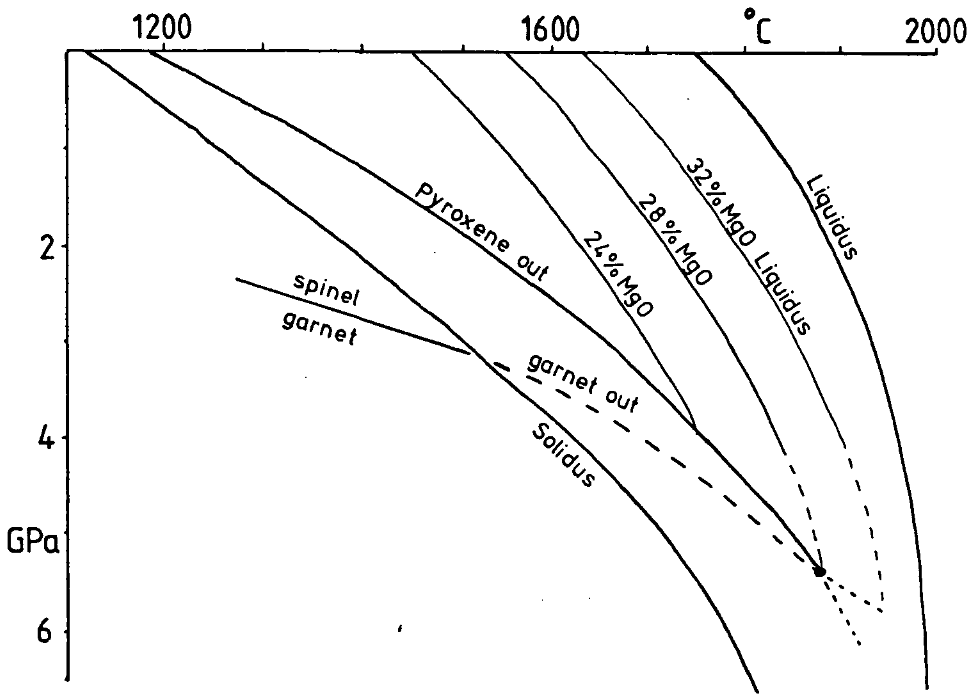

Figure 3. Phase relations for melting mantle-like compositions from experiments on komatiites. Note intersection of garnet melting curve with the pyroxene melting curve is hypothetical.

The chemistry of komatiites is not obviously reconcilable with their being small degrees of eutectic melts. Incompatible element concentrations are surprisingly uniform and are consistent with komatiites being ~50% melts of plausible mantle materials [10,11]. Small degrees of melt would be expected to be substantially enriched in incompatible elements although partition coefficients at the pressures of komatiite genesis are unknown and substantial modifications to komatiite chemistry by wall rock interaction might be expected during their ascent [12].

Komatiite genesis is therefore problematic. However, even the most conservative estimates of komatiite eruption temperatures (a 25% MgO 1500°C lava) implies mantle potential temperatures ~200°C hotter than at present and a 30% MgO, 1600°C lava is inferred to imply mantle potential temperatures ~400°C greater than today. One further complication is the possibility that at high pressure the komatiite melt density exceeds that of solid mantle. If the inversion in density is associated with a change in sign of the pressure derivative of the potential temperature on the melting curve existence of a stable magma ocean at depth is probable [13]. The implications of such a magma ocean for global thermal and chemical evolution are profound.

2. Crustal Thermal Gradients

Metamorphic pressures and temperatures record anomalous thermal conditions in tectonically active crust. If sufficient is known about the tectonic setting of the metamorphism it is possible to invert the perturbed thermal conditions to infer steady state lithospheric thermal gradients [14]. Models for such inversion are mostly based on the thermal time constant over lithospheric thicknesses being rather greater than that of tectonic events (~<50 Ma). Given the possibility of magmatic or fluid heat transfer, such models tend to put upper bounds on lithospheric thermal gradients.

Archaean metamorphic conditions exhibit as wide a range of thermal gradients as modern orogenic provinces. High thermal gradients may at least locally be associated with magmatic advection of heat [15]. The lower thermal gradient, higher P/T metamorphism has attracted most interest as it places limits on the magnitude of lithospheric thermal gradients. The widespread 8-10 Kb, 700°C-900°C conditions recorded by gneiss terrains [16] imply background gradients little different from those in modern continental lithosphere. However, Morgan [17] suggests that these metamorphic conditions are buffered by crustal melting and heat flow in these regions is underestimated. Comparable high P/T metamorphism is known from upper-greenschist and amphibolite facies Archaean terrains [15,18-20] although it is less well documented. This is inconsistent with high heat flow through the underlying crust and not explicable as buffered by melting.

The inference from the metamorphic conditions of relatively low lithospheric thermal gradients has received substantial support from the observation of the formation and preservation of Archaean age diamonds [21]. These imply lithospheric thicknesses of ~150-200 km and mantle heat flux as low as 20 mWm^{-2}.

The observation that greenstone belts may have formed or been preserved in continental crust with relatively low thermal gradients has far-reaching implications for Archaean tectonics. Study of the metamorphism and its tectonic setting in greenstone belts would seem to be one rather neglected area of greenstone tectonics.

Implications on Global Thermal Evolution

The evidence for a significantly hotter mantle implied by komatiites is irreconcilable with the evidence for a thick cool continental lithosphere if the lithosphere behaved as its modern counterpart. There is good evidence from the depth-age relationships of oceanic lithosphere and sedimentary basin evolution that Phanerozoic oceanic and continental lithosphere behaves as a simple thermal boundary layer. To preserve a similar or greater thickness of Archaean lithosphere requires some additional process to stabilise the continental lithosphere. Morgan [17] suggests that increasing the concentration of radiogenic heat production might achieve this. It might but thermal gradients over such enriched lithosphere would have to be at least as high as those over correspondingly thin but unenriched lithosphere. An alternative mechanism is that the stabilisation results from density changes on melting [e.g. 22]. One consequence of a higher temperature mantle is that melting would start at much greater depths (Fig. 2)(~115 km for a 1600°C mantle versus

~60 km for the present day ~1300°C mantle). The depleted zone is comparatively less dense than unmelted mantle although whether the relatively small changes are sufficient to stabilise the lithosphere against convective instabilities is open to question. The mechanism of stabilisation of Archaean continental lithosphere and the formation and preservation of Archaean diamonds is a key question. It has implications both for Archaean tectonic interpretations as well as subsequent global evolution given the significance of the continental lithosphere to continental tectonics.

There is one further significant tectonic implication of a hotter mantle. The amount of melt produced by upwelling mantle is proportional to mantle temperature [Fig. 4; 23]. With a 1600°C mantle any tectonic activity such as

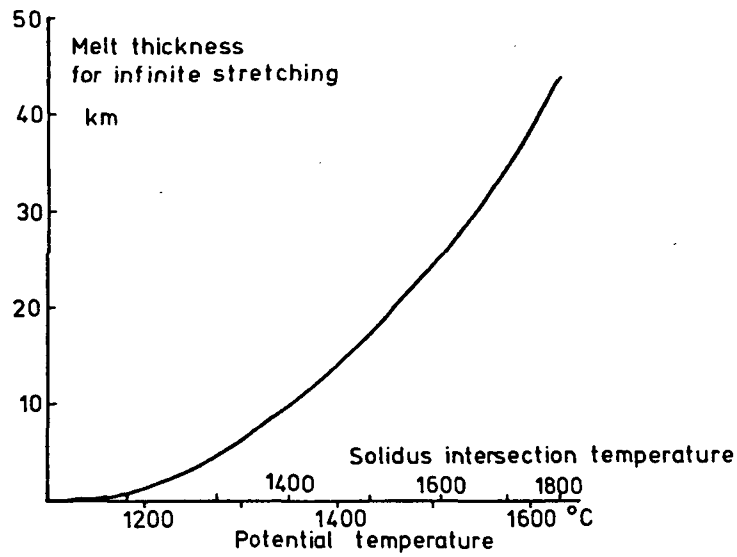

Figure 4. Melt thickness as a function of mantle temperature for infinite stretching (oceanic ridge case) after McKenzie & Bickle [23].

crustal extension which led to mantle upwelling would produce significant magma. It seems probable that the basalt dominated nature of both Archaean greenstone and late Archaean cratonic supracrustal sequences is a reflection of mantle temperature and not necessarily of a special tectonic setting. The extrusion of thick dense basaltic volcanics in supracrustal sequences may be an important factor in the development of the characteristic tectonic style of granite-greenstone terrains.

Archaean Tectonic Regimes

The prime assumption of all the global scale thermal models is that heat loss processes changed only in rate. One hotly debated point is whether plate tectonics or some alternative tectonic scheme operated during the Archaean. For example, Richter [1] has suggested that once convecting mantle penetrated the melt region below continental lithosphere the surface tectonic regime would be dominated by vertical recycling rather than horizontal motions. This scheme does not explain the preservation of the early Archaean crustal relicts for which some special survival mechanism must be proposed. Perhaps the best evidence for major horizontal (plate) motions lies in the linear tectonic belts characteristic of the larger Archaean terrains (Superior Province, Yilgarn Block) and the evidence for large scale overthrust nappe tectonics in the high-grade gneiss belts. Other geological evidence is open to interpretation. For example, the significance of the calc-alkaline-like granite suites, possible analogies between some greenstone belt mafic sequences and ophiolites and the tectonic state of greenstone belts (allochthonous or authochthonous) are all disputed. One additional line of evidence does strongly suggest division of the Archaean earth into continental and oceanic-type regions. The heat loss through the Archaean continental regions inferred from metamorphic thermal gradients is too low by an order of magnitude to be representative of heat loss from the Archaean earth [24,25]. The extra heat is plausibly lost through oceanic-like regions as is the case today. This would involve substantial melting and recycling of volcanic crust.

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