

Were Archean continental geothermal gradients much steeper than those of today?

ARCHEAN geothermal gradients have often been supposed to be much steeper than those of today^{1–6}. Because heat generation from the decay of radioactive nuclides in the Earth was then much greater^{4,7,8}, extra heat, if it escaped by conduction, must have been carried along steeper thermal gradients. Significant measurements of terrestrial conductive thermal gradients are very difficult to obtain, and estimates of thermal gradients in the past are even harder to make. Estimates made from igneous and metamorphic rock occurrences are of limited value both because igneous rocks occur at levels in the earth shallower by unknown amounts than those at which they form and because nearly all igneous and metamorphic rocks are formed at plate boundaries where thermal gradients are much steeper than within plates. In plate margin areas, advective and convective processes dominate so that the normal conductive gradient of the lithosphere can only be measured or estimated in areas away from plate boundaries. We show here that the rocks of the Superior Province (formed roughly in the interval 3,100–2,500 Myr ago) were not subjected to steep regional geothermal gradients after their assembly into a continent by lateral accretion of island arcs⁸, and hence that the extra Archean heat escaped the Earth in some way other than by conduction through the continent. We suggest that this escape was mainly by cooling of the ocean floor as a boundary conduction layer.

The Superior Province⁹ consists of greenstone belts, the rocks of which have been compared to rocks formed in various island arc and marginal basin environments⁸ and intervening gneiss belts that have been compared to more deeply eroded arcs or microcontinents⁸. Although the gneiss belts show great structural complexity and may include some high-grade metasediments granodioritic and tonalitic compositions greatly predominate. To a first approximation, the gneissic terrains can be regarded as of a granodiorite–tonalite average composition⁹. Wise has shown by considering the control on continental thickness exercised by the depth of water in the ocean¹⁰ that continents 2,500 Myr ago were about as thick as they are now. Seismic refraction measurements¹¹ in the Superior Province indicate a depth to the base of the crust of about 35 km.

Rocks of granodioritic composition subjected to pressures appropriate to a depth of 35 km (about 10 kbar) begin to melt at a temperature close to 700 °C leaving a dry and refractory residuum (see, for example, Fig. 1b in ref. 12).

The products of melting which would tend to rise buoyantly in the crust and thus to become exposed by erosion at the surface are typically granites of minimum-melting composition (roughly equal amounts of quartz, albite and potash feldspar). Such granites are abundant in many crystalline terrains, for example: the Grenville, Pan-African and Churchill provinces and have been compared to the acid volcanics of Tibet produced by partial melting of thickened continent¹³. Minimum-melting granites are extremely rare in the Superior Province, and we interpret this scarcity as an indication that the temperature 35 km down at the base of Superior Province crust in Archean time did not generally exceed 800 °C. We reject the idea that minimum-melting granites may have occurred at higher levels now eroded from above the Superior Province, because the preservation of low-grade assemblages in the greenstone belts of the province precludes deep burial and because of the limited occurrence of granulitic rocks in the province. As the temperature at the base of the continental crust today is commonly estimated¹⁴ to be about 500 °C, we conclude that in Archean times a typical continental geothermal gradient was less than 23 °C km⁻¹ compared with 17 °C km⁻¹ today. Because heat generation rates in the Earth between 2,500 Myr and 3,100 Myr ago may have been as much as three times greater than

at present⁷, the possible difference of 30% in the slope of the continental geotherm is insufficient to remove all the extra heat then being generated.

How might the extra heat have left the Earth? Consider how heat leaves the Earth's surface today, escaping from the solid earth in three ways which each account for roughly one-third of the total: by conduction through the continents; by conduction through the ocean floor and by making and ageing oceanic lithosphere as a boundary conduction layer to mantle convection. An accurate assessment of the proportions of heat removed by these three processes is not possible, but it is suggested (J. D. Sclater, personal communication) that one-third may be too low an estimate for making and ageing oceanic lithosphere. During the Archean, the two conduction processes could have accounted for more heat, as both the mantle and the overlying continental and oceanic crust would have contained more heat generating nuclides, but the evidence from the Superior Province (most other Archean terrains are similar) shows that increased conduction through the continents was not significant. Although conduction through the largely unpreserved Archean ocean floor may have been greater than at present, another way of removing very much more heat from the Earth is by making and cooling extra ocean floor. This could have been done by having a greater total length of ridge in the Archean ocean or by spreading and thus making ocean floor faster at ridges, or by both processes. Since the rate at which ocean floor cools decreases as a function of age, more heat is removed from the Earth if the average age at which the ocean floor is subducted is reduced. Ultramafic komatiites¹⁵, rocks that may represent a much larger proportion of partial melting of the mantle than normal basalts, are apparently almost restricted to the Archean and have sometimes been considered as evidence for very steep Archean thermal gradients³. These rocks occur as a small proportion of piles of basalts very similar to mid-ocean ridge basalts and we follow the suggestion¹⁶ that ultramafic komatiites are melts from great depths that have risen diapirically to the surface and escaped the near surface equilibration that is represented by basalt. We associate this process with the more intense convective circulation that we believe characterised the Archean rather than with a steep conductive oceanic thermal gradient.

Some have doubted whether plate-tectonic processes operated in the Archean, but the absence of granite from the Superior Province indicates that the great heat of the ancient Earth was not removed by conduction through continental crust. A convective process seems necessary to dissipate this heat and plate-tectonics is an efficient and familiar convective process capable of doing the job.

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