Calibrating a thermometer for Earth's interior over time

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New high-pressure, high-temperature experiments refine our ability to trace the thermal evolution of the Earth's interior using the geological record of intermittent, large-volume volcanic episodes.

There is no doubt that the Earth's interior is hot. After all, it produces volcanoes that erupt high-temperature lava. The modern geotherm (temperature versus depth in the Earth) is reasonably well constrained from geophysical data and compositions of young volcanic rocks. The potential temperature (how hot a parcel of mantle would be if decompressed adiabatically to atmospheric pressure without melting) is 1350 ± 50°C (1). Hotspots such as Hawai'i are up to ~200°C hotter, indicating that thermal plumes carry a fraction of mantle heat flow. Current mantle potential temperature is reasonably well known because fresh rocks are abundant on the surface and can be easily sampled (2) and melting models are calibrated against a large body of experimental evidence. Today, melting takes place at relatively low pressure (1 to 3 GPa) and depth (<100 km); techniques to access these conditions were developed nearly 50 years ago.

What about the evolution of the geotherm over time, though? How hot was the Earth in the past, and what physical processes govern its cooling (assuming it has cooled)? These are harder questions, with less settled answers. Geophysical data do not extend into deep time. The volcanic rock record is our best source of data, but its interpretation has been entangled in ambiguity (3–5). Ancient rocks are scarce, typically altered, and only available for certain time periods. We are not certain whether they indicate temperatures of ambient mantle or of local hot upwellings. Moreover, experiments to calibrate the melting conditions in a hotter Earth, at much greater pressure (up to 25 GPa), are extremely challenging. The multi-anvil device is the tool of choice for these conditions, but it has taken longer for the devilish details of experimental technique to reach

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the level of accuracy, precision, and consistency needed. There have been issues with pressure calibration, criteria for melting, temperature gradients across the sample, and analysis of recovered products.

In this issue, Pierru *et al.* (6) describe a comprehensive set of new experiments, combining several novel methods to define the pressure-temperature locus of deep mantle partial melting and the melt compositions. Key innovations include careful modeling of temperature gradients and three in situ characterization methods for partial melting. Electrical conductivity is sensitive to the onset of melting (the solidus). X-ray diffraction yields accurate pressure and shows the appearance of liquid diffuse scattering of x-rays at the solidus and the disappearance (or, on cooling, reappearance) of crystalline diffraction peaks at the liquidus (the temperature above which all is liquid). X-ray contrast imaging monitors the position of a small rhenium sphere placed atop the sample. In the solid state and up to a critical melt fraction (about 40%), the sphere stays put. Then, the sphere begins to fall slowly and chaotically as it bounces off crystals. Last, near the liquidus, it rapidly falls straight down. The results of these in situ techniques are remarkably consistent with melt fractions determined by microscopic examination of quenched samples. The new melt fraction and liquid composition data yield a coherent perspective on the conditions where several distinctive lava types can be generated. The onset of deep mantle melting is 100 to 200 K colder than most previous studies. These data are combined with novel perspectives on mantle thermal evolution to define an overall theory for the origin and significance of these lavas, known as komatiites.

Komatiites are divided into aluminum-depleted komatiites, which are all older than 2.8 Ga (billion years ago); aluminum-undepleted komatiites, which persisted until

about 1.9 Ga; and aluminum-enriched komatiites, which are as young as 90 million years old. This time evolution has anchored most empirical estimates of Earth's secular cooling (3). The new experiments suggest particular pressures, temperatures, and extents of partial melting where melting of an assumed upper mantle composition yields liquids with features similar to each class of komatiites. The results are broadly consistent with most previous inferences but offset toward higher pressure and lower temperature and notably better constrained.

The connection to the thermal evolution of the mantle comes from asking how sufficient volumes of hot mantle might be found at the melting depth, given the dynamics of heat transport through the mantle. Mantle heat flow is dominated by thermal convection, the vertical transport of heat by differential motion of hot (buoyant) and cold (dense) material. Given enough time, convecting systems evolve to nearly adiabatic stable average thermal profiles, except in thin boundary layers (7). The adiabatic gradient defines neutral stability because rapidly displaced material will match the temperature of its surroundings and so be neutrally buoyant. A superadiabatic temperature gradient (temperature increases more rapidly with depth) is unstable, whereas a subadiabatic gradient (temperature increases more slowly with depth) leads to stable stratification (like the stratosphere, where temperature decreases with altitude). So it is conventional to assume that the mantle geotherm is adiabatic and has been so throughout Earth history (8) and that melting requires either spreading of the lithosphere, introduction of flux (by subduction), or nucleation of local plumes by instability in the hot lower boundary layer. Komatiite temperatures have therefore been interpreted either as isolated hot plumes from the core-mantle boundary layer (implying

Fig. 1. A komatiite outcrop in Ontario, Canada. The distinctive "spinifex" texture of long, blade-shaped olivine crystals is characteristic of very high-temperature lavas. This flow was emplaced about 2.7 billion years ago. Experiments reported by Pierru *et al.* (*6*) in this issue locate depth, temperature, and extent of melting conditions where the parental magma of such lavas might originate. Photo from Wikimedia Commons. https://creativecommons.org/licenses/by/2.0/legalcode

small volumes) or as ambient mantle (implying that these magmas formed ubiquitously). Pierru *et al.* argue that komatiites and large igneous provinces are voluminous but not ubiquitous and seek a mechanism to generate large upwellings of hot mantle.

But has the mantle been nearly adiabatic through most of Earth history? This idea is challenged by a recent model (*9*) that presumes that initial conditions were determined by a whole-mantle magma ocean after the moon-forming giant impact (*10*). Rapid freezing (a few million years) of the magma ocean and the rheological contrast between liquid, mushy, and solid states yields a highly superadiabatic profile roughly parallel to the solidus, trapping excess thermal energy in the deep mantle. A one-dimensional parameterized convection model tracks the evolution from this unstable superadiabatic state forward in time. Given some rheological assumptions, the superadiabatic instability is (unexpectedly) eliminated very slowly, over billions of years. Hence, large-volume instabilities that become much hotter than their surroundings as they rise adiabatically persist long enough to make the various komatiites (Fig. 1), although such instabilities contribute to removing the excess energy that drives them.

This paradigm is provocative and needs further investigation. The convection model is idealized and may not apply well to present conditions. Three-dimensional convection can behave in ways that one dimension cannot capture. The rheology of partial melts is complex and scale dependent; alternative parameterizations must be examined. While the experiments are a remarkable accomplishment, they investigate only a particular model mantle composition and the match to natural lavas neglects the effects of segregation of partial melts from their residues and changes during transport to the surface.

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