Mantle Melting at High Pressure

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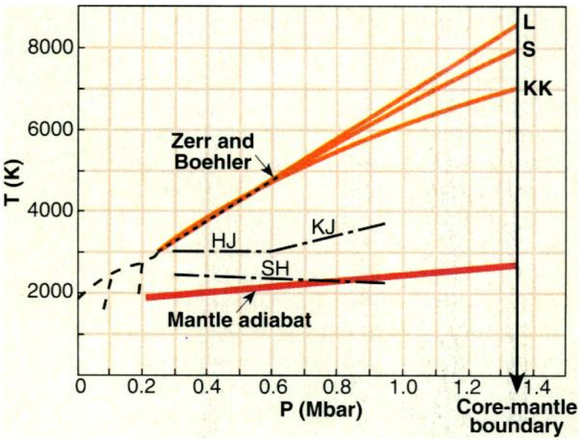
"You can understand physicists' reasoning perfectly if you put your mind to it" (*1*). With this arrogant statement Lord Kelvin chastised a geologist who claimed difficulty in understanding the arguments for a short span of Earth history (less than 100 million years). Kelvin fully admitted that his model for the rapid evolution of Earth depended critically on the pressure and temperature behavior of thermodynamic properties such as specific heat, thermal conductivity, and melting. However, even with wide uncertainties in physical properties "of which we are wholly ignorant," Kelvin felt his estimates were robust bounds for the age of Earth. Although Kelvin's error lay more in his incorrect assumptions that heat is transported within Earth by conduction and that no internal sources contribute to Earth's energy budget, accurate knowledge of materials properties is vital to our understanding of Earth's interior. On page 553 of this issue, Zerr and Boehler present the most recent effort to measure one such property—melting at high pressure (*2*).

The interplay between Earth properties and dynamic theories remains a feature of attempts to understand our planet's interior. However, our view of mantle dynamics has changed substantially since Kelvin's time. In the modern perspective, mantle convection (driven both by radiogenic heat production and secular cooling) is regulated by temperature-dependent viscosity in a solid but ductile mantle (*3*). Heat in the mantle is carried primarily by mass transport. High temperatures at depth decrease viscosity, which speeds convection, leading to more rapid cooling. Cooling in turn increases viscosity, which leads to a retardation of heat transport and concomitant temperature increase. This self-regulation of mantle dynamics may cause a rich spectrum of time-dependent tectonics at Earth's surface. Mantle plumes and changes in plate motions could all be associated with the non–steady-state regulation of Earth's internal temperature.

At high temperatures, solids with deformation controlled by diffusional processes have viscosities that typically scale with melting temperature. The homologous temperature, a ratio of temperature to melting temperature, is therefore conventionally assumed to be a key parameter in Earth dynamics. High homologous temperatures (>0.8) imply ductile, low-viscosity behavior, whereas homologous temperatures below 0.5 are associated with high-viscosity and even brittle behavior. Earthquakes cease in the subducting plate at a depth where the homologous temperature exceeds 0.4 (*4*). Thus, determinations of melting temperatures of minerals at high pressure are thought to hold clues for the rheological behavior of the mantle at depth.

With measurements in diamond anvil cells that now span much of the pressure and temperature range of the mantle and core, Kelvin's shroud of ignorance of the physical properties of materials under deep-Earth conditions is being lifted. Previous work has demonstrated that silicate perovskites are likely to be the dominant mineral phase in the mantle below the seismic discontinuity at 670 km (24-GPa pressure) (*5*). Zerr and Boehler (*2*) of the Max Planck Institute in Mainz, Germany, report the melting temperature of silicate perovskites to a pressure of 63 GPa (corresponding to a depth of 1500 km). They modestly extrapolate their result to the core-mantle boundary pressure of 130 GPa. This new work appears technically superior to previous high-pressure melting experiments in several important ways. Zerr and Boehler isolated a crystal of perovskite in a "clean" environment (the pure argon in which the sample was pressurized). They heated the crystal with a large-diameter CO_2 laser beam (thus minimizing radial temperature gradients). They made temperature measurements over small areas. Their pressure measurements were on unheated ruby chips at the same pressure as the hot sample. Melting was directly observed (textural changes in the crystal). Previous workers (*6–8*) used powder samples with no pressure medium (so the stress gradient may have been large), heated with lasers having significantly smaller spot sizes, determined temperatures more indirectly on the basis of a correction from a measured "average" temperature to a calculated peak temperature, and inferred melting on the basis of less direct criteria.

Several striking features of the results of melting determinations (see figure) shown along with a hypothetical geotherm, merit discussion. All melting measurements converge to similar temperatures at the (multi-anvil determined) triple point between liquid, majorite, and perovskite phases near 22 GPa (*9,10*). A change in melting slope apparent in the work of Heinz and Jeanloz (*6*) combined with measurements of Knittle and Jeanloz (*7*) suggest a further triple point near 60 GPa. However, no data from the solid phase support this supposition. Indeed, Sweeney and Heinz (*8*) at Chicago, in their extension of Heinz's earlier Berkeley work, found no change in slope at 60 GPa. The Chicago melting curve is nearly 1000 K lower than the Berkeley data at 90 GPa. The Zerr and Boehler data appear to match the multi-anvil trend and extend to high pressure with a surprisingly large pressure dependence for melting. At 63 GPa, their melting temperature is 2000 K higher than the Berkeley data.



Melting under pressure. A comparison of melting temperatures versus pressure for the range of conditions found in the lower mantle. Orange lines show fits of Zerr and Boehler's data (short dashed line) to melting relations of Lindemann, Simon, and Kraut-Kennedy [see references in (*2*)]. Long dashed lines show data near and below the triple points (*9, 10*). HJ, SH, and KJ denote the results of earlier work (*6–8*). The red line is the hypothetical geotherm. [Adapted from (*2*)]

The difference in the high-pressure melting temperatures between these various efforts is too large to reconcile with either pressure or temperature calibration problems. It is more likely that one or more laboratories have not measured equilibrium melting of "pure" perovskite; one can endlessly speculate about the various ways in which these difficult experiments could lead to incorrect results. All laboratories are studying minute samples: The mass melted ranges from nanograms to a small fraction of a microgram. Contamination and recrystallization not associated with melting could cause systematic problems. Both the Berkeley and Mainz groups have also investigated the melting of iron, the

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dominant core constituent. For that material, the Berkeley and Mainz data are in partial agreement to 60 GPa but diverge at higher pressure. For iron, the Berkeley data (*11*) give a very high melting temperature, whereas the Mainz data (*12*) suggest only a modest increase in melting temperature with pressure. Thus, melting is not always measured at lower temperatures in Mainz, and differences between the laboratories are not systematically in the same direction.

Zerr and Boehler's data imply a dramatic decrease in the homologous temperature in the lower mantle. Indeed, if they are right, one could ask whether earthquakes might occur in the deep mantle. None has yet been observed. As noted by the authors, high melting temperatures for perovskite would preclude large-scale melting and chemical differentiation in the lower mantle and would allow very high temperature gradients near the core-mantle boundary. On the other hand, the Sweeney and Heinz data (*8*) suggest that the homologous temperature of the lower mantle approaches or exceeds 1. Such a high value also seems at odds with conventional wisdom for the dynamics of the lower mantle. Geophysical determinations (*3*) give lower mantle viscosities 30 times higher than the viscosities in the upper mantle.

In his incorrect estimates for Earth's age, Kelvin took bounds for the melting of the mantle between 1300 and 4300 K—a range nearly as wide as results of all recent experimental data discussed here. Our ability to accept a greater age for the Earth has not been based on a refinement of measured melting temperatures but rather is based on a change in the theoretical framework of interpretation. A lesson can be drawn from Kelvin's overconfidence. It is quite conceivable that some important bit of physics has been overlooked in one or more of the recent high-pressure experiments. Despite best intentions, melting may not have been accurately determined. But more importantly, efforts to understand dynamics in the mantle are probably as limited by inadequate theory as by possibly inaccurate experiments. If either Zerr and Boehler or (on the opposite extreme) Sweeney and Heinz are right, one or more of our current working concepts may require modification. Homologous temperature or conventional views of deep-mantle convection may not be correct theoretical concepts. Both improved experiments (as exemplified by the work of Zerr and Boehler) and better theories are needed to improve our understanding. A consensus on high-pressure melting may require further efforts to replicate these very difficult experiments.

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The Future of DNA Sequencing

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The demand for improved DNA sequencing methodologies posed by the Human Genome Project has spurred the development of both conventional and unconventional approaches (*1*). The conventional approaches employ the same strategy as the method developed by Sanger and co-workers in the mid-1970s; nested sets of DNA fragments are produced by enzymatic termination reactions and are separated by size with denaturing polyacrylamide gel electrophoresis. The overall sequencing process with this strategy is complex and multifaceted. For high-volume use, every aspect must be streamlined and automated, and the individual steps need to be integrated to provide a seamless whole. Solution of these problems comprises much of the sequencing technology development supported by the Human Genome Project, and the resultant systems for large-scale sequence analysis are the most likely near-term candidates for performance of the sequencing.

The majority of the large-scale sequencing being done today employs a random selection (shotgun) strategy and fluorescence-based automated sequencing instruments. Large-scale sequencing is approaching a throughput of 1 megabase (Mb) per year of finished sequence at a cost in the vicinity of a dollar per base (*2*). A further four- to fivefold drop in cost will bring the price into a range commensurate with the budget and goals of the Human Genome Project. The shortfall in throughput capability is more serious: An aggregate capability of sequencing at least 500 Mb per year is needed by the year 2000 for the minimal three billion bases of the genome to be in hand by 2006, the nominal target date for the project. This is at least two orders of magnitude from our present ability.

Two recent developments have the potential to significantly increase the throughput of electrophoresis-based sequencing instruments: ultrathin gel electrophoresis and replaceable "gels." Performing electrophoresis in ultrathin (50 μm) gels increases heat transfer efficiency; this in turn permits higher electric fields to be applied without deleterious thermal effects. The higher electric fields give correspondingly more rapid separations; an increase in separation speed of about an order of magnitude is readily achieved. This gain is not achieved without cost, however. Spacing between the DNA fragments decreases at higher electric field strengths, potentially decreasing resolution and read length (*3*). Nonetheless, in a properly designed system greatly increased separation speeds, and hence throughput, may be obtained. Work is in progress on such systems, both with arrays of capillaries (*4*) and ultrathin slabs (*5*).

The significant increases in speed now attainable in gel electrophoresis highlights another limitation of today's sequencing systems: gel preparation. The cross-linked polyacrylamide gels used in sequencing are not generally reusable nor are they amenable to commercial production due to their chemical instability. Thus the burden of gel preparation continues to rest with the user. This requires significant labor as well as being an undesirable source of irreproducibility in the sequencing process. An electrophoretic system requiring only an hour for the separation would require twenty-four gels for continuous around-the-clock operation. Either manual gel replacement or a cumbersome automated system would be needed, both undesirable features. A possible alternative solution is DNA separation in entangled polymer networks (*6*). These are aqueous solutions of hydrophilic polymers, typically linear polyacrylamide or modified celluloses. The polymer solutions form interpenetrating networks similar to those of cross-linked polyacrylamide gels and permit comparable sieving type separations.

The big advantage is that these non-

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