The high-pressure dimension in earth and planetary science

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By far the bulk of our planet is hidden from view, within the earth, under high pressures and temperatures. The behavior of this material dictates the formation, evolution, and present state of the solid earth. Recent geophysical and geochemical studies of the planet present us with a rich array of large-scale processes and phenomena that are not fully understood. These range from the fate of deeply subducted slabs and the origin of plumes, to the nature of the core–mantle boundary; the differentiation of materials to form the present-day crust, mantle, and core; the distribution of trace elements; and the uptake and recycling of volatiles throughout earth's history.

Addressing these questions experimentally has a long history (1), but it is only recently that the entire range of pressures that prevail within the earth could be produced in the laboratory and the materials probed with the necessary tools (Fig. 1). Experiments have demonstrated that, under these extreme conditions, the physical and chemical behavior of materials can be profoundly altered, causing new and unforeseen reactions and giving rise to structural, elastic, electronic, and magnetic transitions not observed in rocks and minerals in the near-surface environment. Resolving the new issues that have arisen requires an integrated approach involving subfields that include seismology, geochemistry, petrology, and geodynamics, as well as theoretical and experimental high-pressure mineral sciences. The collection of feature articles that follows, which were presented at a recent symposium,[†] highlights an array of new developments in high-pressure geoscience.

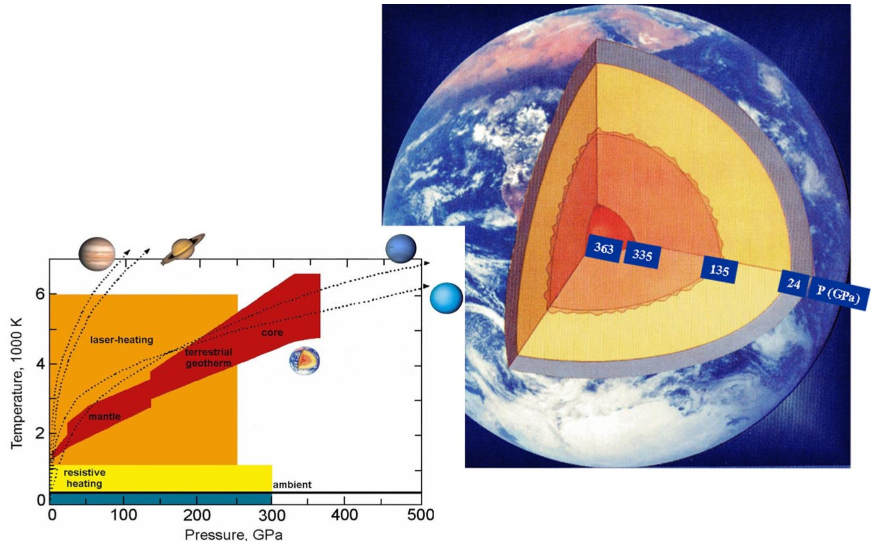

Fig. 1. Range of pressures and temperatures now accessible with static compression techniques in the laboratory. (*Left*) Graphical representation of accessible pressures and temperatures, specifically, those attainable with diamond anvil cell methods, which are used to generate the most extreme conditions. The fields include so-called resistive-heating and laser-heating methods, as described in articles in this issue. Estimated variations in pressure and temperature with depth in various planets are indicated. (*Right*) Cutaway of the earth's interior, showing the pressures at the various boundaries within the planet (i.e., upper and lower mantle, core–mantle boundary, and inner–outer core).

In ultrahigh-pressure metamorphic rocks, solid and fluid inclusions in phenocrysts contain rich information on deep-mantle processes. The structure, texture, strain, chemistry, and exsolution of these micrometer- to nanometer-sized inclusions indicate the formation environment of these rocks and contain rich information about the relevant physical and chemical processes. Diamonds, coesite, and new minerals have been discovered as micro–nano inclusions, in concert with *in situ* high pressure–temperature (*P–T*) experiments that define the conditions of formation. The emerging field of micro-to-nano mineralogy may take center stage in the geosciences with new enabling microanalytical techniques, including synchrotron x-ray nanoprobes, synchrotron infrared probes, electron microscopy, focused ion beam methods, and nanosecondary ion microscopy for analyzing experimental and natural specimens.

"Ultrahigh pressure," in the context of metamorphism, refers to the previously unexpectedly high pressure signature in recovered rocks on the earth's surface. However, at greater depths in the mantle the pressure is much higher, but no samples are available. Instead, studies must be conducted *in situ* by seismology and other geophysical observations, and the results must be compared with mineral data obtained either in the laboratory or from computational theory. There is growing evidence for lateral variations in temperature and hydration in the upper mantle, gained from using long-period seismic waveforms together with new, physically constrained inversion methods. In addition, systematic ultrasonic measurements of mantle minerals as a function of pressure and temperature are providing crucial wave velocity information for comparison. The origin of the paradoxical deep-focus earthquake is examined from the standpoint of the experimental findings of shear instability induced by phase transitions and dehydration.

Deeper in the mantle, many long-standing seismic anomalies in the D″ layer immediately above the core–mantle boundary can now be understood with the discovery of $MgSiO_3$ post-perovskite at pressures >100 GPa (2). The post-perovskite phase provides new insight for modeling the metastable superplume recently inferred from seismology and for understanding the topology of the top of the D″ layer by using three-dimensional simulations of mantle convection. The earth's core plays a cen-

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tral role in the evolution and dynamic processes within the planet; however, the origin of some of its most fundamental properties, for example, the temperature, chemical composition, mineral phases, elasticity, magnetism, and formation of the core, remains elusive. Indeed, new study of earth's core is uniting observational, theoretical, and experimental geophysics, thereby enriching each discipline through interactions and feedback. For instance, geophysical observations are uncovering surprising inner-core properties such as seismic anisotropy, layering, and superrotation. Studies of candidate component materials of the core include first-principles calculations and direct experiments on iron and its alloys. High energy-resolution, nuclear-resonant x-ray spectroscopy provides information on magnetism, as well as on the phonon density of states, bulk longitudinal and shear wave velocities, and thermodynamic properties (3).

Laboratory techniques continue to be developed. It should be possible to produce a very broad range of *P–T* conditions by using laser shocks in precompressed samples. These developments have the potential to provide information essential for addressing numerous questions concerning extrasolar planets, including proposed "super earths." Mechanically pulsing the load of a diamond cell bridges the time domain between conventional dynamic and static compression conditions. Pressure calibration is improving with advances in high *P–T* x-ray techniques. New methodologies are being developed for calorimetry and determination of thermal diffusivity: two challenging measurements on small high-pressure samples. This integrated approach, using a diversity of experimental, observational, and simulation methods, is providing a new window on planetary interiors. Fully exploiting the pressure variable promises to add a new dimension to scientific exploration of a broad range of other fields, to be highlighted in subsequent PNAS Special Features.

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