INVITED CENTENNIAL REVIEW
High-pressure minerals

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ABSTRACT

This article is dedicated to the occurrence, relevance, and structure of minerals whose formation involves high pressure. This includes minerals that occur in the interior of the Earth as well as minerals that are found in shock-metamorphized meteorites and terrestrial impactites. I discuss the chemical and physical reasons that render the definition of high-pressure minerals meaningful, in distinction from minerals that occur under surface-near conditions on Earth or at high temperatures in space or on Earth.

Pressure-induced structural transformations in rock-forming minerals define the basic divisions of Earth’s mantle in the upper mantle, transition zone, and lower mantle. Moreover, the solubility of minor chemical components in these minerals and the occurrence of accessory phases are influential in mixing and segregating chemical elements in Earth as an evolving planet. Brief descriptions of the currently known high-pressure minerals are presented. Over the past 10 years more high-pressure minerals have been discovered than during the previous 50 years, based on the list of minerals accepted by the IMA. The previously unexpected richness in distinct high-pressure mineral species allows for assessment of differentiation processes in the deep Earth.

Keywords: High pressure, deep Earth, crystallography, mineral physics

INTRODUCTION
General aspects of compression of matter over large pressure ranges

The pressure in Earth ranges from atmospheric to 136 GPa at the core-mantle boundary, and further, to 360 GPa in the center of the Earth (Dziewonski and Anderson 1981). These gravitationally generated pressures are not high on a general scale of planetary or stellar objects, where gravitational energy balances, or overcomes, the electronic binding energy in atomic matter such as in the interior of giant planets or in the interior of sun-like stars or beyond (Hund 1936; Landau and Lifshitz 1980). Thus, even in the deepest parts of Earth, matter is well within the range of chemical bonding between discrete atoms rather than that of dense or degenerate plasma. However, in Earth the pressures are high enough to modify the chemical behavior of elements and thereby the compounds that they form and the crystalline or liquid structures that these compounds assume. Roughly, the difference of 100 GPa between Earth’s surface and the bottom of the lower mantle corresponds to an increase in energy of ~1 eV/e−. This approximate value may be obtained by relating the average contraction of the volume of a valence electron in rock-forming minerals over a pressure-interval of 100 GPa to energy through the Mie-Grüneisen equation (Bukowsinski 1994). This increase in energy is equivalent to a temperature of the order 10 000 K. However, the temperature at the inner core-outter core boundary is less than 6000 K (Boehler 1993; Shen et al. 1998; Anzellini et al. 2013; Zhang et al. 2016) and less than 3000 K in the mantle (Brown and Shankland 1981; Korenaga 2008). Hence, in Earth’s deep mantle the effect of pressure on the properties of matter dominates over the effect of temperature.

The general effect of pressure on chemical bonding is a consequence of the nature of electrons as fermions: The Pauli exclusion principle restricts the occupancy of an electronic state to two electrons with up and down spin. In consequence, increasing pressure induces an increase in electron kinetic energy with a power 2/3, whereas their binding potential energy increases with power 1/3 (Landau and Lifshitz 1980). Hence, at sufficiently high pressure, the kinetic energy causes electrons to be released from their bond states resulting in an electron fermion plasma that is spatially confined by the Coulomb attraction through the nuclei (Hund 1936; Landau and Lifshitz 1980). These processes occur at pressures beyond the pressure range within Earth. However, the approximate scale of the pressure-induced increase in electron energy in Earth has observable effects on the chemical behavior of elements because it is of a magnitude comparable to energy differences between valence electronic states in solids, which are of the order 1 eV. This distinguishes Earth from smaller planets like Mercury and Mars. The increase of kinetic energy of the electrons is observable as shifting and broadening of their energy states. Within this context, the local density of the different orbital states is relevant: d- and f-electrons exhibit pressure-induced shifting and broadening at lower pressures than s- and p-electrons (Duthie and Pettifor 1977; Nellis et al. 1988; Holzapfel 1995). Eventually, these states overlap with other electronic states and thereby reconfiguration of bonding and antibonding states with...