2.7. High-pressure devices

A. Katrusiak

2.7.1. Introduction

Although life in the biosphere of Earth exists within narrow limits of temperature and pressure, these thermodynamic conditions are unusual *on* Earth and in the Universe. Most of the matter in the Universe is contained in black holes, stars and planets, where it is exposed to extreme temperature and pressure. On the other hand, interstellar space constitutes most of the Universe's volume, where both pressure and temperature are close to their absolute-zero values. On Earth's surface at sea level, atmospheric pressure is about 1000 hPa [1 atm = kG cm^{-2} = 9.807×10^4 Pa $\simeq$ 0.1 MPa; currently, the pascal (abbreviated Pa) is the generally accepted pressure unit recommended by the International System of Units]. Under water on Earth, the pressure increases by 0.1 MPa for every 10 m depth, and rises to 120 MPa at the bottom of the Mariana Trench, 11 km below the sea's surface. A relatively low pressure change, to about 0.3 MPa at a depth of 20 m, affects the dissolution of nitrogen in human blood and can lead to decompression sickness (caisson disease); at 300 m in the oceans (3 MPa) and 288 K, methane forms stable hydrates, which constitute the most abundant deposits of carbon on Earth. All geological deposits are exposed to some pressure; at a depth of 1000 m this is about 300 MPa. Consequently, the structure and properties of very many minerals, formed and deposited in the crust, can transform considerably after their exposure to the surface. The syntheses of numerous minerals require high-pressure conditions. Thus, high-pressure experiments can provide indispensable information about the geological and stellar mechanisms, transformations and properties governing the matter forms, properties and distribution inside stars and planets.

Therefore, the pressure dependence of crystal structures is of primary interest to geologists, planetologists and astrophysicists (Hazen, 1999; Merlini *et al.*, 2012). The most cited examples of the effects of extreme conditions are thermonuclear synthesis, the formation of diamond (the dielectric carbon allotrope), the formation of stishovite (the dense form of SiO_2) and the propagation of seismic waves through the Earth's crust. The understanding of these and other phenomena requires that extreme conditions be reproduced and crystal structures investigated in laboratories. Most importantly, the conditions that are ubiquitous across the Universe are viewed as extreme only from our perspective of a narrow thermodynamic space, of a few tens of kelvin and a few megapascals around the triple point of water. From this narrow thermodynamic space, most of our knowledge of materials science has been developed. Extreme conditions allow theories to be verified and developed to a more general level. Moreover, extreme conditions can be utilized to produce new materials with desired properties (Hanfland *et al.*, 2011; Senyshyn *et al.*, 2009), including diamond or its other super-hard substitutes, or new forms of pharmaceutical drugs (Boldyreva, 2010; Boldyreva *et al.*, 2002, 2006; Fabbiani, 2010; Fabbiani & Pulham, 2006; Fabbiani *et al.*, 2004, 2005, 2009). The key element for such research is a sample-environment device for generating high pressure in the laboratory.

The pressure at the centre of Earth is about 364 GPa, one order of magnitude higher again inside the giant planets Jupiter and Saturn, and over 1 000 000 GPa (*i.e.* 1000 TPa) inside small stars like the Sun. Structural determinations under varied thermodynamic conditions are essential for the general understanding of physical and chemical phenomena, and to gain knowledge about the properties of materials and to describe the world around us. Indeed, the biosphere where we live is confined to a range from 0.33 atm (0.033 MPa) at the top of Chomolungma (Mt Everest), 8848 m above sea level, to about 1200 atm (120 MPa). The most commonly discussed and studied thermodynamic parameters are temperature (T), pressure (P) and composition (X). In principle, they affect the structure of matter differently. For example, the primary change induced by temperature is in the energy of atomic, molecular and lattice vibrations, whereas increasing pressure always reduces the volume. These changes are interdependent, and the compression of a structure can also reduce its thermal vibrations, change the types of cohesion forces and reverse the balance between competing compounds of different composition. This concerns all compounds, not only minerals deep under the Earth's surface. An exciting example of a molecular compound undergoing such transformations is water, transforming between at least ten polymorphic structures at high pressure, and also forming hydrates, depending on the thermodynamic conditions. Hence, pressure is now utilized to generate new polymorphs and solvates that cannot be obtained under normal conditions (Patyk *et al.*, 2012; Tomkowiak *et al.*, 2013; Fabbiani, 2010; Boldyreva, 2010).

For these reasons, high-pressure techniques have been developed dynamically, and the breakthrough invention of the diamond-anvil cell and its development in the second half of the 20th century greatly intensified high-pressure research. Today, the effects of high pressure on various materials and their reactions are studied both in small laboratories in universities and at large facilities, which provide powerful beams of X-rays from synchrotrons and beams of neutrons from reactors and spallation targets. The large facilities are either international initiatives, like the European Synchrotron Radiation Facility (ESRF) and Institute Laue–Langevin (ILL) in Grenoble, France, or national ones, like the Diamond Light Source and ISIS at the Rutherford Appleton Laboratory in Oxfordshire, UK, the Deutsches Elektronen Synchrotron (DESY) in Hamburg, Germany, the Photon Factory in Tsukuba, SPring-8 (Super Photon ring – 8 GeV) in Hyōgo Prefecture and the Japan Proton Accelerator Research Complex (J-PARC) in Tokal near Tokyo, Japan, the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory, USA, the Advanced Photon Source (APS) at Argonne National Laboratory and Los Alamos National Laboratory (LANL), New Mexico, USA, the Lawrence Livermore National Laboratory, California, USA, the Joint Institute for Nuclear Research (JINR) in Dubna, Russian Federation, the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory, USA, and others. They provide access to the beams and high-pressure equipment to the general scientific community.

2.7.2. Historical perspective

The earliest concepts of pressure are often associated with Evangelista Torricelli's famous statement '*Noi viviamo sommersi nel fondo d'un pelago d'aria*' ('We live submerged at the bottom

  references