Hardness, toughness, and modulus of some common metamorphic minerals

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ABSTRACT

Studies of the hardness and toughness of minerals have historically focused on minerals of the Mohs scale, although, with the exceptions of quartz, orthoclase, and calcite, Mohs phases are not common rock-forming minerals. We report new hardness (H), toughness (resistance to fracture, KIC), and indentation modulus (E*) data obtained by microhardness and depth-sensing indentation (DSI, or nanoindentation) experiments for common metamorphic minerals: sillimanite, kyanite, andalusite, garnet, quartz, and orthoclase feldspar. Because the experimental techniques involve indentation-induced cracking as well as depth-sensing indentation, the new data set can be used to investigate a range of plastic behavior for minerals in the crust and mantle.

The three Al2SiO5 polymorphs have similar H values (~10–12 GPa): kyanite has the largest values and andalusite the smallest. These values are similar to that of quartz (~12 GPa) and greater than that of orthoclase (~7 GPa). Garnet H values vary with composition: for grossular, H ~ 13 GPa, and for almandine-pyrope, H ~ 15 GPa. Although H values for the minerals we analyzed span a range of ~10 GPa, most fracture toughness values are between 1–1.8 MPa·m½. Garnet is much harder than Al2SiO5, but has a similar to slightly lower KIC (grossular ~1.2 MPa·m½; almandine-pyrope ~1.4 MPa·m½; andalusite 1.8 MPa·m½; sillimanite 1.6 MPa·m½); kyanite KIC is difficult to measure owing to the ease with which kyanite cleaves. Garnet has properties similar to those of cubic zirconia (ZrO2), which we measured as a reference. Another reference mineral, periclase (MgO), has the lowest H (~5 GPa) and the highest KIC (~4 MPa·m½) of minerals we measured. Among the silicates, E* varies significantly from orthoclase (~89 GPa) to quartz (~117 GPa) to garnet (245–260 GPa), and Al2SiO5 has intermediate values: kyanite ~186–253 GPa, sillimanite ~207 GPa, andalusite ~232 GPa.

Keywords: Fracture toughness, hardness, indentation, metamorphic minerals, modulus, mechanical properties, garnet, quartz, Al2SiO5

PHYSICAL PROPERTIES OF METAMORPHIC MINERALS

Mineral properties such as hardness, resistance to fracture, and elastic modulus can be used to understand the brittle and ductile behavior of metamorphic rocks during deformation. Although much attention has focused on the physical properties of rheologically significant minerals such as quartz, feldspars, and calcite, much less is known about the mechanical properties of important metamorphic phases such as the Al2SiO5 polymorphs, which are widely used for evaluating pressure-temperature (P-T) conditions of metamorphism. Our study was motivated in part by the need for a systematic physical properties data set that can be used to model geological phenomena, such as the brittle fracture of minerals during decompression in the crust or mantle (e.g., garnet: Whitney et al. 2000) or during earthquake-generating faulting at or near the Earth’s surface (quartz: Goldsby et al. 2004). In addition, physical properties are relevant for interpreting seismic velocity data and for calculating lattice strain associated with ionic substitution and trace-element partitioning in solid-solution phases (e.g., garnet: van Westrenen et al. 1999). All of our data were collected at room temperature, so are not directly applicable to the deformation of minerals during metamorphism, but nevertheless represent a fundamental data set that is a starting point for understanding the material properties of important metamorphic phases.

SAMPLES AND METHODS

We determined hardness, toughness, and modulus for the three Al2SiO5 polymorphs (andalusite, kyanite, sillimanite), two garnet compositions (Ca-rich and Fe-Mg-rich), quartz, orthoclase, cubic zirconia (ZrO2), and periclase (MgO). With the exception of the cubic zirconia and periclase samples, which were synthetic, all samples were natural minerals from rocks, and the garnets, andalusite, and sillimanite were gem-quality. The periclase was polycrystalline MgO, with an average grain size of 10 μm, and represents the same material used by Cook and Liniger (1992). All other samples were single crystals. Our characterization of these minerals included their composition, crystal system, indentation plane (if known), hardness determined by two methods—microindentation and depth-sensing indentation (DSI, or nanoindentation)—toughness, and indentation modulus (Table 1). All samples were analyzed on highly polished surfaces obtained by polishing with fine diamond or alumina suspensions (0.2–0.3 μm).

For microindentation experiments, we used a Vickers square-pyramid diamond probe, and for DSI, we used a Berkovich triangular-pyramid diamond probe. For most minerals, the indented plane in our experiments was a cleavage plane or crystal face. For highly anisotropic minerals such as kyanite, we indented different planes to capture the range of hardness values. Details of the experimental technique and