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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, K_{IC}), 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 Al_2SiO_5 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·m$^{1/2}$. Garnet is much harder than Al_2SiO_5, but has a similar to slightly lower K_{IC} (grossular ~1.2 MPa·m$^{1/2}$; almandine-pyrope ~1.4 MPa·m$^{1/2}$; andalusite 1.8 MPa·m$^{1/2}$; sillimanite 1.6 MPa·m$^{1/2}$); kyanite K_{IC} is difficult to measure owing to the ease with which kyanite cleaves. Garnet has properties similar to those of cubic zirconia (ZrO_2), which we measured as a reference. Another reference mineral, periclase (MgO), has the lowest H (~5 GPa) and the highest K_{IC} (~4 MPa·m$^{1/2}$) of minerals we measured. Among the silicates, E^* varies significantly from orthoclase (~89 GPa) to quartz (~117 GPa) to garnet (245–260 GPa), and Al_2SiO_5 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, Al_2SiO_5