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Fatigue properties for the fracture strength of columnar accessory minerals embedded within metamorphic tectonites: implications for stress magnitude in continental crust at the depth of the brittle–plastic transition zone

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1. Introduction

Previous studies have compiled yield-strength profiles of continental lithosphere based on the results of laboratory measurements and numerical calculations; however, yield-strength values remain poorly constrained, especially at depths below the brittle–plastic transition zone. Recent studies by the authors have refined the microboudin technique for estimating palaeostress magnitude in the deep crust (> 10 km depth). This technique has the potential to provide important information on stress levels in the deep continental crust, an environment to which available in situ stress measurements and palaeopiezometric methods cannot be applied.

In applying the microboudinage technique, obtaining an estimate of the palaeostress magnitude requires knowledge of the fracture strength of columnar accessory minerals (e.g., tourmaline, amphibole, and epidote) that are subjected to brittle fracturing during plastic deformation of the surrounding matrix minerals. The absolute magnitude of fracture strength is known to show a marked reduction in the case of fatigue fracture.

Fatigue fracture falls into two categories: static fatigue and cyclic fatigue. In the field of experimental rock deformation, stress corrosion by water molecules (static fatigue) is commonly invoked as the mechanism of fatigue fracture; however, evidence of both static and cyclic fatigue has been reported from studies of natural geological samples. The present study focused on the fatigue properties of columnar accessory minerals at high temperatures, with the aim of improving the accuracy of estimates of natural palaeostress magnitude at depth in the crust.

2. Constant stress-rate test

A constant stress-rate test was performed to determine the influence of static fatigue on the strength of columnar accessory minerals. The test was conducted under three-point bending with a span distance of 10 mm. Temperature conditions and the crosshead speed were set in the ranges of ambient to 600°C, and 0.0005 to 0.2 mm/min, respectively. Pressure and relative humidity were set to room conditions. Tourmaline was chosen for testing (as representative of columnar accessory minerals embedded within metamorphic tectonites) because this is the only mineral for which crystals are available of sufficient size and quality. A total of 120 prism-shaped tourmaline test pieces (dimensions, $2\times2\times12$ mm) were prepared from a single tourmaline block collected from Minas Gerais, Brazil.

The flexural strength of tourmaline shows a clear decrease with decreasing crosshead speed at ambient temperature (with $n \approx 15$ as the static fatigue parameter); however, this trend weakens with increasing temperature ($n > 50$); that is, the influence of static fatigue on the strength of tourmaline decreases with increasing temperature. A comparable result has been reported for glass materials because of difficulties in the absorption of moisture on sample surfaces under high-temperature conditions. The fabric pattern of fracture planes developed in tourmaline specimens in the present study, which show rectilinear scratches, arrests, or Wallner lines on smooth surfaces, is similar to that observed for glass materials.

3. Fractography of naturally deformed minerals

A ‘striation-like’ pattern resulting from cyclic fatigue fracture was observed by scanning electron microscope (SEM) analysis of a natural fracture plane developed within marble-hosted amphibole. The sample was collected from the eastern flank of the Red River shear zone (Luc Yen district), northern Vietnam. The brittle fracturing of amphibole (open fractures were filled by calcite, which deforms plastically) is considered to have occurred at 6 km depth at 25 Ma, based on geological criteria.

4. Order of stress magnitude in continental crust at the depth of the brittle–plastic transition zone

Assuming that the fracture behaviour of columnar accessory minerals during the development of microboudinage is independent of the mineral species, the above results raise the possibility that the fracturing of columnar accessory minerals at deep crustal levels is governed by cyclic fatigue, possibly attributed to mechanical degradation rather than stress corrosion associated with water molecules, and that the fracture behaviour of columnar accessory minerals is similar to that of glass materials. Thus, cyclic fatigue studies of glass materials are expected to provide a good reference for approximate estimates of the fatigue limit of columnar accessory minerals. According to the literature, the fatigue limit for many glass materials is approximately 10% of the ultimate tensile strength.

Taking into account the influence of fatigue fracture, the obtained magnitudes of palaeodifferential stress at crustal depths of 10–20 km, as estimated using the microboudinage technique, are in the low tens of megapascals (e.g., 10 MPa at 9 km depth, as obtained from metacherts within high-pressure rocks in Japan; 25 MPa at 12 km depth, as obtained from metachert within a metamorphic sole in the UAE; 9 MPa at 18 km depth, as obtained from metachert within high-pressure rocks in China; and 14 MPa at 18 km depth, as obtained from metachert within high-pressure rocks in Turkey). These values are much lower than those obtained from laboratory measurements.