THERMAL STRESS MICROFRACTURING
OF CRYSTALLINE AND SEDIMENTARY ROCK

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1 Abstract

Slow uniform heating of crustal rocks is both a pervasive geologic process and an anticipated by-product of radioactive waste disposal. Such heating generates microcracks which alter the strength, elastic moduli, and transport properties of the rock. The research program was to understand mechanisms of thermal cracking in rocks. It included development of a theoretical understanding of cracking due to thermal stresses, laboratory work to characterize crack strain in rocks thermally stressed under different conditions (including natural thermal histories), microscopic work to count and catalog crack occurrences, and geologic application to determine paleostress history of granites from the midcontinent.

2 Experimental Results

Several experimental techniques were integrated to characterize the behavior of granite during slow heating to 300 °C while under confining pressures to 55 MPa. Acoustic emissions were counted and compressional wave velocities were measured while a sample was heated. After a heating cycle, crack porosity and crack compressibility were measured, and the cracks were counted under an SEM, sorted by grain boundary and intragranular types and by mineral pair occurrence. The results were:

1. Most newly created thermal cracks closed at pressures between 20 and 40 MPa (1.5 km depth).
2. Quartz grain boundaries were preferentially cracked.
3. The threshold temperature for acoustic emissions was a linear function of pressure.
4. Total acoustic emission counts over the temperature range 20 to 300 °C decreased slightly when the confining pressure was decreased from 55 to 28 MPa, and decreased sharply when the confining pressure was decreased from 28 to 7 MPa.
5. The compressional velocity decreased 22% when heated to 300 °C at 7 MPa, 15% at 28 MPa, and 10% at 55 MPa.
6. The acoustic emission counts in Westerly granite during heating showed one or more peaks of activity as a function of temperature, with more peaks at lower pressures.

3 Theoretical Results

A micromechanical, fracture mechanics model was developed to simulate grain boundary cracking due to slow thermal cycling in granite under confining pressure. The model consisted of an array of four hexagonal grains embedded in an infinite medium with homogeneous and isotropic elastic and thermal expansion properties. Elastic moduli within the four grain array were assumed to be identical to those of the matrix, but each grain was allowed to have its own independently oriented, anisotropic thermal expansion tensor. The mode I stress intensity factor was calculated for an initial flaw of assumed length, originating at either triple junction and lying along the central facet.

The numerical model predicted experimentally observed acoustic emission data during thermal cycling of Westerly granite to 300 °C under 7, 28, and 55 MPa confining pressure. In particular, the model was able to match the acceleration of acoustic emission events above 200 °C in the 7 MPa experiment, with reasonable values of model parameters, which included the temperature and pressure dependence of Young's modulus and the distribution of initial crack lengths. The model also provided a reasonable explanation for crack density trends found in thermally cycled Westerly and Illinois granites. Mode I cracking is favored along feldspar-feldspar facets in heating and along quartz-quartz facets in cooling. In heating, the relatively small volumetric expansion of feldspar grains along the facet face and the relatively large thermal expansion of quartz grains along either edge of the facet favor cracking. In cooling, the large volumetric contraction of quartz grains along the facet face and the relatively small contraction of feldspar grains along the facet edges favor cracking.

4 Geologic Application

A consistent orientation of healed cracks from several localities within the Wolf River Batholith and Illinois borehole UPH-3 about 250 kilometers to the southwest suggested that a paleostress field with the maximum horizontal stress oriented NW-SE $\pm 20^\circ$ existed at the time of crack formation. Fluid inclusion data suggested that the cracks were probably generated and healed in the initial cooling of the pluton over a fairly wide range of temperatures, starting at near 400 °C. Along a single crack, fluid inclusion salinities were very consistent, indicating that cracks were not partially reopened by later

cracking events. However, a wide range of salinities existed between cracks, and this variation was about the same for the major NW-SE trending set as it was for the minor sets in other directions. This suggested that the minor sets formed at the same time as the major crack set and were not related to a later re-orientation of the stress field.

The NW-SE orientation for the maximum horizontal stress direction during the cooling of the Wolf River Batholith is subparallel to the proposed orientation of the paleostress field prior to the emplacement of the Wolf River Batholith during an unnamed event that deformed late Proterozoic quartzites, and it is consistent with a long period of continental collision and accretion, which formed NE trending belts along the southern and southeastern margin of the continent. The orientation of the regional stresses may have remained fairly constant during much of the period from Penokean up to the start of the Keweenawan, when the maximum regional horizontal stress changed from a northwesterly orientation to a northeasterly one. The data show that even in periods of relative tectonic quiescence, such as during intrusion of the Wolf River Batholith, microcracks may provide a record of paleostress orientations.

5 Papers Published

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