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The influence of mineralogy on the initiation of microfractures in granite

Influence de minéralogie sur le déclenchement des microfractures dans les granites

Einfluss der Mineralogie auf das Auslösen von Mikrorissen in Granit

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ABSTRACT: Strain gauge, acoustic emission and scanning electron microscope observations were used to identify and characterize the development of stress-induced brittle microfractures in samples of Lac du Bonnet granite loaded in uniaxial compression. Results suggest that initial cracking occurred along grain boundaries between neighbouring quartz and feldspar grains, and intragranularly within feldspar grains. The point where the majority of these fractures began to initiate was defined as the crack initiation threshold. At increased loads, further cracking was observed to initiate intragranularly within the stronger quartz grains. This point was identified as the secondary cracking threshold. It is believed that this secondary crack initiation threshold may be more significant, with respect to the degradation of material strength, than the initial crack initiation threshold since it marks the point where continuous microfracturing (i.e. damage) occurs within the sample.

RÉSUMÉ: On a utilisé des observations par jauge de contrainte, des émissions acoustiques et par microscope électronique de lecture pour identifier et caractériser le développement de microfissures fragiles provoqués par la tension dans les échantillons de granit de Lac du Bonnet chargés dans le compactage uniaxial. Les résultats suggèrent que les fentes initials se produit le long des bords des grains voisins de quartz et de feldspath, et dans des grains de feldspath. On a défini le point où la majorité de ces ruptures a commencé à lancer comme le seuil de déclenchement des fentes. Aux efforts plus forts, on a observé l'initiation des autres fentes dans les grains plus forts de quartz. On a identifié ce point comme le seuil fendant secondaire. On le croit que ce seuil secondaire de déclenchement des fentes peut être plus significatif, en ce qui concerne la dégradation de la force matérielle, que le seuil initial de déclenchement des fentes, parce qu'il répresent le point où la microfissuration continue (c.-à-d. des dommages) se produit dans l'échantillon.

ZUSAMMENFASSUNG: Messwerte eines Dehnungsmeßgeräts, der akustischen Emission und eines Rasterelektronenmikroskops wurden benutzt, um die Entwicklung von druckverursachten brüchigen Mikrorissen in Proben des Granits aus Lac du Bonnet, welche einachsig komprimiert wurden, zu identifizieren und charakterisieren. Die Resultate deuten darauf hin, daß die Ausgangspunkte der Risse entlang den Kristallgrenzen zwischen benachbarten Quarz- und Feldspatkörnern sowie innerhalb der Feldspatkörner liegen. Die Belastung, unter welcher diese Risse vornehmlich ausgelöst wurden, wurde als 'crack initiation threshold' definiert. Unter erhöhter Belastung wurden auch Risse in den stärkeren Quarzkörnern beobachtet. Dieser Punkt wurde als 'secondary crack initiation threshold' gekennzeichnet. In Bezug auf die Verminderung der Materialfestigkeit wird diesem 'secondary crack initiation threshold' eine möglicherweise grössere Bedeutung zugeschrieben als dem 'crack initiation threshold', da er den Punkt kennzeichnet, von dem an in der Probe kontinuierlich Mikrorisse (d.h. Beschädigungen) auftreten.

1 INTRODUCTION

Some of the key concerns regarding the design of a future nuclear waste storage facility include the implications of potential ground disturbance by the excavation method and the redistribution of *in situ* stresses around the excavation. Both of these factors relate to the extent of brittle fracture damage which could adversely affect the stability of the excavation boundary and could increase the permeability of the near-field host rock. Establishing the initiation and development of stress-induced microfractures in brittle rock is thus of key interest. Work at Atomic Energy of Canada Limited's Underground Research Laboratory (URL), shown in Figure 1, has concentrated on identifying and quantifying these microfracturing processes.

An extensive laboratory study was undertaken to examine the initiation and development of stress-induced microfractures in samples of Lac du Bonnet granite. This paper reports some of the key findings from this study with respect to the initiation of the microfracturing process, emphasizing some of the underlying mechanisms relating to the mineralogy of the granite samples.

2 CRACK INITIATION

2.1 *Detection of the crack initiation process*

The initiation of the microfracturing process, as determined through uniaxial compression testing, has been defined as the point where the axial stress versus lateral strain curve departs from linearity (Brace et al. 1966, Bieniawski 1967, Lajtai & Lajtai 1974). Referred to as the crack initiation stress threshold, this point represents the stress at which a significant number of critically orientated cracks initiate and propagate in the σ_1 direction. Thus the opening of these cracks perpendicular to the axial load (i.e. perpendicular to σ_1) is reflected in the deviation of the lateral strain curve from an approximate linear trend.

Noting the difficulty in using lateral strain data, especially in damaged samples, Martin & Chandler (1994) suggested using the calculated crack volumetric strain to identify crack initiation. In this respect, crack initiation can be defined as the stress level at which dilation begins in the crack volume plot (Fig. 2). Still, this method is somewhat dependent on the assumption that the elastic constants can be determined with a high degree of certainty. Eberhardt et al. (1998) have shown that discrepancies in the calculation of the Poisson's ratio due to the non-linearity of the lateral strain response introduces a large degree of uncertainty into the crack volume calculation and thus the determination of the crack initiation threshold by means of this method.

It was found that the crack initiation threshold could be more accurately determined through the combined use of electric resistance strain gauge and acoustic emission (AE) measurements (Eberhardt et al. 1998). Further verification may be gained by combining these two techniques with measured changes in the

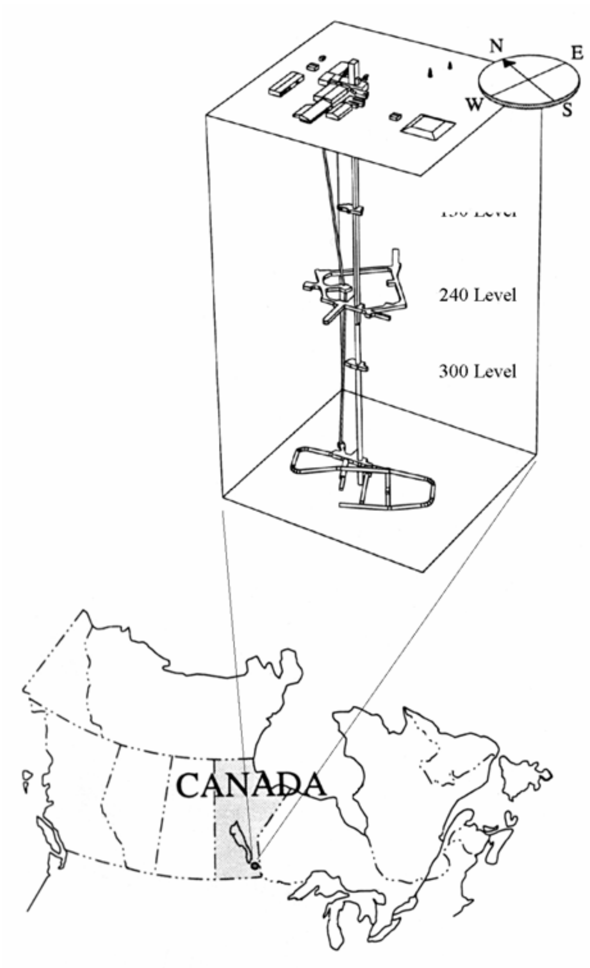

Figure 1. Location and layout of the URL.

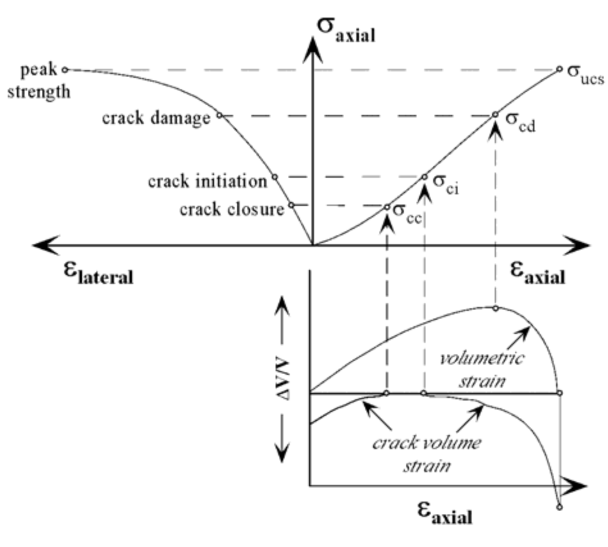

Figure 2. Determination of the crack initiation stress threshold, σ_{ci}, based on the calculated crack volume curve from a uniaxial compression test (after Martin & Chandler 1994).

AE event ringdown count, event duration, peak amplitude and rise time (Eberhardt et al. 1997). These parameters are defined in Figure 3 through a schematic representation of an AE event waveform. An example of their use, with reference to the crack initiation threshold for Lac du Bonnet granite from the 130 Level of the URL (i.e. 130 m depth), is presented in Figure 4. Several further stages of crack development were also resolved using these techniques including the crack closure, crack coalescence and crack damage thresholds. The detection and significance of these stages are not within the scope of this paper but are discussed in more detail in Eberhardt et al. (1998).

2.2 *Crack initiation threshold for Lac du Bonnet granite*

Uniaxial compression tests were performed on 20 samples of pink Lac du Bonnet granite from the 130 Level of the URL. The granite is medium- to coarse-grained with an average grain size between 3 and 4 mm. Samples, 61 mm in diameter, were prepared for testing according to ASTM standards (Designation D4543-85) with length to diameter ratios of approximately 2.25. Considerable care was taken in minimizing the influence of end effects on strain gauge and AE transducer readings. This entailed the use of a specially constructed frame that allowed for the sample ends to be highly polished. Each sample was instrumented with six electric resistance strain gauges (3 lateral and 3

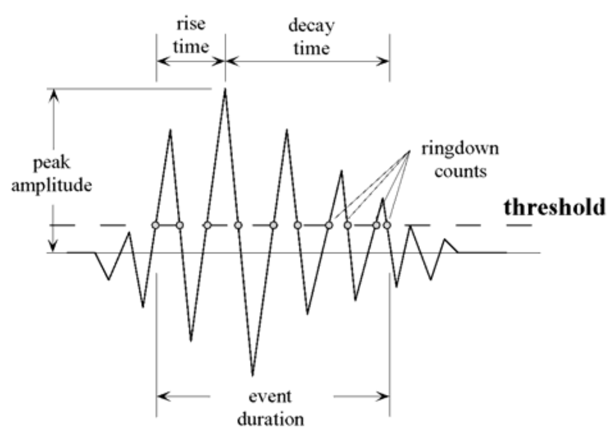

Figure 3. Common acoustic emission waveform parameters.

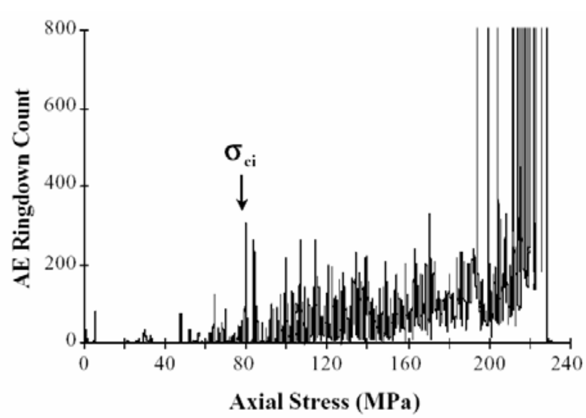

Figure 4. Example of an AE event ringdown count -*vs*- axial stress plot used in determining the crack initiation stress threshold, σ_{ci}.

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axial at 60° intervals and four 175 kHz piezoelectric AE transducers. Acoustic emissions were recorded using a gain of 40 dB and a threshold value of 0.1 V.

The crack initiation threshold for the Lac du Bonnet granite was determined to be 81.5 MPa, or 40% of the uniaxial compressive strength. This threshold point corresponds to the point in the AE data where significant cracking begins. However, it is unlikely that this point represents a stress state in which the entire crack population simultaneously initiates and propagates. Instead, heterogeneities in the rock matrix must be considered. Using the basic principles assumed through Griffith's theory and linear elastic fracture mechanics (Whittaker et al. 1992), the initiation of a propagating crack is dependent on the stresses that form at the tip of an existing microcrack and the strength of the material at the crack's tip. In the first instance, the stress anomaly at the crack tip can be associated with the length of the crack and the angle it's orientation makes with the applied load. Given that the sources of these stress concentrating cracks include grain boundaries and intragranular flaws, numerous combinations of crack lengths and orientations potentially exist in a randomly distributed population throughout the rock sample. The crack tip stresses available to initiate crack extension, therefore, will vary on a localized scale depending on the length and orientation of the individual cracks. Bortolucci & Celestino (1996) and Gorelic et al. (1996), for example, both cite statistical variations in crack length and orientation as controlling factors in the modelled behaviour of propagating cracks. Analysis of acoustic emission data conducted in this study suggests that the initial detection of cracking in the Lac du Bonnet granite appears to follow a normal distribution with a mean equal to the crack initiation threshold (Fig. 5). The detection of minor AE activity prior to and following the crack initiation threshold suggests that these events can be attributed to cracks with lower or higher initiation thresholds. Comparable results were obtained by Chudnovsky & Kunin (1987), who used probabilistic models to calculate the extent of brittle crack propagation. Using critical crack length as a random variable, their models produced similarly shaped probability density functions as the conceptual model depicted in Figure 5.

3 SECONDARY CRACKING THRESHOLD

The second, and in this case the more significant, component of the crack initiation process involves the strength of the material surrounding the crack tip. The Lac du Bonnet granite is primarily made up of feldspar and quartz grains with minor mica and other accessory minerals. Grain-sized heterogeneities in the rock will therefore exist since individual quartz and feldspar grains have contrasting elastic moduli and hardness values. In terms of the mismatch in elastic moduli, Dey & Wang (1981) found that the modelled response between two different minerals in welded contact with each other and subjected to the same external loading, will result in additional boundary tractions between the two minerals. In other words, as neighbouring grains of quartz and feldspar deform under load, their respective rates of deformation will vary resulting in the formation of tensile stresses acting across the grain boundary and shear stresses acting parallel to it. These localized stress inhomogeneities could in turn induce boundary cracks to initiate and propagate. The development of these fractures were confirmed through the analysis of thin-sections taken from two samples of Lac du Bonnet granite loaded past the crack initiation threshold. Scanning electron microscope (SEM) observations revealed that approximately 50% of the observed microcracks occurred along grain boundaries between neighbouring feldspar and quartz grains (Fig. 6).

SEM observations also suggest that the remaining 50% of observable cracks are primarily located within feldspar grains (Fig. 7). The feldspar grains, which include both plagioclase and potassium feldspar, have a lower hardness value than quartz (6 compared to 7 on the Moh's scale, respectively). Accordingly, mineral hardness can play a contributing role with respect to the initiation of microfractures in situations where harder minerals induce a point load in softer neighbouring minerals. For example, Hallbauer et al. (1973) found that point loading of grains by other grains was a frequent source of cracks in triaxial tested samples of quartzite. Hardness can also be loosely correlated with strength (Franklin & Dusseault 1989). It then follows that the weaker feldspar grains will be the source of the first intergranular cracks to initiate and propagate. Eventually, at higher loads, the harder and stronger quartz grains will begin to crack thereby resulting in a second crack initiation interval.

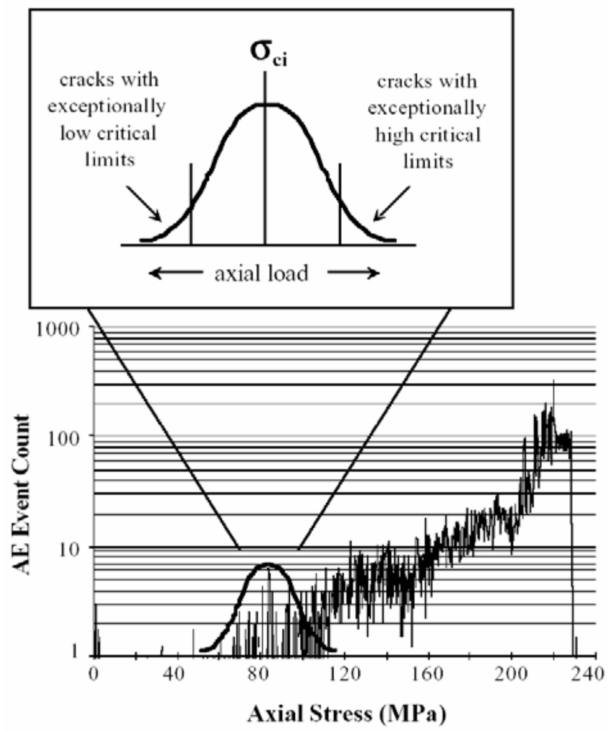

Figure 5. Log plot of the AE event count *-vs-* axial stress showing a hypothesized normal distribution fit of the critical crack initiation limits with a mean value equal to the crack initiation threshold, σ_{ci}.

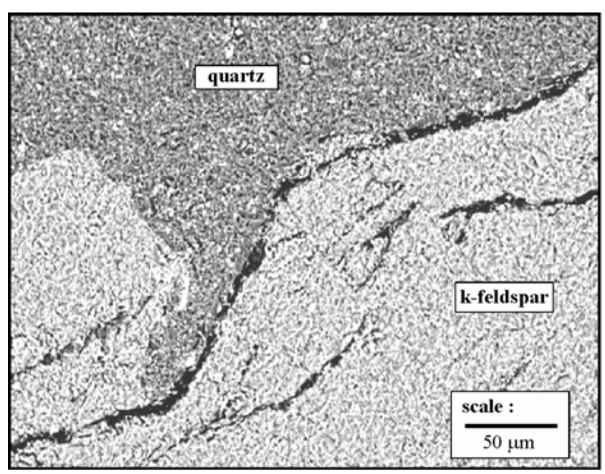

Figure 6. SEM image of a stress-induced crack originating along a quartz-feldspar grain boundary.

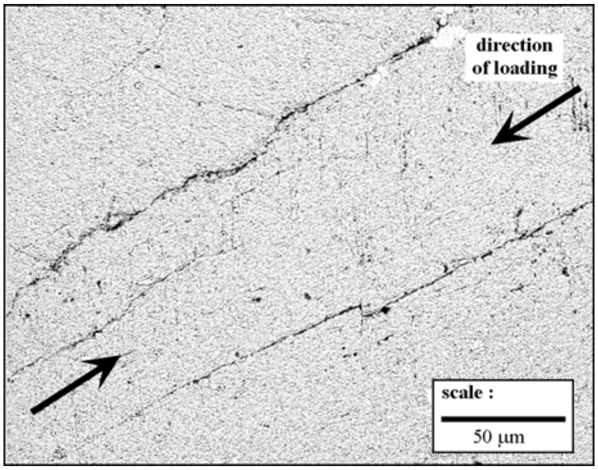

Figure 7. SEM image of a feldspar grain with stress induced cracks aligned parallel to the direction of loading (i.e. σ_1).

These deductions can be substantiated through the measured AE response of the Lac du Bonnet granite samples, which showed two separate bursts of AE activity. The initial burst coincided with the crack initiation threshold at 80 MPa as cracks began to propagate along grain boundaries and through the weaker feldspar grains. Similar observations have been made by Svab & Lajtai (1981) who found that grain boundaries and feldspar cleavage act as the primary microstructural path controllers for a propagating crack in Lac du Bonnet granite. A second crack initiation type process then followed at approximately 104 MPa as cracking began in the relatively stronger quartz grains. This threshold, referred to as the secondary cracking threshold, σ_{ci2}, also marks the point where continuous AE activity is recorded as cracking takes place in all of the constituent minerals of the granite. Furthermore, significantly large increases were seen in the calculated acoustic event "energy" at this threshold point (it should be noted that the AE event "energy" is based on the event's duration and peak amplitude, and is not an exact measure of energy). This implies that the energy of the events originating from the harder quartz grains is somewhat greater than those seen at the crack initiation threshold arising from the feldspar grains and quartz/feldspar grain boundaries (Fig. 8). This "energy" increase was observed in each of the 20 uniaxial compression tests performed, making it an ideal marker for the secondary cracking threshold.

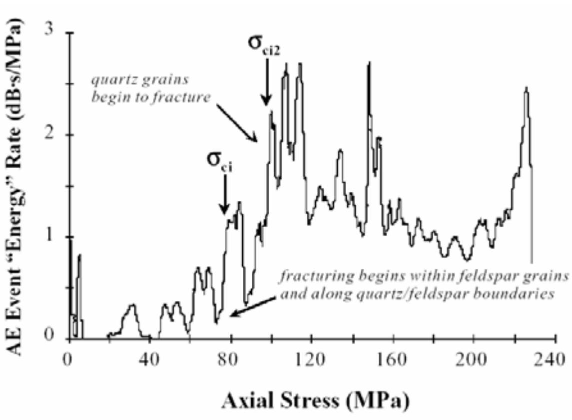

Figure 8. Plot of the stress dependent elastic impulse "energy" rate -vs- axial stress.

4 CONCLUSIONS

The initiation of new fractures in samples of Lac du Bonnet granite loaded in uniaxial compression was seen to be predominantly dependent on the mineralogy of the sample. Initial cracking seemed to originate along grain boundaries between neighbouring quartz and feldspar grains, and intragranularly within the feldspar grains. The point where the majority of these fractures began to initiate was defined as the crack initiation threshold, σ_{ci}. The crack initiation threshold for the pink Lac du Bonnet granite from the 130 Level of the URL was found to be 81.5 MPa or 0.40 σ_{UCS}. This point was detectable in both strain gauge and acoustic emission measurements.

At increased loads, microcracking began to originate within the stronger quartz grains. This point was referred to as the secondary cracking threshold, σ_{ci2}, and was characterized by increases in the AE event rate and the AE event "energy". The secondary cracking threshold for the Lac du Bonnet granite was detected at 103.9 MPa or 0.50 σ_{UCS}.

In rocks with a more varied composition and with grains of starkly contrasting strengths, it may be possible that a number of these points exist, each marked by a stress level required to initiate intragranular cracking within that mineral constituent. In the case of the Lac du Bonnet granite, it is believed that the secondary crack initiation threshold may be more significant, with respect to the degradation of material strength, than the initial crack initiation threshold since it marks the point where continuous microfracturing (i.e. damage) occurs within the sample.

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