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IN GRANITIC ROCKS

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A RAPID TECHNIQUE FOR COUNTING CRACKS IN ROCKS* (Running head: Rapid Crack Counting Technique for Rocks)

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ABSTRACT

Using a scanning electron microscope and an image analyzer, we have developed a technique for counting and measuring cracks in rocks which is more efficient than traditional techniques in which an operator performs all image analysis functions. The key aspect of the technique is that black-on-white tracings of fresh cracks, which can be made rather quickly by an operator, are fed to an image analyzer which then digitizes and tabulates data. The most time-consuming step in the process has now become the generation of SEM micrographs and pertinent chemical (mineralogical) information, not the quantification of crack structure. The technique has been applied to two studies involving nuclear waste isolation in a granitic rock, Climax Stock (Nevada Test Site) quartz monzonite, a rock which is structurally very inhomogeneous. One study detected a relationship between crack structure and distance from a hammer-drilled borehole; the other study was unable to detect a relationship between crack structure and gamma irradiation treatment in rocks loaded to near failure.

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KEY WORDS: crack counting, image analysis, waste isolation, SE vs. BSE imaging, damage in rocks, granites, Climax Stock quartz monzonite

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INTRODUCTION

Mechanical and transport properties of rocks, such as failure strength, elastic moduli, and fluid permeability, are generally more sensitive to cracks and pores within and between grains of a rock than to the composition of the grains themselves. Thus an understanding of important physical processes which manifest themselves as mechanical properties requires characterization of the cracks and pores of a rock. Once characterized and understood, the cracks and pores in a rock serve both for prediction of how the rock will respond to physical change (e.g., how much more load the rock can withstand) and for diagnosis of the change which has already occurred (e.g. how much the rock has been previously loaded).

Microcracks and pores in rocks can be observed and studied in several ways. Indirectly, one can measure cracks and pores through their influence on elastic properties using sonic velocity or elastic strain vs. stress as the measured quantities. One can even "hear" microcracks as they form or grow under stress, using acoustic emission techniques. Microstructure can also be observed directly, most commonly by optical microscopy of thin sections and scanning electron microscopy (SEM) of prepared surfaces. Paterson (1978) has reviewed these and other more exotic techniques. Each technique has advantages and drawbacks, with the particular situation generally determining the appropriate technique. In our studies we have used SEM for direct observation.

During work related to an operating underground nuclear waste storage experiment, called the Spent Fuel Test - Climax or SFT-C (Ramspott et

al., 1979), we have undertaken two separate substudies involving use of SEM to analyze the cracks and pores of rock. For both studies, the rock in question was Climax Stock quartz monzonite (CSQM), a granitic rock from the site of SFT-C. We discovered quickly that CSQM is structurally a highly heterogeneous rock and that in order to use the predictive/diagnostic ability the cracks provide, we would have had to observe and measure hundreds of cracks. Resources for the substudies were rather limited, so rather than make detailed, individual measurements of cracks in the traditional manner (e.g. Sprunt and Brace, 1974; Hadley, 1976; Tapponnier and Brace, 1976; Kranz, 1979) we attempted to increase measurement speed through simplification and partial automation.

THE TWO STUDIES

The experimental nuclear waste repository, SFT-C, lies approximately 420 m below ground level in the Climax Stock, located in the NE corner of the Nevada Test Site. Eleven spent fuel assemblies sealed in stainless steel canisters were stored in an array of other (electrical) heat sources in order to simulate, in the central region of the array, the conditions within a very large repository. Our substudies were (1) Study A, an assessment of damage to rock incurred during hammer drilling of the canister emplacement holes (i.e. the holes into which fuel assembly canisters were placed), and (2) Study B, a study of the failure mechanism in CSQM as a function of gamma-ray dosage to the rock. In particular, we were interested in finding out if crack growth prior to failure in CSQM was assisted by prior gamma irradiation. In both studies, the SEM sections were 25.4 mm-diameter cores, prepared by the method outlined below. For Study A, the cores were taken directly from the vicinity

of the canister emplacement hole. For Study B, cores 25.4 mm in diameter by 63 mm long were taken to the laboratory and half of them given a gamma ray dosage of approximately 10 MGy (10^9 rads) from a ^{60}Co source. All were then end-loaded to near failure and then cut through their mid-plane to provide the SEM sections. In the geometry of this experiment, microcracks induced by the compressive load tend to run parallel to the load (i.e. the cylinder) axis. Hence the SEM section was taken normal to the major crack direction in order to intersect as many cracks as possible.

Further details on Study A are given in Weed and Durham (1982) and on Study B in Beiriger and Durham (1984).

TECHNIQUES

Preparation and Operation. Sections were cut on a diamond saw to a thickness of 5 mm, and approximately 1 mm was rough ground from the face of interest in order to remove cutting damage. They were then polished with abrasive grit and finished with 2- μm alumina on a cloth lap. The polished surfaces were next ion-milled in order to remove the thin layer (10-20 μm) which had been smeared and damaged by the polishing procedure. After ion milling, samples were coated with approximately 20 nm of carbon by vacuum evaporation to increase surface conductivity and prevent static charge accumulation under electron bombardment in the SEM. This method generally follows that outlined by Brace et al. (1972) and is probably the most commonly used preparation technique for the SEM study of rocks.

The SEM used was an AMR (AMRAY) 1000 equipped with a Kevex 7000 energy dispersive spectrometer (EDS). In all cases, the working distance was 12 mm and the accelerating voltage was 20 kV. All micrographs used for measurement purposes covered approximately 0.035 mm^2 of rock (500 x magnification). For some of the work the secondary electron (SE) detector was used to generate micrographs and in other cases a quadrupole solid-state backscattered electron (BSE) detector was used. When the SE detector was used, the specimen tilt angle was set at 30° and a slightly positive potential was applied to the cage over the scintillator in order to increase the proportion of BSE relative to SE. We found that at intermediate magnification ranges microfractures stand out in better contrast when the proportion of BSE is higher, no doubt because of the sharp change in topography which an open microfracture defines. With the quadrupole BSE detector, specimen tilt angle was set to 0° (the detector was positioned on the pole piece of the electron column). Interestingly, the topographic contrast provided by microcracks in this mode was not as strong as the chemical contrast they provided (since cracks have zero atomic weight), so the polarity of the poles of the detector was set to maximize chemical differences. The mode using the SE detector is hereafter referred to as the BSE/SE mode and that using the BSE detector as the BSE mode.

Microcrack Measurement. In order to minimize operator bias toward "interesting" areas, the photographic conditions and locations (referred to as "spots") to be photographed were selected before specimens were introduced into the SEM. Figure 1 shows the selection for Study A. In both studies, micrographs were taken at 2 mm intervals (as determined by vernier settings of

the stage controls) along a linear trace across the section. The orientation of the trace was arbitrary, but again, preselected. The trace was either a diameter or within 2 mm of the diameter of the section. Starting and ending points were allowed no closer than 1 mm to the edge of the section, in order to avoid possible artifacts of coring. Thus a given trace yielded seven to nine micrographs upon which measurements could be made.

At every spot, a qualitative chemical analysis of every grain was made with the EDS. Ninety-nine percent of the volume of CSQM is made up of one of five different mineral phases, so qualitative analysis was adequate for mineral identification. Additionally, a low magnification overview was made every second or third spot for mapping purposes, to cover the eventuality that some spots would have to be reinvestigated. Although we did not know it at the time the SEM work was being done, the chemical information turned out not to be used in any of the post-measurement analysis.

The crack quantification procedure consisted of three steps:

- (1) Operator discrimination of fresh cracks;
- (2) Digitization of the discriminated crack pattern;
- (3) Numerical analysis of the digitized image.

The first step required some subjective operator decisions to discriminate pre-existing cracks from "fresh" cracks introduced by operations associated with SFT-C (in the case of Study A) or by laboratory testing (Study B). A crack was usually judged on the basis of physical appearance: a sharply defined edge and pieces which fit together marked an obvious fresh crack; a

crack which intersected many pores and had a varying width along its trace or which was partially filled with material fixed to the crack walls was obviously pre-existing. A full spectrum of cracks existed, grading from obviously fresh to obviously pre-existing so operator judgments were sometimes arbitrary. We tried to shield the data from being systematically affected by day-to-day variations in the quality of operator judgement. In particular, when the judgements were made (by tracing, see below), the identity of the micrographs was masked and the order of measurement was randomized by shuffling the micrographs.

The primary innovation of our work is represented by step (2). It was accomplished by making pencil tracings of the fresh cracks on transparent, matte-finish overlays, one micrograph at a time, then photocopying the overlays on white paper to produce an unambiguous black on white image of the cracks. Figures 2 and 3 illustrate the results of the process for the BSE/SE and BSE modes of operation. The photocopied image was then digitized and analyzed with a Quantimet 700 image analyzer. By an operator-invoked convention within the image analyzer, two intersecting cracks were counted as two cracks. Output from the image analyzer consisted of a list of cracks along with their areas, perimeters, and locations. Since all cracks had been forced to have the same width (the width of a pencil trace), the area and perimeter information were combined to give a single parameter, length.

Step (3) was a matter of transferring the image analyzer lists to a computer, combining the lists into one large table, and deriving the desired information from the large table using database analysis software.

In summary, by simplifying crack measurement to a single parameter (length), and using an image analyzer in a fairly unsophisticated mode, we were able to greatly reduce the operator time involved in measurement. The key step, identification and tracing of fresh cracks, required well under one minute per micrograph. Processing in the image analyzer (including setup) averaged 2-3 minutes per micrograph. In the two studies, the average number of cracks per micrograph was 5.6; hence, the total time spent quantifying microfractures was well under one minute per crack. In fact, operating the SEM and EDS became the longest step of the process, requiring roughly 15 minutes per spot, or 3 minutes per fresh crack.

RESULTS

In Study A, two traces were run on each of six sections (orientation with respect to the canister emplacement hole is shown in Figure 1), resulting in 88 spots photographed and 674 fresh cracks identified and measured. All micrographs were taken in BSE/SE mode. In Study B three traces were run on each of nine sections, resulting in 207 spots and 990 fresh cracks. One of the three traces on each section was run in BSE/SE mode, the other two in BSE mode.

From the measurements, we computed three parameters (only two of which are independent): crack density (number of cracks per unit area), average crack

length, and average length of crack per unit area. In Study A, all measurements on a given section were combined to give a single set of parameters. A plot of any given parameter vs section, appropriately adjusted for the distance between the center of the section and the wall of the emplacement hole, gave a measure of crack damage as a function of distance from the hole (Figures 4 and 5). Figures 4 and 5 show clearly that material within the first few tens of millimeters of the canister emplacement hole is more cracked than material further out. The figures also show that a great deal of scatter exists in the data. In trace-to-trace comparisons of density or average length in any given section, differences of a factor of two are not unusual.

The scatter in the data became a serious problem in Study B. The three crack parameters are compiled by trace and by sample in Table 1 in order to illustrate the scatter. Again, note that differences of a factor of two are not unusual, even when the BSE traces alone are compared. The scatter is so large that when the crack parameters are grouped by radiation treatment (Table 2), they are only subtly different and are accompanied by standard deviations which are comparable to the means. Hence, we were not able to resolve a dependence on radiation treatment.

Note that in Tables 1 and 2 the BSE/SE mode in the SEM appears to reveal more cracks than the BSE mode. The cracks so revealed in BSE/SE, however, are on average less than half as long as those revealed in BSE, resulting in an average total length of crack per unit area that is slightly greater in BSE. The difference, especially in average crack length, is unmistakable, but since we have not made comparisons of the two techniques on the same area of rock, and since the rocks show such inhomogeneity from point to point, we can only

hypothesize as to the cause of the difference. SE do typically provide better areal resolution than BSE because of the physics of electron interaction with surfaces, so it may be that the BSE signal doesn't resolve the shorter, narrower cracks. Another possible explanation is related to the fact that we tried to avoid counting grain boundary cracks. The BSE signal is much more sensitive to chemistry than BSE/SE (compare Figures 2 and 3), so that grain boundaries, and therefore cracks which lie along them, are more obvious in BSE. Therefore, some of the cracks counted in BSE/SE mode may be grain boundary cracks while few, if any, of the cracks counted in BSE mode are grain boundary cracks.

DISCUSSION AND CONCLUSIONS

Is it possible that the technique itself is responsible for the large scatter in the data? There is good evidence against this, based on a comparison of CSQM and other granites.

Among granitic rocks which have been mechanically tested and otherwise observed in the laboratory, CSQM is unusually heterogeneous. (Note that this is not because CSQM is an unusual rock; laboratory testing materials are frequently selected on the basis of homogeneity.) Petrographically, CSQM is strongly heterogeneous on the millimeter scale (Fig. 6). Most of the rock is composed of grain sizes ranging from 0.25 to 2 mm, but contains irregular quartz phenocrysts (about 10% by volume) typically 5 mm across and potassium feldspar phenocrysts (about 5% by volume) that are as much as 150 mm long. In contrast Westerly granite is finer-grained (0.25 to 1 mm) and

petrographically much more uniform than CSQM. Comparison of failure strength statistics for CSQM and other granites is striking: for Westerly, one standard deviation is $< 3\%$ of the mean at 100 MPa confining pressure (Costantino, 1978). Kranz and Scholz (1977) indicate that the unconfined strength of Barre granite is 220 ± 10 MPa (although they give no raw data). The scatter in unconfined strength of Oshima granite is clearly less than $\pm 5\%$ based on eight test results published by Sano et al. (1981). For CSQM unconfined, one standard deviation is typically $> 15\%$ of the mean.

The trend toward lower scatter in the more homogeneous granites carries over to quantitative crack measurement. Crack statistics on Westerly and Barre granites based on manual techniques are compared to our measurements in Table 3. Each of the four other studies in Table 3 has precise enough statistics to indicate that either the number of cracks or the length of cracks, or both, increases with magnitude and duration of load.

To put matters in perspective, the motivation for speeding up the crack counting procedure resulted from dealing with a "noisy" material. The semi-automated procedure was developed during the course of Study A when it became apparent that qualitative SEM examination would not produce useful results and that manual measurement would quickly use up the resources allocated to the study. As it turned out, CSQM was so "noisy" that even the semi-automated technique was barely acceptable: Study A gave a useful result (hammer drilling damage is confined to a 10-30 mm skin around the borehole) but Study B did not (gamma irradiation may or may not enhance microfracturing under load prior to failure).

Analysis of the time spent on the various aspects of our semi-automated crack quantization technique indicates that roughly 10-20% of operator time is spent identifying fresh cracks and tracing SEM images, roughly 30% of the time is spent processing line images in the image analyzer, and 50% of the time is spent generating SEM micrographs and chemical information pertaining to minerals present in the micrographs. It is interesting to note that further speed increase can be accomplished with relatively unsophisticated, presently available (but perhaps expensive) items: automatic sample feeding, stage stepping, focusing, and microphotography for the SEM; and automatic feeding for the image analyzer. The most difficult task in total automation, machine discrimination of fresh cracks, would only slightly speed up our present procedure. Such artificial intelligence would, however, greatly improve the quality of measurement by eliminating operator bias and by providing information on such important parameters as crack width, straightness, and interconnectivity.

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FIGURE CAPTIONS

1. The location of six sections (numbered 1-6) used in Study A with respect to underground mine workings at SFT-C. Two views, both in plan and both to scale, are shown. The large view at the top shows the location of six 25.4 mm-diameter sections taken from a piece of 150-mm core. The inset at the lower left shows the relationship of 150-mm core (labeled "CORE") to canister emplacement hole ("BOREHOLE") and underground tunnel ("DRIFT") in which spent nuclear reactor fuel was stored. Note that the 150-mm core is eclipsed where it intersects the previously bored canister emplacement hole. Heavy marks across the circumferences of the 25.4-mm-diameter sections are orienting saw cuts. Dashed lines indicate the positions of the SEM traces.
2. Crack counting example, BSE/SE pass. a) SEM photomicrograph, scale bar = 100 μm ; b) cracks identified as fresh, same magnification as a). There are ten fresh cracks identified here ranging in length from 4 to 104 μm . Mean length is 24.5 μm . Most of the right half of the picture area is a plagioclase grain. A single quartz grain dominates most of the left half of the picture (lighter contrast). Two other quartz grains are at the upper left and lower right. Note the poorer grain-to-grain contrast as compared to Fig. 2.
3. Crack counting example, BSE pass. a) SEM photomicrograph, scale bar = 100 μm ; b) cracks identified as fresh, same magnification as a). There are five fresh cracks identified here ranging in length from 19 to 113

μm with mean length $48.0 \mu\text{m}$. The three major phases are, in order of increasing brightness, quartz, plagioclase, and orthoclase. The subtle shadings in the plagioclase probably represent local variations of the Ca/Na ratio within a single grain. The small bright grain at the top was not identified.

4. Crack density vs. distance from the center of the canister emplacement hole for Study A. Numbers next to each of the symbols correspond to section locations in Figure 1. Triangles indicate the results for one trace on each section; circles, that for the other trace. For sections 1 and 5, the trace statistics are combined.
5. Average crack length vs. distance from the center of the canister emplacement hole for Study A. Same conventions apply as for Figure 4.
6. Low magnification SEM photomicrograph illustrating the heterogeneity of grain sizes in CSQM. Image is BSE only and the scale bar represents 1 mm. The four major contrast levels indicate, in order of increasing brightness, quartz, plagioclase, orthoclase, and biotite. Small bright spots are various heavier element phases such as iron oxide and zircon. Not shown is the variation in grain size of orthoclase: phenocrysts 100 μm across are not unusual. The grain scale heterogeneity of CSQM may be the principal cause of the noisy crack and strength measurements made on this rock.

TABLE 1: Crack Statistics by Sample, Study B

Sample	# cracks counted	Areal number density (mm ⁻²)	Average length (μm)	Areal length density (mm/mm ²)
2 (no γ)	* { 18	85	52	4.41
	31	177	14	2.47
	38	120	30	3.59
3 (γ)	45	157	30	4.70
	66	206	14	2.79
	20	81	32	2.64
4 (no γ)	23	109	36	3.98
	48	171	15	2.54
	51	182	26	4.67
5 (γ)	22	90	41	3.66
	49	124	14	1.74
	22	75	33	2.46
6 (no γ)	12	57	35	1.99
	64	214	12	2.47
	15	71	44	3.12
7 (γ)	25	119	36	4.27
	62	158	13	2.07
	30	107	38	4.01
8 (no γ)	49	175	28	4.89
	45	117	15	1.78
	14	67	29	1.95
9 (γ)	24	114	34	3.88
	46	131	16	2.15
	47	167	23	3.78
10 (no γ)	18	86	30	2.53
	71	285	16	4.44
	35	125	33	4.06

*Each of the groups of three numbers give the statistics for { BSE pass 1
BSE/SE pass
BSE pass 2

TABLE 2: Crack Statistics by Irradiation Treatment, Study B

BSE/SE Trace					BSE Traces			
	# counted	density (mm ⁻²)	$\bar{L}$ (μ m)	$\overline{L/Area}$ (mm/mm ²)	# counted	density (mm ⁻²)	$\bar{L}$ (μ m)	$\overline{L/Area}$ (mm/mm ²)
no γ	223	149 $\pm$ 153*	14 $\pm$ 12	2.11 $\pm$ 2.31	235	115 $\pm$ 105	32 $\pm$ 30	3.64 $\pm$ 3.42
γ	259	190 $\pm$ 178	14 $\pm$ 13	2.71 $\pm$ 2.64	273	113 $\pm$ 100	32 $\pm$ 33	3.61 $\pm$ 3.15
untreated, unstressed					54	91 $\pm$ 91	36 $\pm$ 47	3.24 $\pm$ 3.16

*1 standard deviation

TABLE 3: Comparison of Crack Counting Studies using SEM

	Rock	Loading Conditions	Confining Pressure (MPa)	# Counted	Density (mm ⁻²)	$\bar{L}$ (μm)	$\bar{L}/a_{90}$ (mm/mm ²)
Sprunt & Brace (1974)	Westerly granite	virgin	-	80		3-10 ^a	
		.95σ _f	not given	80	10-30 ^a		
Hadley (1976)	Westerly granite	virgin	-	344 ^c		1-5 ^a	
	" " (T5)	>.95σ _f	50	632 ^c		10-50 ^a	
	" " (W5)	failed	150	850 ^c		10-50 ^a	
Tapponnier and Brace (1976)	Westerly granite	virgin	-	182 ^d	196±73 ^e		
	" " (T3)	.58σ _f	50	502 ^d	239±48 ^e		
	" " (T5)	>.95 σ _f	50	861 ^d	354± 102 ^e		
Kranz (1979)	Barre granite	virgin	-	56	7 ^f	54±36	
	" "	.87σ _f , 7s	0.1	262	26 ^f	72±42	
	" "	" , 37s	"	282	23 ^f	90±79	
	" "	" , 125s	"	190	9 ^f	146±91	
	" "	" , 136s	"	183	8 ^f	164±88	
This study ⁹	CSQM	virgin	-	54	91±91 ^h	36±47	3.24±3.16
	" , no γ	.80±.24σ _f	0.1	235	115±105	32±30	3.64±3.42
	" , γ	.93±.21σ _f	0.1	273	113±100	32±33	3.61±3.15

Footnotes for Table 3

- a median values
- b σ_f = failure strength
- c includes pores
- d cracks encountered in axial traverses not included
- e approximated as

$$\text{density} = \frac{\# \text{ of crack intersections along traverse}}{\text{traverse length}} \times \frac{\text{traverse length}}{\text{mm}^2}$$

- f approximated as

$$\text{density} = \frac{\# \text{ intersections}}{\text{trace length}} \times \frac{1}{L}$$

- g BSE data only; Sample 2 (which failed) not included
- h 1 standard deviation

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6