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Figure 8. Sketch of the texture of the Lac du Bonnet 45
granite. Note the extensive area of contact between quartz grains, and between quartz and feldspars.

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**Microcrack Structures in Plutonic
Rocks from the Whiteshell Nuclear
Research Establishment, Eastern Manitoba, and
Atikokan, Northwestern Ontario.**

by

Peter James Chernis

**A Thesis submitted to the Faculty of Science
in Partial fulfillment of the requirements of
Master of Science**

**Carleton University
Ottawa, Ontario**

December, 1984

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Abstract

Analysis of laboratory-measured rock properties of core samples from the Lac du Bonnet granite at the Whiteshell Nuclear Research Establishment (WNRE), Manitoba, indicates that porosity increases with sampling depth. In contrast, interpretations of geophysical logs of the same boreholes show no such correlation. Scanning electron microscopy (SEM) reveals that increases in mean crack width (from $0.12\mu\text{m}$ to $0.31\mu\text{m}$), crack density (from 1.96 cracks/mm to 4.07 cracks/mm), and total porosity (from 0.08% to 0.28%) are a result of increasing abundance of sharp-tipped, parallel-walled microcracks. Based on their physical characteristics, these cracks are believed to have been formed as in situ stresses were relieved during drilling. The contribution of these fresh, stress-induced cracks can be estimated, allowing assessment of in situ engineering properties.

Similar studies on granodiorite core samples from the Eye-Dashwa Lakes pluton, Atikokan (ATK), Ontario, show no evidence of a comparable trend, but a rough correlation between decreasing permeability and increasing alteration is present. Stress cracks are also present in the ATK samples but their blunt tips, irregular walls, and bridges indicate that these are old, partially healed cracks associated with faults and macrofractures in the pluton.

Given the variability of porosity and permeability and

observations by SEM of extensive crack healing in an altered sample and variable crack healing in an "unaltered" sample, rock properties of altered, fractured granitic rock must be interpreted in terms of the initial amount of penetrative fracturing and the subsequent amount of healing of microcracks.

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1. INTRODUCTION

The Canadian Nuclear Fuel Waste Management Program (NFWMP) directed by Atomic Energy of Canada, Ltd., is focussing its research effort towards an assessment of the feasibility of disposing Canada's nuclear wastes in plutons deep within the Precambrian Shield in Ontario. This program, described more fully by Rosinger et al. (1982), has required the development and refinement of geological and geophysical surface, borehole, and laboratory techniques to define large and small scale discontinuities and inhomogeneities in rocks. Large scale discontinuities of interest are faults and joints which could affect the long term stability of a repository. Small scale discontinuities (microcracks) affect such laboratory-measured rock properties as porosity, density, thermal conductivity, permeability and engineering properties. Changes in these properties during or following mechanical or thermal stressing reflect adjustments of the microcrack structure to new stress conditions. The adjustments signal changes in the ability of a rock formation to act as a barrier to migrating fluids, or as a structural support.

Values of laboratory-measured rock properties of core samples from the Lac du Bonnet granite at the Whiteshell Nuclear Research Establishment (WNRE), Pinawa, Manitoba (Figure 1), can be correlated with depth (Figure 2) (Katsube 1981, Annor and Jackson 1982): Compressive strength and wave velocity decrease, while porosity and permeability increase with increasing sampling depth. Similar trends are not observed in corresponding geophysical borehole logs.

Figure 1. Location of Whiteshell Nuclear Research Establishment
(WNRE) Manitoba and Atikokan, Ontario drill sites.

FIGURE 1

Figure 2. Rock properties of WNRE core samples. Compressive strength and compressional wave velocity decrease, porosity and permeability increase with depth. Shown are data from boreholes WN-1, -2 and -4.

Sources: Annor and Jackson (1982) - compressive strength, compressional wave velocity (dots); Stesky (1980) - compressional wave velocity (open circles); Drury (1980) - porosity (x); Wadden (1979), Radwan (1980) - porosity (open squares); Cooley and Butters (1979), Peterson and Cooley (1980) - permeability.

FIGURE 2 ROCK PROPERTIES OF WNRE CORE SAMPLES

These trends, indicating increasing porosity with depth, are contrary to those observed in sedimentary rocks (Athy 1930; Thomas and Oliver 1979; Berner 1980, Hoholick et al. 1984) but have been observed in cores of other crystalline rocks (Simmons and Nur 1968; Kowallis and Wang 1983). Wang and Simmons (1978), Katsube (1981) and Kowallis and Wang (1983) attributed these trends to cracking of core as overburden stress is relieved by drilling.

In contrast, a wide range of values of the same rock properties without well defined correlation with depth is observed for core samples from the Eye-Dashwa Lakes pluton, Atikokan (ATK), Northwestern Ontario (Figures 1 and 3). Porosity and permeability of borehole ATK-1 core samples have been correlated with alteration (Katsube and Kamineni 1982): Highly altered samples were, in general, found to be less porous and permeable than less altered samples, and also have higher uniaxial compressive strength (A. Annor, pers. comm.).

Geological processes which increase or decrease the strength of rock have important bearing in engineering studies, such as repository design, that require measurements of rock properties of core samples. It is important to know if and why rock in the laboratory behaves differently from that in situ, so that reasonable predictions for in situ behaviour of rock can be made from laboratory tests.

This thesis examines the microcrack structures of samples of the Lac du Bonnet granite and the Eye-Dashwa Lakes Pluton, using

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Figure 3. Rock properties of ATK-1 cores samples. Compressive strength, compressional wave velocity, porosity, permeability do not show a good relation with depth but have been correlated with alteration (Katsube and Kamineni (1983). Numbers adjacent to the points plotted are the alteration intensity (related to the colour) of the samples: 1, unaltered (grey); 2, low alteration (pinkish grey); 3, moderate alteration (grey pink); 4, high alteration (pink).

Sources: Katsube and Kamineni (1983) - porosity (x), permeability, alteration index;

Drury (1980) - porosity (dots); Jackson and Mears (1982), McKay (1980) - compressive strength, compressional wave velocity.

2. General Geology and Sample Descriptions.

The specimens under study are from the Lac du Bonnet batholith, an Archean granitic pluton located in eastern Manitoba 16 km from the Ontario-Manitoba border, and the Eye-Dashwa Lakes pluton which is situated approximately 15 km northwest of Atikokan, Ontario.

2a. Lac du Bonnet Granite

The Lac du Bonnet batholith (Figure 4) is post-tectonic, Late Kenoran in age (2680 Ma), and has a faintly foliated core and foliated margins (Cherny et al. 1980, Tammemagi et al., 1980). Drill holes from which the specimens were collected are located at the Whiteshell Nuclear Research Establishment (WNRE), near Pinawa, Manitoba.

The samples display primary igneous textures and are representative of the homogeneous central portion of the batholith at the WNRE drill site. They are medium grained inequigranular, massive granites.

The average composition of 17 specimens collected over the 928 m length of borehole WN-4 is 30.4% quartz (standard deviation, $S=2.49$), 34.5% plagioclase feldspar ($S=3.23$), 30.2% microcline ($S=4.07$), and 4.4% mica (biotite, primary muscovite and chlorite; $S=1.37$) (Chernis 1981). Accessory minerals are sphene, epidote,

Figure 4. General geology of the WNRE-URL research areas (after
Tammemagi et al. 1980).

apatite, opaque minerals, monazite, zircon and fluorite.

Plagioclase grains (oligoclase) are white to pink, prismatic, zoned and less than 5 mm in cross section. Pink to grey prismatic, zoned microcline grains are up to 22 mm long and enclose euhedral plagioclase inclusions. The feldspar prisms are loosely packed and the interstices between grains are filled by quartz. Quartz grain boundaries have not been recrystallized although undulatory extinction is present.

Two suites of specimens were initially chosen to compare pore-microcrack structures from different depths at the WNRE site (Chernis 1983b). A "shallow suite" consisted of one moderately altered (pink) specimen from the 134 m vertical depth of borehole WN-1 and moderately altered samples from the 445 and 457 vertical depths of borehole WN-4. Specimen 134 contained part of a visible crack, which may be the tip of a larger-scale fracture. A "deep suite" consisted of three unaltered (grey) specimens from the 738 m vertical depth of borehole WN-4.

For this study, three new samples were cut from the 134 m interval of borehole WN-1. The previously collected data for specimen 134 have been discarded, as the cracking event which formed the visible crack affected the intragranular porosity and the grain boundary porosity of that sample. Specimens 445 and 457 have been grouped together to represent specimens from intermediate depths and are labelled suite 451, the midpoint of the two sampled intervals.

Figure 5. General geology of the Eye-Dashwa Lakes pluton,
Northwestern Ontario (from Brown et al. 1980). The ATK drill
site (black rectangle) is east of Forsberg Lake.

2b. Eye-Dashwa Lakes Pluton

The Eye-Dashwa Lakes pluton is an oval shaped composite body of syenodiorite, granite, and granodiorite which intrudes sodic to amphibolitic gneisses of the Dashwa gneiss complex (Figure 5). Its K-Ar age is 2500 Ma (Kaminen 1983). Brown et al. (1980) recognized three compositional phases within the pluton:

1. A coarse grained syenodiorite phase of variable composition and texture occurs both as a border phase to the main mass of granite, and as a small separate stock. Massive to flow banded and discontinuously layered portions are present.
2. A second border phase of massive-to-gneissic leucocratic granite occurs in the south and east portions of the pluton, and also surrounds gneissic xenoliths in the main granite body.
3. The main mass of the pluton is massive to foliated, porphyritic, homogeneous granite to granodiorite. The hornblende and plagioclase contents decrease and quartz content increases as the contact with the country rock is approached. Foliation defined by alignment of feldspars and mafic minerals parallels the contour of the contact.

Two samples from the Eye-Dashwa Lakes pluton were collected from borehole ATK-1 for microcrack analysis. The borehole cuts a

portion of the pluton which is fractured to varying degrees. Feldspars in approximately 80% of the core have been stained pink by fine iron oxide particles (Dugal et al. 1981; Kamineni and Dugal, 1981). Fracture zones are characterized by a particularly strong development of the pink coloration.

A moderately altered sample was chosen from the 120 m vertical depth level. Although sample 120 comes from near the bottom of a zone of high fracturing (up to 50/ m interval of core at 100 m depth), the immediate vicinity of the sample contains less than 5 fractures per metre. A grey, unaltered sample was taken from a zone of relatively few fractures ($< 5/m$) at approximately the 720 m vertical depth level.

The ATK-1 samples are categorized as granodiorites according to the classification of Streckeisen (1976). The average modal composition of a suite of 35 standard samples from borehole ATK-1 is 25.5% quartz ($S=5.45$), 46.7% plagioclase ($S=5.57$), 20.3% microcline ($S=5.88$), 1.0% hornblende ($S=1.00$) and 3.0% biotite ($S=1.74$) (Chernis 1981). The average modal composition of eighty specimens sampled at 5 m intervals over a length of 400 m from borehole ATK-3 is 25.0% quartz ($S=1.81$), 47.2% oligoclase ($S=0.91$), and 21.0% microcline ($S=1.77$) (Chernis and Nuyens 1982). Average hornblende and biotite contents are 0.9% ($S=0.50\%$) and 3.3% ($S=0.71\%$). Accessory minerals are epidote, sphene, opaques, calcite and fluorite. Boreholes ATK-1 and ATK-3 are approximately 320 m apart.

The higher standard deviations of the ATK-1 suite are attributed to a smaller measurement (thin section) area compared with the ATK-3 suite. The small standard deviations indicate that there is little variation in modal composition in the portion of the pluton where the specimens were chosen; therefore, variations in microcrack structure are not the results of mineralogical differences.

The ATK-1 specimens have a granitic texture and are composed of plagioclase feldspar, microcline, and quartz with undulatory extinction. The degree of continuity of the quartz grains is on average not as high as in specimens from WNRE. Plagioclase occurs as anhedral and euhedral grains with oscillatory zoning, and is less than 4 mm long. Microcline grains are anhedral to subhedral and less than 13 x 8 mm in cross section. Euhedral plagioclase inclusions and vein perthite are common in microcline.

Although deformation features are present the samples are not highly deformed and original granitic textures have not been disturbed. Mechanical twins and bent albite twin lamellae are present in plagioclase. Breaks without large offsets commonly occur across the albite twins along the basal plane. Basal cracking has also occurred in microcline along with development of a patchy or undulose extinction. These deformation features were formed late in the cooling history of the pluton, and are probably related to the fractures and fracture zones noted in core logs and surface geological mapping (Brown et al. 1980, Dugal et al. 1981; Hillary 1982).

3. History of Microcrack Studies by Scanning Electron Microscope

The first scanning electron micrographs of pores in crystalline rocks were published by Timur et al. (1971), but the large pores described in that paper were likely produced, or at least enhanced by their mechanical preparation methods. The following year Brace et al. (1972) used a device called an ion miller to remove the damaged surface layer produced by mechanical polishing methods. This was the first time that pristine sections through rock samples could be examined and natural microcracks identified with confidence. Since then, workers under the direction of Brace (Sprunt 1973; Sprunt and Brace 1974ab; Montgomery and Brace 1975; Hadley 1976; Tapponnier and Brace 1976) and Simmons (Simmons and Richter 1974; Batzle and Simmons 1976; Feves and Simmons 1976; Richter and Simmons 1977a, b; Siegfried et al. 1977; Simmons 1978; Shirey et al 1979, Batzle et al. 1980, Simmons and Caruso 1982; Padovani et al. 1982) of the Massachusetts Institute of Technology (MIT) have used microstructural analysis by SEM as support to laboratory studies of rock properties of granitic rocks. More recently, Beiriger and Duram (1984) used SEM techniques to study quartz monzonite samples from Nevada. Kranz (1983) presents a comprehensive review of microcrack terminology, observation techniques, and formation.

Modified versions of the techniques developed by the two groups at MIT are being used to provide information on the basic microstructure and thermal cracking behaviour of granitic rocks,

for the Nuclear Fuel Waste Management Program. The data obtained, principally porosity and crack density, complement results of laboratory-measured P-wave velocity and acoustic emission experiments, and are useful to the Program's studies of rock permeability, engineering properties and in-situ stress analysis.

4. Sample Preparation Techniques

Traditionally, one surface of a core 1 cm in diameter would be prepared as a polished section for use in microcrack studies (Sprunt and Brace 1974a). However, relations between microcracks and grains are often uncertain in polished section work - distinguishing cracks within grains from those surrounding grains may be impossible. Richter and Simmons (1977) overcame this problem by preparing from the end of 1 cm cores of rock samples, 100 μ m thick "crack sections" which allowed the use of a transmitted light microscope to differentiate between cracks within the crack sections.

The samples used in the current study are similar to the crack sections of Simmons and Richter (1974), but unlike the crack sections both upper and lower surfaces are ion milled to completely rid the sections of enhanced cracks. These samples may be used for serial section work if 3-dimensional analyses of cracks are desired. The sections are called DIM (doubly ion milled) sections.

Production of the DIM Sections initially involves carefully preparing one of the faces of a 20 x 20 x 3 mm tablet cut from a 45mm diameter core as a polished section. Tabular specimens cut from rock samples by use of a low speed (ISOMET) saw are favoured over those cored from larger samples (see Padovani et al. 1982), as drilling is a much more violent process. Saw-induced artifacts are removed by polishing with progressively finer grits at load

pressures of less than 2 kg. The final polishing stage uses particles of $1\mu\text{m}$ size. Samples are cut perpendicular to any fabric which may be present in the core.

The polished surface of the slab is then ion milled for a minimum of 12 hours with a Technics MIM IVC ion miller (described briefly below) to remove scratches and other artifacts produced by the polishing technique. The long exposure to the ion beam also produces a surface with an exaggerated topography that provides for an improved bond of the polished surface to a glass slide. The polished surface is then ion milled to remove scratches and other damage which has occurred in a thin surface layer of the section. The milling time in this final stage is kept to a maximum of about six hours to avoid the production of an over-exaggerated topography with a high density of milling-induced hummocks which may mask surface features.

An ion miller produces a beam of ionized argon, accelerated through a potential of typically 4-6 kV. The ionized beam bombards a target (sample) surface contained within a vacuum chamber and individual atoms are ejected from the surface. No direct relationship exists between physical hardness of minerals and their milling rates. The rate at which material is removed seems to depend on the atomic weight of constituent atoms and nature of bonds in the target. Physically soft materials are often not milled entirely away. Other factors which control the absolute rates of milling are the ion current, milling angle (the angle between the ion beam and the target surface) and the vacuum level.

The origin of milling artifacts has been attributed to microscopic surface unevenness or foreign particles (Stewart and Thompson 1969; Tsong and Barber 1973), dislocation arrays (Mazey et al. 1968), and orientation of crystal surface elements having different sputtering rates (Barber et al. 1973). The hummocks observed in the DIM sections appear to be related to imperfections in the minerals. The imperfections act as nucleation sites for hummocks which enlarge and become more numerous with increased exposure to the ion beam. The hummocks are commonly developed at locations where rutile micro-needles in quartz intersect the surface of the DIM section.

Microcracks much less than $1\mu\text{m}$ in width may contain delicate features which span the width of the cracks, and which Brace et al. (1972) termed bridges. Specimens prepared in the above manner lack microcracks with broken bridges and are considered to be mechanically undisturbed.

5. Sample Observation Technique

Mosaics of colour photomicrographs with a magnification of approximately X30, are used for preliminary observations of the specimen prior to observation by SEM, and as "base maps" during SEM examination. The micrographs are produced with a 35mm camera accessory mounted on a petrographic microscope, and illustrate the entire area of the DIM sections (approximately 4 cm²). The above mosaics allow a more representative sampling of microcracks than is possible with a mosaic covering a small area and composed of low magnification SEM micrographs (see Batzle and Simmons 1976; Hadley 1976). In addition, the mosaics are produced at a much lower cost, and do not require valuable SEM time.

The specimens are coated with a 25-50 Å thick layer of Au-Pd alloy before examination with the SEM. This thin coating produces a high secondary electron emission for high magnification work, but does not hinder optical microscopy that may be necessary.

Measurements of microcrack widths or lengths, in previous studies were made directly from the SEM cathode ray tube (CRT), or from polaroid images. In this study a high resolution U-matic video tape recorder (VTR, Sony Model Y0-2610) is used for all image storage during routine examination of the DIM sections. This recording format produces images of comparable quality to polaroid photomicrographs, at a considerably reduced cost. The speed of videotape recording allows three to four times the number of images

to be recorded per SEM session, compared to photographic methods. One disadvantage of this system, is that only one image may be viewed at a time. However, polaroid photographs of the image on the video monitor may be taken and used to compare features in two or more images.

The method of recording involves placing the image into a capacitor storage unit within an ETEC Autoscan SEM, then transferring the image to the videotape recorder.

The specimens are mounted in the SEM on a stage which allows translation in the X and Y directions. Data is gathered following the lineal analysis techniques described by Underwood (1970): Traverses are made across the specimen with the SEM, and an image of each grain boundary crack or transgranular crack which crosses the traverse line is recorded.

Preliminary work showed that pores similar to those in plagioclase feldspar are almost absent in quartz, and cracks in quartz are rare. For these reasons, microcracks within quartz grains are grouped with the grain boundary cracks. Intragranular crack analyses of other major minerals are done on a number of representative grains of each major mineral constituent, by traversing perpendicular to the direction of dominant intragranular microcrack alignment in each grain examined, in feldspar usually the 001 and 010 cleavages. Approximately 200 grain boundaries and 70 intragranular cracks for each major mineral are examined. Given

the limited amount of time available on the SEM, crack lengths were not measured.

6. Method of Data Collection and Analysis

In this study, the total crack porosity of the rocks consists of:

- (a) Smooth wall crack (SWC) porosity, the part of interconnected porosity due to idealized parallel-sided smooth-walled cracks.
- (b) Crack wall (CW) porosity, the porosity produced by irregularities (pits, asperities) in the walls of the cracks.
- (c) Isolated pores are not included in the microcrack analyses.

Three intercepts are measured with vernier calipers along a traverse line T, placed on the screen on the video monitor (Figure 6):

- Crack width intercept (l_w for clarity, shown at location a, Figure 6)
- Total crack porosity intercept (l_{tc} , b on Figure 6)
- Smooth-wall crack porosity intercept (l_{swc} , c on Figure 6)

The crackwall porosity intercept (Q_{cw}) is

$$Q_{cw} = Q_{tc} - Q_{swc}$$

Since cracks were not always oriented exactly perpendicular to the traverse line, the porosities of individual cracks are slightly overestimated. However, these errors in this type of analysis are considered to be negligible (Underwood 1970, p. 67).

This information, along with the crack types and image magnifications is placed on coding forms (Appendix I) and then typed into a computer data file. The data are then manipulated by a computer program (Appendix II), which sorts out the data by crack type and crack width.

The mean and standard deviation, and also the minimum and maximum crack width of each crack type are calculated, along with the frequency of each grain boundary or intragranular crack, and the proportion of each type that are open (not bridged) at the measurement point.

The arithmetic and geometric mean crack widths and the crack density are calculated for the grain boundary crack population and the intragranular crack population of each major mineral. The arithmetic mean crack width A , is found by summing the crack widths W and dividing by the number of cracks N :

Figure 6. Crack parameters measured along the SEM traverse line (T)
are: a, crack width; b, total crack porosity; c, smooth wall
crack porosity. The crack wall porosity is $b-c$.

FIGURE 6
CRACK PARAMETERS MEASURED
ALONG THE SEM TRAVERSE LINE

$$A = \frac{W}{N} \quad (2)$$

The geometric mean crack width G (logarithmic form), is given by (Underwood 1970):

$$G = 10^a \text{ where } a = \frac{\text{Log } W}{N} \quad (3)$$

Crack density D , is found by dividing the number of open cracks N , by the traverse length L :

$$D = N/L \text{ (Cracks /mm of traverse length)} \quad (4)$$

The porosity Φ , of each crack type and crack width class is found by summing the appropriate intercept length (l_{tc} , l_{cw} , l_{swc}), Figure 6) and dividing by the traverse length:

$$\Phi_{(tc, cw, swc)} = \frac{\sum l_{(tc, cw, swc)}}{L} \times 100 \quad (5)$$

Crack width distributions (crack width versus porosity) are plotted by a batch program using DISSPLA library routines (Appendix III). The total porosity of the rock sample is calculated by a weighted average procedure as shown in Figure 7:

1. Intragranular porosities are weighted by the modal volume of each respective mineral.

2. The weighted intragranular porosities are summed and divided by the sum of the weights to give the intragranular porosity of the sample.

3. The intragranular porosity and grain boundary porosity are weighted by their respective crack densities. (A weighted average intragranular crack density is used for the intragranular crack density).

4. The weighted porosities are summed and divided by the sum of the weights to give the total porosity of the sample.

The crack density, arithmetic and geometric mean crack widths, and total intersected crack aperture of the rock sample are produced by the above weighting procedure.

The results of SEM lineal analyses of the samples are presented in graphic form (Figures 9-12 (WNRE samples), and 13-16 ATK samples). The logarithmic horizontal axes (crack width) are divided into 10 classes with limits of: $< 0.03 \mu\text{m}$, $0.03-0.06 \mu\text{m}$, $0.06-0.10 \mu\text{m}$, $0.10-0.18 \mu\text{m}$, $0.18-0.32 \mu\text{m}$, $0.32-0.56 \mu\text{m}$, $0.56-1.00 \mu\text{m}$, $1.00-1.76 \mu\text{m}$, $1.76-3.16 \mu\text{m}$ and $> 3.16 \mu\text{m}$. The total crack porosity of each crack width class is plotted on the left vertical axis, subdivided into smooth wall crack porosity (shaded portion of bars) and crack wall porosity (unshaded bars) (Figure 6) The right vertical axis, labelled "Relative Frequency", is used to plot the relative number of cracks expressed as a percentage of the

Figure 7. Weighting procedure for the microcrack statistics. Total intersected crack aperture (A_T), crack density (D), arithmetic mean crack aperture (A), and geometric mean crack aperture (G). Pl=plagioclase, Kfs=microcline, Int=intragranular, Gb=grain boundary, Rs=rock sample.

Figure 7: Weighting Procedure for the Microcrack Statistics.

total number of cracks observed in each crack width class (vertical black bars). The geometric and arithmetic mean crack widths (G and A, respectively) are also plotted on each histogram. The crack wall and smooth wall crack porosities, and the crack densities (number of cracks per mm of traverse) are given in the legend of each diagram.

The porosities observed with the SEM are generally about 50% lower than measured in the laboratory by an immersion technique (Table 1), primarily because of the inability of the SEM to resolve cracks finer than about $100\text{\AA}$. As discussed below such fine cracks may provide undetected links between "isolated" pores such as are common in plagioclase, and the bulk of the crack structure. Nevertheless, the values presented here are internally consistent.

Table 1 Rock Properties of the WNRE Samples Under Investigation

Sample	SEM	Porosity (Z) Immersion ¹	Permeability ² (Microdarcies)	Compressional Wave Velocity ³ (km/s)	Compressive Strength 3 (MPa)
WN1-134	0.078	a 0.35 b 0.2	0.7	4.8	213
WN4-451	0.195	a 0.31 b 0.4	4.3	3.9	176
WN4-738	0.276	a 0.56 b 0.6	17.3	2.6	166

Sources: 1. a Wadden (1979), Radwan (1980) b Drury (1980)
 2. Cooley and Butters (1979), Peterson and Cooley (1980)
 3. Annor and Jackson (1982)

7. Results of Lineal Analyses

7a Lac du Bonnet granite.

In a previous study, Richter and Simmons (1977) concluded that Precambrian igneous rocks in the central United States contain few open microcracks. These authors and others (Brace et al. 1972; Sprunt and Brace 1974) also showed that cracks in crystalline rocks are most commonly associated with grain boundaries. The proportion of grain boundaries occupied by open space may be as high as 90% in some granites (Sprunt and Brace 1974). In addition, spherical and slot-like pores that are possibly connected to grain boundaries have been observed in specimens of plutonic plagioclase in amounts of up to 2.3% by volume (Montgomery and Brace 1975). The present study confirms that grain boundary cracks form a continuous network of cracks, but they are by no means the most abundant crack type present in the Lac du Bonnet granite.

Quartz, plagioclase, and microcline - the three major minerals comprising the specimens - contain microcracks and pores which account for a major portion of the porosity and microcrack structure of the samples. Plagioclase is sericitized in its calcium rich zones, and the sericite is observed with the SEM as fine flakes occupying pores (Plate 1). The pores may be isolated within grains, or intersected by cleavage cracks. Many cleavage cracks are so fine that they do not contribute significantly to the porosity of the samples, unless they intersect pores. Cracks within plagioclase may be lined with sericite, clay minerals, albite

L

Plate 1. Extremely fine cleavage cracks in plagioclase intersecting
irregular shaped pores. Lac du Bonnet granite.

Plate 2. Basal cleavage crack with irregular walls, bridges (B),
and blunt termination (T), in microcline, Lac du Bonnet
granite.

or iron oxide.

The most obvious cracks within microcline grains are basal cleavage cracks. These cracks range from straight narrow features with clean walls to large gaping cracks over $1\mu\text{m}$ in width, with irregular walls. Crack terminations are typically blunt (Plate 2). Pores, common in plagioclase, are rare in microcline.

Quartz also has fewer pores than plagioclase. Rows of isolated spherical or tubular pores in quartz are healed cracks (Plate 3). Cracks associated with quartz are variable in character, ranging from straight features with clean parallel walls to cracks with large amounts of filling material such as calcite, iron oxide or clay.

The morphology of grain boundaries is influenced by the crystallography of the minerals that make contact. Grain boundaries between biotite and microcline for example, are very straight where the contact is along the basal plane of the mica, but are otherwise extremely jagged. Cracks at contacts between feldspars tend to be jagged or densely bridged (Plate 4).

Although feldspars comprise a large proportion of the volume of the rock, they have a relatively small area of mutual contact; this limits the number of feldspar-feldspar grain boundaries in a given volume of rock. The most common grain boundaries in the Lac du Bonnet granite are associated with quartz grains. This is because of the large relative surface area of contact between

Plate 3. Row of isolated pores in quartz is a remnant of a healed crack. Lac du Bonnet granite.

- Plate 4. Grain boundary crack between two plagioclase grains. This densely bridged, rough-walled crack is typical of grain boundary cracks between feldspars in the Lac du Bonnet granite.

quartz grains, and between quartz and feldspars (Figure 8).

Sharp-tipped microcracks with clean parallel walls (Plates 5, 6) are present in samples WN4-451 and WN4-738. These cracks are absent in specimen WN1-134. Approximately 30% of the cracks in sample WN4-738 have the sharp-tipped form; about 5% of the cracks in sample WN4-451 have this form. They are up to $5.1\mu\text{m}$ wide in sample WN4-738, but are an order of magnitude narrower in sample WN4-451 (Plate 7). The sharp-tipped, parallel-walled microcracks occur at grain boundaries or as intragranular cracks.

Similar sharp-tipped cracks have been observed in specimens of granite (Feves and Simmons 1979; Tapponnier and Brace 1976; Kranz 1979), and were interpreted as stress induced features. Their origin is discussed below.

Each of the three samples has different microcrack properties which reflect the apparent increase in porosity with sampling depth (Figure 9 a-c):

- The total crack porosity increases from 0.078% at 134m to 0.195% at 451m and to 0.276% at 738m.
- The smooth wall crack porosity increases from 0.038% at 134m, to 0.107% at 451m, and to 0.237% at 738m.
- The arithmetic (A) and geometric (G) mean crack widths increase from $A=0.12\pm 0.18\mu\text{m}$, $G=0.06\mu\text{m}$ at 134m, to $A=0.17\pm 0.30\mu\text{m}$, $G=0.07$

Figure 8. Sketch of the texture of the Lac du Bonnet granite. Note the extensive area of contact between quartz grains, and between quartz and feldspars.

FIGURE 8

Plate 5. Low magnification view of sharp tipped cracks (SC) in sample WN4-730, Lac du Bonnet granite. These cracks occur in quartz (QTZ), plagioclase (PL), and microcline (Kfs).

Plate 6. Sharp tipped crack in sample WN4-738, showing characteristic clean, parallel-walled and sharp tipped form.

Kfs

1004M

Plate 7. Left: Low magnification view of sharp-tipped stress induced crack in sample WN4-451, Lac du Bonnet granite. Right: Higher magnification view of the central portion of image on left. These two plates, photographed with a hand held polaroid camera, are photos of images stored on videotape and replayed on a video monitor.

Figure 9. Rock sample crack spectra for samples WN1-134 (9a), WN4-451 (9b) and WN4-738 (9c). The logarithmic horizontal axis (crack width) is divided into 10 classes with limits of $< 0.03\mu\text{m}$, $0.03-0.06\mu\text{m}$, $0.06-0.10\mu\text{m}$, $0.10-0.18\mu\text{m}$, $0.18-0.32\mu\text{m}$, $0.32-0.56\mu\text{m}$, $0.56-1.00\mu\text{m}$, $1.00\mu\text{m}-1.76\mu\text{m}$, $1.76-3.16\mu\text{m}$, and $>3.16\mu\text{m}$. The total crack porosity (in percent) of each class is plotted on the left vertical axis and is subdivided into smooth wall crack porosity (shaded bars) and crack wall porosity (unshaded bars). On the right vertical axis is plotted the relative number of cracks observed in each class (vertical narrow black bars), expressed as a percentage of the total number of cracks, and is labelled "Relative Frequency". The geometric and arithmetic mean crack widths (G and A, respectively) are also plotted (arrows). The crack wall and smooth wall crack porosities, and the crack density (cracks/mm of traverse) and given in the legend.

FIGURE 9A SAMPLE WN1-134

FIGURE 9B SAMPLE WN4-451

FIGURE 9C SAMPLE WN4-738

μm at 451m, and to $A=0.31\pm0.65\mu\text{m}$, $G=0.09\mu\text{m}$ at 738m.

- The proportion of cracks wider than $1.0\mu\text{m}$ increases from less than 1% at 134m, to 3.0% at 451m, and to 12.0% at 738m.
- The proportion of cracks narrower than $0.1\mu\text{m}$ is largest at 134m (77.6%); and decreases to 58.6% at 451m, and 57.3% at 738m.
- The lowest cracks density occurs at 134m ((1.96 cracks/mm). Crack densities are similar at 451m (4.72/mm) and 738m (4.07/mm).

From figures 10-12, increases in grain boundary and intragranular crack density and porosity with increasing sampling depth are apparent:

- Grain boundary smooth wall crack porosity increases from 0.010% at 134m, to 0.043% at 451m, and to 0.132% at 738m.
- Plagioclase intragranular smooth wall crack porosity increases from 0.025% at 134m, to 0.088% at 451m, and to 0.102% at 738m.
- Microcline intragranular smooth wall crack porosity increases from 0.059% at 134m, to 0.100% at 451m, and to 0.218% at 738m.
- Grain boundary crack density increases from 0.73 cracks/mm at 134m, to 1.01/mm at 451m, and to 1.46/mm at 738m.

Figure 10. Grain boundary crack spectra for samples WN1-134
(10a), WN4-451 (10b), and WN4-738 (10c). See caption to
Figure 9 for explanation of the plotted quantities.

FIGURE 10A WN1-134:GB

FIGURE 10B WN4-451:GB

FIGURE 10C WN4-738:GB

Figure 11. Plagioclase intragranular crack spectra for samples WN1-134 (11a), WN4-451 (11b), and WN4-738 (11c). See caption to Figure 9 for explanation of the plotted quantities.

FIGURE 11A WN1-134:PL

FIGURE 11B WN4-451:PL

FIGURE 11C WN4-738:PL

Figure 12. Microcline intragranular crack spectra for samples WN1-134 (11a), WN4-451 (12b), and WN4-738 (12c). See caption to Figure 9 for explanation of the plotted quantities.

FIGURE 12A WN1-134:KFS

FIGURE 12B WN4-451:KFS

- Plagioclase intragranular crack density increases from 1.65 cracks/mm at 134m to 5.04/mm at 451m, and 4.99/mm at 738m.

- Microcline intragranular crack density increases from 3.24 cracks/mm at 134m, to 5.99/mm at 451m then falls to 4.00/mm at 738m.

Table 2 lists the ratios of grain boundary crack wall, smooth wall crack, and total crack porosities to the sample crack wall, smooth wall crack, and total crack porosity. With the exception of ratio 1 (grain boundary total crack porosity to sample total crack porosity) the ratios in Table 2 for sample 451 have values intermediate between those of samples 134 and 738. The values of ratio 2 indicate that the total crack porosity of all three samples is approximately equally divided between grain boundary porosity and intragranular porosity. Ratio 2 shows a trend of decreasing proportions of grain boundary crack wall porosity to sample crack wall porosity with depth.

Ratio 3 shows a trend of increasing proportions of grain boundary smooth wall crack porosity to sample smooth wall crack porosity, with depth. Ratio 4 shows a trend of increasing proportions of rock sample smooth wall crack porosity to rock sample total crack porosity, with depth.

Table 3 lists the proportions of the grain boundary total crack porosity and grain boundary cracks which are associated with quartz. In all three samples, quartz is the most important source

Table 2 Porosity Ratios for Lac du Bonnet Granite Samples. Ratios are:

1. Grain boundary total crack porosity to sample total crack porosity
2. Grain boundary crack wall porosity to sample crack wall porosity
3. Grain boundary smooth wall crack porosity to sample smooth wall crack porosity
4. Sample smooth wall crack porosity to sample total crack porosity.

Sample Ratio	WN4-134	WN4-4510	WN4-738
1	0.50	0.49	0.52
2	0.72	0.59	0.33
3	0.26	0.40	0.56
4	0.49	0.55	0.86

Table 3

Percentage of: 1. Grain boundary total crack porosity associated with quartz;
and
2. Grain boundary cracks associated with quartz
for Lac du Bonnet granite samples

Sample	WN1-134	WN4-451	WN4-738
Percentage			
1.	93.3	95.5	93.9
2.	89.8	87.7	89.2

of grain boundary porosity and grain boundary cracks. The proportion of cracked grain boundaries increases with sampling depth: 37% are cracked in sample 134, 56% are cracked in sample 451 and 62% are cracked in sample 738.

In summary, in the WNRE samples the amount and proportion of crack wall porosity decreases with depth. The amount and proportions of smooth wall crack porosity, the crack density, arithmetic and geometric mean crack widths of the samples increase with depth. Quartz is the most important site of grain boundary total crack porosity. Porosity is equally divided between grain boundary cracks and intragranular cracks.

7b Eye-Dashwa Lakes pluton

Although the texture of the ATK samples is similar to that of the WNRE specimens, the lower modal volume of quartz and smaller grain size of plagioclase makes quartz grain boundaries less predominant, and feldspar-feldspar contacts more prominent.

Both suites from ATK-1 contain stress cracks similar to those observed in previous studies of granitic rocks (Feves and Simmons 1976, Tapponnier and Brace 1976, Kranz 1979, Kowallis and Wang 1983). Their form suggests an extensional origin, but these stress cracks have features which indicate that they were formed well before the drilling operation commenced.

Newly formed stress cracks, such as those observed in WN-4

samples, have clean parallel walls and sharp tips (Plate 6). In contrast, the stress cracks in the shallow ATK-1 suite show signs of extensive healing, such as irregular walls and blunt terminations (Plate 8), or have developed slot-like internal structures while retaining remnants of sharp terminations (Plate 9).

Stress cracks in the deep suite have retained their sharp terminations, and their walls may be variably affected by precipitation or dissolution processes (Plates 10-12).

Plate 10 shows a microcrack which has developed along the (010) cleavage in plagioclase. Albitic infilling materials partially block the crack at area B, where the crack has departed from the (010) cleavage. Albitic fillings are also present at area C, along tensional cracks which parallel the (001) cleavage. Area D illustrates that well-preserved, sharp crack tips can occur along fractures which contain filling materials, in unaltered specimens.

Delicate infillings are also present along the straight-walled portions of the crack shown in Plate 10 (Plate 11 a few hundred microns beyond the field illustrated in Plate 10), indicating that reactivation of such cracks by relaxation of stress, as at WNRE is not likely to have happened.

Plate 12 illustrates another old stress crack in plagioclase in specimen 720, that has undergone a relatively large amount of healing in comparison to the crack in Plate 10. Bridges have

Plate 8. A: Partially healed stress crack still exhibits characteristic form, but has developed irregular walls and blunt tips. B: View of blunt crack tips in image on left. Sample ATK1-120.

Plate 9. Partially healed stress crack in sample ATK1-120. A slot-type structure has developed in the crack tip region.

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Plate 10. Stress crack following (010) cleavage in plagioclase, sample ATK1-720. In-filling materials are present where the crack departs from the (010) direction (B), and also in pores along the basal direction (C, detail at left), while portions of the crack walls remain clean and straight, and crack tips are sharp (D, detail at left).

10 μm

Plate 11. Delicate in-filling material (albite?) along the crack in Plate 10. Such intact filling indicates that this is an old natural crack which has not been reactivated by the drilling process.

22
OF / DE

Plate 12. Variably healed stress crack in plagioclase, sample ATK-720. Bridged of albitic material are arrowed. Note the extensive healing of a portion of the crack marked by the second arrow from the bottom of the photo, compared to the portion of the crack at the top of the photo.

10 μm

developed at numerous points (arrows). The second arrow from the bottom indicates a portion of the crack that has been almost completely healed.

Cracking in plagioclase and microcline is common along the two cleavage directions but basal cracks predominate (Plate 13) in accordance with petrographic observations (Chernis and Nuyens 1982). Hornblende in both suites appears to have very low porosity. Chlorite and biotite may have high densities of basal cleavage cracks, but the narrow widths of cracks provide very little pore space. Ilmenite inclusions in sphene contain relatively large amounts of porosity, but because they are present in only trace amounts they probably do not contribute significantly to the pore-microcrack structure of these rocks.

The crack spectra of the shallow and deep samples are distinctive and are quite dissimilar to those of the WNRE samples. Their differences are illustrated in Figures 13-16. Compared to sample 120, sample 720 has higher total crack porosities, SWC porosities, larger arithmetic and geometric mean crack widths and greater crack densities.

- Crack porosity of microcline in sample 120 (0.018%) is less than the crack porosity of microcline in sample 720 (0.026%).
- Crack density in microcline of sample 120 (3.33/mm) is similar to the crack density of microcline in sample 720 (3.97/mm).

Plate 13. Basal cleavage crack in plagioclase, sample ATK1-720.

Shear cracks (S) have developed along antiperthite lamellae (light bands) and slots with round ends have formed between the lamellae (B).

Figure 13. Rock sample crack spectra for samples ATK1-120 (13a)
and ATK1-720 (13b). See caption to Figure 9 for
explanation of plotted quantities.

FIGURE 13A SAMPLE ATK1-120

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FIGURE 13B SAMPLE ATK1-720

Figure 14. Grain boundary crack spectra for samples ATK1-120 (14a) and ATK1-720 (14b). See caption to Figure 9 for explanation of plotted quantities.

FIGURE 14A ATK1-120:GB

FIGURE 14B ATK1-720:GB

Figure 15. Plagioclase intragranular crack spectra for samples
ATK1-120 (15a) and ATK1-720 (15b). See caption to Figure 9
for explanation of plotted quantities.

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FIGURE 15B ATK1-720:PL

Figure 16. Microcline intragranular crack spectra for samples
ATK1-120 (16a) and ATK1-720 (16b). See caption to Figure 9
for explanation of plotted quantities.

FIGURE 16A ATK1-120:KFS

FIGURE 16B ATK1-720:KFS

- The arithmetic mean (A) and geometric mean (G) widths of cracks in microcline of sample 120 are lower than those of sample 720:
 $A_{120}=0.06\pm0.11\text{ }\mu\text{m}$, $A_{720}=0.08\pm0.17\text{ }\mu\text{m}$, $G_{120}=0.03\text{ }\mu\text{m}$, $G_{720}=0.04\text{ }\mu\text{m}$;

Table 4 lists the ratios of grain boundary crack wall, smooth wall crack and total crack porosities to sample crack wall, smooth wall crack and total crack porosities for the two samples from ATK-1. Ratio 1 shows that grain boundaries are important sites for porosity in both samples. However, while most (80%) of the total crack porosity of sample 120 occurs along grain boundaries, only 44% of the total crack porosity in sample 720 occurs at grain boundaries. Ratio 2 indicates that in sample 120, most (87%) of the crack wall porosity occurs along grain boundaries, while in sample 720, 41% of the crack wall porosity occurs along grain boundaries. Ratio 3 indicates that about one half of the smooth wall crack porosity of each sample is grain boundary smooth wall crack porosity ($R_2(120)=0.47$, $R_2(720)=0.46$). However, only 17% of the total crack porosity of sample 120 is smooth wall crack porosity (Ratio 4), while 59% of the total crack porosity of sample 720 is smooth wall crack porosity (Ratio 4).

Table 5 shows the importance of quartz and plagioclase grain boundaries for the porosity of the samples. Almost 98% of the grain boundary total crack porosity of sample 120 occurs around quartz grains, and just over 50% of the grain boundary total crack porosity of sample 720 occurs around quartz grains. Almost 75% of

Table 4 Porosity Ratios for Eye-Dashwa Lakes Pluton Samples. Ratios are:

1. Grain boundary total crack porosity to rock sample total crack porosity;
2. Grain boundary crack wall porosity to rock sample crack wall porosity;
3. Grain boundary smooth wall crack porosity to rock sample smooth wall crack porosity;
4. Rock sample smooth wall crack porosity to rock sample total porosity.

Sample Ratio	ATK1-120	ATK1-720
1	0.80	0.44
2	0.87	0.41
3	0.47	0.46
4	0.17	0.59

Table 5 Percentages of:

1. Grain boundary total crack porosity associated with quartz;
2. Grain boundary total crack porosity associated with plagioclase;
3. Grain boundary cracks associated with quartz;
4. Grain boundary cracks associated with plagioclase,

for Eye-Dashwa Lakes Pluton samples.

Sample	ATKI-120	ATKI-720
Percentage,		
1	97.5	51.6
2	7.7	51.8
3	73.8	46.2
4	53.7	57.3

the grain boundary cracks in sample 120 are associated with quartz. In sample 720, 46.2% of the grain boundary cracks occur around quartz.

Plagioclase grain boundaries are a more important source of porosity in sample 720 than in sample 120: 51.8% of the grain boundary total crack porosity of sample 720 occurs at plagioclase grain boundaries, while just 7.7% of the grain boundary total crack porosity of sample 120 occurs around plagioclase grains. 53.7% of the grain boundary cracks encountered in sample 120 are around plagioclase grains (33% are between plagioclase and quartz). A similar proportion of grain boundary cracks (57.3%) in sample 720 are associated with plagioclase (16% are between plagioclase and quartz).

In summary, the total crack porosity of sample 120 is significantly lower than that of sample 720. Both grain boundary and intragranular porosities of sample 120 are low (0.076 % and 0.018% respectively). Smooth wall crack porosity of sample 120 is extremely low (0.016%). Crack wall porosity is concentrated along grain boundaries in sample 120. Smooth wall crack porosity of both samples is approximately equally divided between intragranular and grain boundary cracks.

The arithmetic and geometric mean crack widths and the crack densities of sample 120 are lower than those of sample 720.

Quartz is the most important source of grain boundary total crack porosity in sample 120. The most common grain boundary cracks in sample 120 are those around quartz grains. In sample 720, both quartz and plagioclase grain boundaries are important locations of cracks and porosity.

8. Interpretation of Results

(a) Lac du Bonnet Granite

The higher total porosity of the deep sample, a result of a much higher smooth wall crack porosity, can be attributed to the presence of sharp-tipped microcracks (Plates 5, 6) which are interpreted to be newly formed stress-induced cracks. An extensional origin for these cracks is suggested by their clean, parallel, sometimes jagged walls (Plate 14).

According to Nur and Simmons (1970), stress cracks can form in the rock ahead of a drill core bit which is advancing through a stressed rock. Discing of core occurs when stresses are high. Discing has been observed in core from WNRE site (Brown 1982), and high horizontal stresses have been measured in borehole WN-4 (Haimson, 1982).

Wang and Simmons (1978) proposed that cracking of core results from the relief of stress when the samples are removed to the surface. This stress relief interpretation is supported by the restoration of "normal" compressional wave velocities (4.2-4.9 km s⁻¹) to samples from deeper than about 400m, with application of confining pressure. The confining pressure required to restore the velocities also increases with sampling depth (Chernis and Stesky, 1984).

The sharp-tipped cracks seen in the WNRE specimens (samples 451,

Plate 14. Step-like portion of stress crack in sample WN4-738,
Lac du Bonnet granite. Presence of unbroken, jagged
matching walls indicates that this crack is a result of
tensional stress.

Plate 15. Plagioclase (pl)-quartz (Qtz) grain boundary, sample WN4-451, blocked with Fe. Bright triangular grain to right of center is an Fe-rich particle. This type of crack filling gives the specimens a pink cast.

738) are therefore likely stress-induced cracks formed by the relief of horizontal and vertical stresses. The amount of stress cracking in the specimens from the WNRE site appears to increase with sampling depth. This is reflected by increased porosity, permeability and decreased P-wave velocity of core samples, with increasing sampling depth (Figure 2).

However, although stress cracks are present in sample WN4-451, they are not sufficiently numerous or wide to account for the larger porosity compared to sample WN1-134. The difference in porosity of these two samples is, therefore, largely natural, and not attributable solely to stress cracking. Alteration may have affected the crack structure of sample WN1-134 more than sample WN4-451.

The formation of stress cracks in sample WN4-738 caused an increase of crack density, average crack width, and smooth wall crack porosity. Stress cracks up to $5.1\mu\text{m}$ in width formed.

To recover the in situ microcrack properties of sample WN4-738 (porosity, crack density, mean crack width) fresh sharp-tipped stress cracks were removed from the data set. The result is shown in Figure 17. The resultant "in situ" crack porosity does not account for any expansion of pre-existing cracks that may have taken place during the early stages of stress cracking, as is observed during compressive loading of granitic rock (Tapponnier and Brace 1976). Since broken bridges and filling materials were

Figure 17. Rock sample crack spectrum for sample WN4-738 (in situ). See caption to Figure 9 for explanation of plotted quantities.

FIGURE 17 WN4-738 IN SITU

not observed in the natural cracks, it is concluded that expansion has not had as large an effect on the porosity as has the formation of new cracks. This agrees with Hadleys (1976) observations in stressed Westerly granite.

Removing these cracks lowers the porosity by almost 50% (see also Figure 9c). The most significant effect of stress cracking in the sample is the increase in porosity and crack density due to formation of cracks over $1\mu\text{m}$ wide.

The crack spectra of sample WN4-738 (in situ) and WN4-451 are similar (Figures 17 and 9b). The total crack porosity of sample WN4-738 (in situ) is 22% lower than that of sample WN4-451, but it is almost double the total crack porosity of sample WN1-134. The smooth wall crack porosities of sample WN4-738 (in situ) and sample WN4-451 are similar, but the crack wall porosity of sample 451 is much greater (2.4 times) than the crack wall porosity of sample WN4-738 (in situ). This is consistent with the higher alteration state of sample WN4-451. The geometric mean and arithmetic mean crack widths of sample WN4-738 (in situ) and WN4-451 are identical, and reflect the similar frequency distributions of crack widths of the two samples. Given the similar porosities and crack densities of samples WN4-451 and WN4-738 (in situ), their in situ rock properties should also be similar.

Pores which are intersected by cracks, or formed by dissolution

of material from crack walls, are generally larger in the shallow sample. The larger proportion of crack wall porosity in sample 134 compared to sample 778 may be an indication of long term presence of fluids in sample WN1-134 which have modified the microcrack walls through dissolution and precipitation of material. This is supported by the pink colour of the shallow specimens, a result of iron staining of microcracks with irregular walls (Plate 15). The gray granite (sample 738) on the other hand, contains fewer cracks with highly irregular walls (lower crack wall porosity), and lacks iron-stained cracks. These observations may indicate a lower rate of fluid flow attributable to a lower porosity at depth and/or a drier environment.

(b) Eye-Dashwa Lakes Pluton

Relationships between alteration intensity and uniaxial compressive strength (Annor, pers. comm. 1983), porosity, permeability, tortuosity (Katsube and Kamineni 1983), and magnetic susceptibility (Morris Magnetics 1979), have been observed by investigators in the NFWMP. However, these authors have not described the metamorphosis of the microcrack structures of the rocks during progressive alteration. The following paragraphs are an interpretation of the patterns of rock properties observed in borehole ATK-1 (Figure 3) which result from local variations in fracturing and alteration intensities of the rock matrix.

The ATK-1 core is variably fractured: Portions of the core

contain more than 50 macrofractures m^{-1} while other portions contain less than 5 macrofractures m^{-1} (Figure 18).

In a rock body with such a wide range of fracture density, a wide range of properties would be expected for the wall rock even without any alteration effects. Rock with relatively high porosity ($>1\%$) would be expected near fracture zones or faults; rock with lower porosity would be found in areas less affected by fracturing. Superimposed on this variability of fracture-imposed matrix porosity are the effects of alteration, which are most intense in or adjacent to fracture zones and which diminish as the distance from the fractures increases (Chomyn et al, 1984). The effect of alteration is the opposite of fracturing: the porosity of the rocks tends to be reduced.

Thus, the rock property values obtained in measurements of ATK core will depend on the initial matrix porosity which is the result of varying amounts of fracturing, and any subsequent alteration effects.

The combined effects of these two factors on rock properties from borehole ATK-1 core samples are seen in Figure 18: The numbers are the alteration intensity of the samples from Katsube and Kamineni (1983). The scale of alteration ranges from 1 (low; grey coloured samples) to 4 (high; pink samples).

The relationship of permeability and porosity to alteration

Figure 18. Generalized geology, fracture in-fillings and

occurrence of natural fractures and faults encountered in borehole ATK-1 (Dugal et al, 1984). The alteration scheme of Kamineni and Dugal (1981) (large numbers on right of Figure) corresponds to the colour of the core as follows: Alteration intensity 1 (unaltered to very low alteration) - grey and pinkish grey; alteration intensity 2 (low alteration) - grey pink; alteration intensity 3 (moderate alteration) - greyish-pink; alteration intensity 4 (high alteration) - pink.

**GENERALIZED LITHOLOGY, FRACTURE INFILLINGS AND OCCURRENCE OF
NATURAL FRACTURES AND FAULTS ENCOUNTERED IN BOREHOLE ATK-1
FIGURE 18**

intensity (Katsube and Kaminen 1983) is only a general one (Figure 3, p. 8). Although the samples with highest porosity and permeability are those with alteration intensity 1, a few samples with low permeability and porosity also have an alteration intensity of 1. Also, in general, samples with the lowest permeability and porosity have alteration intensities of 2, 3 or 4, but two samples (105m and 975m vertical depth) with relatively high permeability have alteration intensities of 3. One sample with high porosity (1010m vertical depth) has an alteration intensity of 4, but has low permeability. This sample also has high compressive strength and high compressional wave velocity.

The variability in rock property values of samples with alteration intensity 1 can be explained with the aid of the core fracture logs (Figure 18). The interval 450-650m vertical depth is one of low alteration intensity (on the core log alteration intensity 1 includes grey and pinkish grey colourations). A fault zone with a narrow (2m) alteration halo (intensity 4) occurs at the 525m interval.

In the low alteration zone, samples with lowest compressive strength and wave velocity, and highest porosity and permeability are those which are closest to the fault. As the distance from the fault increases the compressive strength and wave velocity increase and the porosity and permeability decrease. These trends, in the absence of alteration effects, indicate that samples near the fault have higher matrix porosity, and the matrix porosity decreases as

the distance from the fault increases. SEM examination of the unaltered sample from 720m, also in a zone of low fracturing, has shown that the matrix porosity of unaltered samples has an abundance of natural stress-induced microcracks which are related to macrofractures. The density and size of these microcracks controls the values of rock properties of unaltered samples.

The similar rock fabric of the two samples examined by SEM and the presence of stress cracks in an advanced stage of healing in sample 120 and at an initial stage of healing in sample 720 allows the effects of alteration on the crack structures to be evaluated.

The crack structures of the two suites of specimens from borehole ATK-1 were initially similar. These structures consisted of a network of sheet-like cracks which formed during the cooling of the magma, and sharp-tipped smooth-walled stress cracks which formed when the pluton became solidified enough to respond to stress in a brittle manner. The stress cracks which have developed pervasively through the rock body were formed at the same time as the fractures and fracture zones which have been observed in outcrop and noted in core logs.

Hydrothermal activity caused healing of some of the large fractures (Kaminen and Dugal 1981) and also of microcracks. The feldspars in sample 120 were stained pink by iron in invading solutions and were variably sericitized, chloritized and epidotized. Hornblende developed epidote rims, and biotite was

variably chloritized. Bridges or healed portions of cracks formed and are of material similar in composition to that of the particular host mineral.

The healing process reduced the geometric mean crack width ($0.03\text{ }\mu\text{m}$ vs. $0.07\text{ }\mu\text{m}$, altered vs. unaltered), arithmetic mean crack width ($0.04\text{ }\mu\text{m}$ vs. $0.23\text{ }\mu\text{m}$), crack density ($2.8/\text{mm}$ vs. $3.8/\text{mm}$) and SWC crack porosity (0.016% vs. 0.164%) of the altered sample. Alteration also tended to reduce the length of microcracks through bridge formation (Plate 8). Intragranular porosity was reduced by a greater extent than was the grain boundary porosity, which is now predominantly crack wall porosity associated with quartz grains.

Sample 720 escaped the bulk of the crack healing event; plagioclase feldspar remains only deuterically altered, microcline, biotite and hornblende remain fairly fresh. Although crack healing has occurred in specimen 720, it is to a comparatively minor extent and on a local scale. Healing consists of the formation of variable amounts of bridging materials and development of slightly irregular crack walls in stress cracks: Neither a large reduction in smooth wall crack porosity nor the formation of a large amount of crackwall porosity have occurred.

9. CONCLUSIONS

The most significant observation at the WNRE drill site is the presence of fresh stress-induced cracks - recognized by their clean, parallel, well-matching walls, lack of infilling materials, and sharp terminations - in samples from below 450m vertical depth. The occurrence of these fresh stress-induced cracks in the samples from below 450m confirms that the observed trends of laboratory-measured rock properties of WNRE samples with depth are not representative of in situ conditions. The in situ properties of samples from below 400m vertical depth, where stress cracking initiates, should be similar to the rock properties above 400m. The fresh stress-induced cracks were most likely formed by the release of in situ stresses when the samples were removed from the surrounding rock. The orientation of these fresh stress-relief cracks should be perpendicular to the greatest principal stress, which has an undetermined horizontal orientation.

Drill-induced stress cracks are also likely to be present in the core, at least in areas where discing is observed. These microcracks should be oriented perpendicular to the core axis, in a region of tensional stress which develops at the end of a core drilled in a stressed rock (Stesky and Chernis 1982). The appearance of drill-induced and stress-induced microcracks should be the same, but measurements of wave velocity in samples cut from the core at various orientations should distinguish which type of

crack predominates. Maximum stress directions can also be determined in this manner, if stress-relief cracks are present.

At the ATK site, in contrast to the WNRE site, the principal factors influencing microcrack structures are alteration and penetrative tectonic fracturing. Tectonic stress-induced cracks are present in unaltered and altered samples from the Eye-Dashwa Lakes pluton. Porosity of the rocks was increased by tectonic fracturing, but decreased by alteration. The variability of alteration and fracture density in the ATK core suggest that rock properties will depend on the initial amount of penetrative fracturing of a pluton, and the amount of subsequent crack healing which accompanies alteration. Newly formed (fresh) stress-induced cracks were not observed in the ATK samples. The presence of unbroken filling or bridging materials along all tectonic stress cracks indicates that these ancient stress cracks have not been reactivated by stress-relief during drilling. The absence of rejuvenated or fresh stress-induced cracks may indicate that stresses are not sufficiently high to cause stress-relief or drill-induced microcracking.

The importance of the effect of alteration on the microcrack structures of rocks has been demonstrated. However, the alteration at the ATK site is not necessarily representative of the type of alteration which has affected crystalline rocks elsewhere (Gresens 1967; Babcock 1973; Ferry 1979; Cherry 1982, 1983). Large additions or subtractions of elements such as Si, K,

Na, or Ca, which might have resulted in complete compositional and textural changes, have not occurred. The effects of different intensities and styles of alteration on microcracks should be evaluated.

The techniques used to evaluate the crack structures of the WNRE and ATK samples may be applied to the study of other rock bodies, such as the development and evolution of cracks associated with mineral deposits and their associated alteration haloes, and development of fractures in shocked rocks. The petroleum industry routinely uses SEM studies to evaluate the influence of diagenesis, metamorphism, and petroleum production on reservoir rock.

In summary, the microcrack structures of crystalline rocks appear to be site-specific, and are a result of the tectonic, metamorphic, and alteration history of plutons, as well as the effects of the local and regional stress fields. Microcrack-dependent rock properties, therefore, are also site-specific.

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APPENDIX 1: CODING FORM

APPENDIX II: MICROCRACK STATISTICS PROGRAM

PROGRAM CRACKS (INPUT, OUTPUT, TAPE1, TAPE2, TAPE99)

THIS PROGRAM ACCEPTS A FILE OF SEM DATA CALLED TAPE1, WHICH
CONSISTS OF A MATRIX (CRDATA) WITH COLUMN VALUES OF:

- 1. CRACK TYPE
- 2. CRACK WIDTH INTERCEPT
- 3. CRACK POROSITY INTERCEPT
- 4. CRACK POROSITY INTERCEPT
- 5. SMOOTH WALL CRACK POROSITY INTERCEPT.

FROM THE CRACK INTERCEPTS, POROSITIES ARE CALCULATED AND RESULTS
ARE PRINTED IN TABLE FORM. THE TABLES INCLUDE:

- 1. MIN, MEAN, MAX, STD DEVIATION OF EACH CRACK TYPE
- 2. SMOOTH WALL CRACK POROSITY OF EACH CRACK TYPE
- 3. RATIOS OF CRACK WALL POROSITY TO EACH CRACK TYPE
- 4. AVERAGE WALL CRACK POROSITY IN EACH CRACK TYPE
- 5. TOTAL CRACK POROSITY IN EACH CRACK TYPE
- 6. TOTAL CRACK POROSITY IN EACH CRACK TYPE
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- 90. TOTAL CRACK POROSITY IN EACH CRACK TYPE
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- 93. TOTAL CRACK POROSITY IN EACH CRACK TYPE
- 94. TOTAL CRACK POROSITY IN EACH CRACK TYPE
- 95. TOTAL CRACK POROSITY IN EACH CRACK TYPE
- 96. TOTAL CRACK POROSITY IN EACH CRACK TYPE
- 97. TOTAL CRACK POROSITY IN EACH CRACK TYPE
- 98. TOTAL CRACK POROSITY IN EACH CRACK TYPE
- 99. TOTAL CRACK POROSITY IN EACH CRACK TYPE
- 100. TOTAL CRACK POROSITY IN EACH CRACK TYPE

THE CRACK BOUNDARY AND INTERPOLATED RESULTS ARE COMBINED
USING A WEIGHTED AVERAGE PROCEDURE TO PRODUCE AND TABULATE
POROSITY AND OTHER PROPERTIES OF THE ROCK SAMPLE.

THE FOLLOWING VARIABLES ARE USED IN THE PROGRAM :

```

AVAPCT(65) = AVERAGE APERTURE OF EACH CRACK TYPE
AVGB(10) = AVERAGE APERTURE OF EACH APERTURE CLASS (GRAIN
          BOUNDARY DATA SET)
AVWID2(10) = AVERAGE APERTURE OF EACH APERTURE CLASS
          (INTRAGRANULAR DATA SETS)
AVWID3(10) = AVERAGE APERTURE OF EACH APERTURE CLASS (ROCK SAMPLE)
BIGCRK(65), SMLCRK(65) = MAX AND MIN APERTURES OF EACH CRACK TYPE
BIGR(65), SMLR(65) = MAX AND MIN R-VALUES OF EACH CRACK TYPE
R = RATIO OF CRACK POROSITY INTERCEPTS/SMOOTH WALL CRACK
    POROSITY INTERCEPTS.
CRKPI1(65), CWP1(65), CRKW1(65), SWCP1(65) = SUM OF
CRACK POROSITY INTERCEPTS, CRACK WALL POROSITY INTERCEPTS
CRACK WIDTH INTERCEPTS, SMOOTH WALL CRACK POROSITY INTERCEPTS
FOR EACH CRACK TYPE
CRKPI2(10), CWP2(10), CRKW2(10), SWCP2(10) = SUM OF
CRACK POROSITY INTERCEPTS, CRACK WALL POROSITY INTERCEPTS
CRACK WIDTH INTERCEPTS, SMOOTH WALL CRACK POROSITY INTERCEPTS
FOR EACH APERTURE CLASS
CRKPI(65), CWP1(65), SWCP1(65) = CRACK POROSITY, CRACK WALL POROSITY
AND SMOOTH WALL CRACK POROSITY FOR EACH CRACK TYPE
CRKPI(10), CWP2(10), SWCP2(10) = CRACK POROSITY, CRACK WALL POROSITY
AND SMOOTH WALL CRACK POROSITY OF EACH APERTURE CLASS
CRKPI(10), CWP3(10), SWCP3(10) = CRACK POROSITY, CRACK WALL POROSITY
AND SMOOTH WALL CRACK POROSITY OF EACH APERTURE CLASS
(FOR THE ROCK SAMPLE)
DINT1(10) = INTRAGRANULAR CRACK DENSITY OF EACH APERTURE CLASS
CRKDATA(500,8) = RAW DATA
CRKDATA(J,1) = STATION NUMBER

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[illegible]

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STDDEVCT(65),VARCT(65)- STANDARD DEVIATION AND VARIANCE OF
 MEAN OF EACH CRACK TYPE
 STDEV(65),VAR(65)- STANDARD DEVIATION AND VARIANCE OF MEAN
 R-VALUES OF EACH CRACK TYPE
 TITLE(7)- DATA IDENTIFIER
 CRKWI- SUM OF ALL CRACK WIDTH INTERCEPTS
 SUCPI- SUM OF ALL SMOOTH WALL CRACK POROSITY INTERCEPTS
 CUPPI- SUM OF ALL CRACK WALL POROSITY INTERCEPTS
 CRKPI- SUM OF ALL CRACK POROSITY INTERCEPTS
 MEAN- ARITHMETIC MEAN APERTURE OF DATA SETS
 GEDAP- GEOMETRIC MEAN APERTURE OF DATA SETS
 TOTOPEN- TOTAL NUMBER OF CRACKS OPEN AT THE MEASUREMENT POINT
 FOR EACH DATA SET
 WT- WEIGHT (FOR GRAIN BOUNDARY DATA SETS WT= 1. FOR
 INTRAGRANULAR DATA SETS WT= NORMALIZED MODAL AMOUNT
 OF THE MINERAL)
 T- TRAVERSE LENGTH
 MAGFAC- MAGNIFICATION FACTOR OF VIDEO MONITOR
 TICA- TOTAL INTERSECTED CRACK APERTURE OF EACH DATA SET
 POPEN- PERCENTAGE OF CRACKS OPEN AT THE MEASUREMENT POINT
 IN EACH DATA SET
 FREQ- TOTAL NUMBER OF CRACKS EXAMINED IN THE ROCK SAMPLE
 THAT ARE OPEN AT THE MEASUREMENT POINT
 CRKD3- ROCK SAMPLE CRACK DENSITY

[illegible]

```

STODEV,VAR= STANDARD DEVIATION AND VARIANCE OF MEAN APERTURE
TICA3= ROCK SAMPLE TOTAL INTERSECTED CRACK APERTURE
DINT3= WEIGHTED INTRAGRANULAR CRACK DENSITY
AVAP3= ROCK SAMPLE ARITHMETIC MEAN APERTURE
STODEV3= ROCK SAMPLE STANDARD DEVIATION OF THE MEAN APERTURE
GEOP3= ROCK SAMPLE GEOMETRIC MEAN APERTURE
SUMWT= SUM OF INTRAGRANULAR WEIGHTS
GBAVAP= GRAIN BOUNDARY ARITHMETIC MEAN APERTURE
GSTO= GRAIN BOUNDARY STANDARD DEVIATION OF THE MEAN APERTURE
GBGEOP= GRAIN BOUNDARY GEOMETRIC MEAN APERTURE
GOTICA= GRAIN BOUNDARY TOTAL INTERSECTED CRACK APERTURE
GBDENS= GRAIN BOUNDARY CRACK DENSITY
GBGVP= GRAIN BOUNDARY CRACK WALL POROSITY
GBSWCP= GRAIN BOUNDARY SMOOTH WALL CRACK POROSITY
GBCRKP= GRAIN BOUNDARY CRACK POROSITY
VTAP= ARITHMETIC MEAN APERTURE OF THE ROCK SAMPLE
REAL= MAGFAC,LBOUND,LB1,MEAN
INTENGER TOPEN
DIMENSION AVAPCT(65),AYGB(10),AVWID2(10),AVWID3(10),
DIMENSION BIGR(65),CRKP1(10),CRKP11(65),CRKP12(10),
DIMENSION CRKP1(65),CRKP2(10),CRKP3(10),CRKW11(65),
DIMENSION CWP1(65),CWP2(10),CWP3(10),DINT1(10),
DIMENSION CRKDATA(500,6),GBD(10),NOPEN(65),NR(65),
DIMENSION N2(10),N3(10),NTYPE(65),RELDP2(10),RELDP3(10),
DIMENSION POP(65),RELPI(65),RELPI2(10),RELPI3(10)

```



```

STDDEVCT(I)=0.
VAR(I)=0.
STDDEVRI(I)=0.
RATIO(I)=0.
SUMR(I)=0.
BIGCRK(I)=0.
NR(I)=0
CONTINUE

```

2

```

DO 3 I=1,10
  SMCPI2(I)=0.
  CRKPI2(I)=0.
  NZ(I)=0
  RELPRQ2(I)=0.
  AVMID2(I)=0.
  SMCPI2(I)=0.
  CRKPI2(I)=0.
  CVP2(I)=0.
  CONTINUE

```

3

```

READ NUMBER OF OBSERVATIONS (NPTS), WEIGHT (WT),
TRAVERSE LENGTH (T), MAGNIFICATION FACTOR (MAGFAC)
AND DATA IDENTIFIER (TITLE)
READ(1,*) NPTS, WT, T, MAGFAC
READ(1,4) TITLE
FORMAT(7A10)

```

4

```

IF WT EQUALS 0., COMPUTE STATISTICS OF ROCK SAMPLE
IF(WT.EQ.0.) GO TO 64
OTHERWISE, READ IN THE RAW DATA (CRKDATA),
CALCULATE TRUE INTERCEPT LENGTHS,
AND SUM CRACK WIDTHS FOR CALCULATION OF ARITHMETIC MEAN ;
GEOMETRIC MEAN APERTURE AND VARIANCE OF ARITHMETIC MEAN ;

```

CCCCCCCC

```

5
DO 6 J=1,NPTS
  READ(1,5) (CRKDATA(J,I), I=1,7)
  IF (CRKDATA(J,4).EQ.0) GO TO 6
  CRKDATA(J,4)=CRKDATA(J,5) / (CRKDATA(J,2) * MAGFAC)
  CRKDATA(J,6)=CRKDATA(J,6) / (CRKDATA(J,2) * MAGFAC)
  CRKWT=CRKWT + CRKDATA(J,5)
  SWCP=SWCP + CRKDATA(J,6)
  SWCP=SWCP / CRKWT
  VAR=VAR + CRKDATA(J,4)**2 - CRKDATA(J,6)
  TOTOPEN=TOTOPEN + CRKDATA(J,4)
  GEDAP=GEDAP + TOTOPEN + ALGO10( CRKDATA(J,4) )
CONTINUE

```

```

6
CCCCCCCC
CALCULATE VARIANCE, STANDARD DEVIATION, CRACK DENSITY,
POROSITIES, ARITHMETIC AND GEOMETRIC MEAN APERTURES,
TOTAL INTERSECTED CRACK APERTURE, FOR THE DATA SET:

```

```

  VAR=(VAR - (CRKWT**2 / TOTOPEN)) / (TOTOPEN - 1)
  STDOEV=SQRT(VAR)
  CRKD=TOTOPEN / T
  CRKP=CRKP / T / 10
  CWP=SWCP / T / 10
  SWCP=SWCP / T / 10
  P=SWCP / CRKP
  MEAN=CRKWT / TOTOPEN
  GEDAP=10**((GEDAP / TOTOPEN)
  TICA=CRKWT / T
  POPEN=FLOAT(TOTOPEN) / NPTS * 100

```

```

7
CCCCCCCC
SORT DATA BY CRACK TYPE TO CALCULATE POROSITY INTERCEPTS
FOR THE CRACK TYPES, AND FIND THE MIN, MEAN, MAX APERTURE
OF EACH CRACK TYPE:

```


CALCULATE POROSITIES AND ARITHMETIC MEAN POROSITY OF EACH APERTURE CLASS, AND WEIGHT AND SUM EACH POROSITIES; EACH CLASS FOR CALCULATION OF ROCK SAMPLE POROSITIES;

[illegible]

```

IF CURRENT DATA SET IS FOR GRAIN BOUNDARIES, SKIP TO
STACRACK=35, OTHERWISE WEIGHT AND PATTERN,
THE STRAIGHT LINE AND GEOMETRIC MEAN APERTURE,
ARITHMETIC OF THE ARITHMETIC MEAN APERTURE.
DEVIATION OF THE ARITHMETIC MEAN APERTURE.

```

```

C      AVERAGE ALSO FOR EACH CRACK CLASS, WEIGHT AND CRACK SUM THE
C      THEN SKIP TO STATEMENT LABELLED 37
33      DO 34 I=1,10
C      IF(AVWID(I).EQ.0) 34, 33
C      SUMWT(I)=SUMWT(I) + WT
C      DINT1(I)=DINT1(I) + N2(I) / T * WT
C      AVWID3(I)=AVWID3(I) + AVWID2(I) * WT
34      GO TO 37
C      IF DATA SET IS FOR GRAIN BOUNDARIES, CRACK DENSITY, ETC.
C      STORE USE IN CALCULATING STATISTICS FOR THE ROCK SAMPLE :
35      DO 36 I=1,10
C      GBD(I)=N2(I)/T
C      AVGB(I)=AVWID2(I)
C      CON=1/INUE
36      GRAV=ID-MEAN
C      GBDSTD=STDDEV
C      GBDTCA=TIICA
C      GBDTENS=CRKD
C      GBDMP=CMCP
C      GBSMCP=SMCP
C      GBCRKP=CRKP
C      PRINT RESULTS IN TABLE FORM :
37      CALL CONNEC(99,2)
C      WRITE(99) NCHAR1, NCHAR2
38      PRINT(//,20X,TITLE)
39      FORMAT(//,2X,CRKVI, CRKPI, SMCPI, MAGFAC, MM,

```



```

DO TYPE(I)=1,65
IF(SNT(I).EQ.0) GO TO 50
PRINT 49,I,RATIO(I),SMR(I),BIGR(I),STDEV(I),MR(I)
FORMAT(3X,I2,4(4X,F6.2),5X,I3)
CONTINUE
PRINT 51
FORMAT(//,2X,"AVERAGE OF CRACK WALL POROSITY INTERCEPTS"
1//,16X,30(,""),CRACK POROSITY INTERCEPTS)
2 16X"SMOOTH WALL CRACK POROSITY INTERCEPTS")

C
52
PRINT 52
FORMAT(3(//,2X"APERTURE"3X"AVERAGE"1X"RELATIVE"2X"CRACK"
3X"CRACK WALL"2X"SMOOTH WALL"3X"RELATIVE"
2 4X"RANGE"POROSITY"2X"CRACK POROSITY"1X"RELATIVE"
3 1X"POROSITY"1X"POROSITY")
1 LBOUND=-1.5
2 LBOUND=-1.25
3 LBOUND=-1.1,10
UBOUND=50
LB1=10+UBOUND
UB1=10+UBOUND
IF(I.EQ.1) LB1=10+UBOUND
PRINT 53,I,B1,AVID2(I),RELFRQ2(I),CRKP2(I),CWP2(I)
53
1 GO TO 56
54
IF(I.EQ.10) 55,56
55
PRINT 60,I,B1,AVID2(I),RELFRQ2(I),CRKP2(I),CWP2(I)
1 GO TO 56
56
PRINT 61,I,B1,UB1,AVID2(I),RELFRQ2(I),CRKP2(I),CWP2(I)
57
1 LBOUND=LBOUND + 0.25
58
UBOUND=UBOUND + 0.25
59
CONTINUE
60
FORMAT(3X,"E4.2,2XF5.2,5XF4.1,4X"2XF5.3,3X"3XF5.3,
1 6XF5.2,2XF5.2,5XF4.1,4X"2XF5.3,3X"3XF5.3,
60
1 6XF5.3,2XF5.2,2XF5.2,2XF5.2,2XF5.3,3X"3XF5.3,
1 6XF5.3,2XF5.2,2XF5.2,2XF5.2,2XF5.3,3X"3XF5.3,
61
1 PRINT 62,2X"CRKP",CWP,5X"SMCP"
62
FORMAT(34X,F5.3,3X"1"3XF5.3,8XF5.3,3(//))

```

```

C
63 PRINT 63, MEAN, STDEV, GEDAP, CRKD, TICA, P, MICROMETRES"/
FORMAT(2X, "ARIHMETIC MEAN", F5.2, "MICROMETRES"/
1 2X, "STANDARD DEVIATION", F5.2, "MICROMETRES"/
2 2X, "GEOMETRIC MEAN", F5.2, "MICROMETRES"/
3 2X, "CRACK DENSITY", F5.2, "CRACK APERTURE", F5.2, "MM/CM"
4 2X, "TOTAL INTERSECTED CRACK APERTURE", F5.2, "MM/CM"
5 2X, "OF TRAVERSE", F5.2, "MM/CM"
6 2X, "SVC POROSITY", CRACK POROSITY, " F5.2, ///)

```

```

CCCCC
WRITE RESULTS ONTO TAPE 2
WRITE(2,*) (SWCP2(I), I=1,10), (CRKP2(I), I=1,10)
1 WRITE(2,4) TITLE

```

```

READ IN NEXT DATA SET
GO TO 1

```

```

CALCULATE STATISTICS OF THE ROCK SAMPLE:

```

```

1. CALCULATE POROSITY RATIOS :

```

```

LBOUND=-1.5
P1=GBWCP / SWCP4
P2=GBWCP / CRKP4
P3=GBWCP / CRKP4
P4=SWCP4 / CRKP4
DINT3=CRKD3/SUMWT

```

2. CALCULATE ARITHMETIC AND GEOMETRIC MEAN APERTURES, STANDARD DEVIATION OF THE ARITHMETIC MEAN APERTURE, TOTAL INTERSECTED CRACK APERTURE, AND CRACK DENSITY OF THE ROCK SAMPLE USING THE WEIGHTED AVERAGING FORMULA :

WEIGHTED AVERAGE(X) =

$$\frac{(X(\text{INTRAGRANULAR}) * \text{DINT3} + X(\text{GRAIN BOUNDARY}) * \text{GBDENS})}{(\text{DINT3} + \text{GBDENS})}$$

AVAP3=((AVAP3 / SUMWT * DINT3) + (GBAVAP * GBDENS)) / (DINT3 + GBDENS)
 GEDAP3=((GEDAP3 / SUMWT * DINT3) + (GBGEDAP * GBDENS)) / (DINT3 + GBDENS)
 STDEV3=((STDEV3 / SUMWT * DINT3) + (GBSTD * GBDENS)) / (DINT3 + GBDENS)
 TICAP3=((TICAP3 / SUMWT * DINT3) + (GBTICA * GBDENS)) / (DINT3 + GBDENS)
 CRKD3=((CRKD3 * 2) + (GBDENS * 2)) / (DINT3 + GBDENS)

3. CALCULATE CRACK DENSITY, AND ARITHMETIC MEAN APERTURE FOR EACH APERTURE CLASS USING THE WEIGHTED AVERAGING FORMULA :

DO 68 I=1,10
 IF(SUMWT(I).EQ.0.) 65, 66
 WTAP=0
 DINT1(I)=0
 WTAP=AVWID3(I) / SUMWT(I)
 DINT1(I)=DINT1(I) + GBD(I) * SUMWT(I)
 IF(DINT1(I).EQ.0.) 60 TO 68
 AVWID3(I)=(WTAP * DINT1(I)) + (AVGB(I) * GBD(I)) / (DINT1(I) + CRKP3(I) / CRKP4 * 100
 RELFRO3(I)=DINT1(I) / FREQ * 100
 CONTINUE

CC PRINT RESULTS IN TABLE FORM :

WRITE(99) NCHAR1, NCHAR2
PRINT 36, TITLE
PRINT 37, I=1, 10

69 1 GO TO 74
70 IF(I.EQ.10) 71, 72
71 PRINT 60, LB1, AVID3(I), RELFRQ3(I), CRKP3(I), CWP3(I),
1 SUCP3(I), RELP3(I)

72 GO TO 74
73 PRINT 61, LB1, UB1, AVID3(I), RELFRQ3(I), CRKP3(I), CWP3(I),
1 LBOUND=LBOUND + 0.25
74 UBOUND=UBOUND + 0.25
CONTINUE
PRINT 62, CRKP4, CWP4, SUCP4

CC
75 PRINT 75, AVAP3, STDEVA3, GEOPA3, CRKD3, TICA3
FORNAT(2X, ARITHMETIC MEAN APERTURE=5.2 MICROMETRES/
3X, GEOMETRIC MEAN APERTURE=5.2 MICROMETRES/
3X, CRACK DENSITY=5.2 CRACK APERTURE=5.2 MM/MM
5 OF TOTAL TRAVERSE=//)

CC
76 PRINT 76, P1, P2, P3, P4, BOUNDARY CRACK WALL POROSITY/
FORNAT(3(//), 2X, "GRAIN", 2X, "BOUNDARY", 2X, "SMOOTH", 2X, "SAMPLE", 2X, "CRACK WALL", 2X, "CRACK POROSITY", 3(//)
1 2X, "GRAIN", 2X, "BOUNDARY", 2X, "SMOOTH", 2X, "SAMPLE", 2X, "CRACK WALL", 2X, "CRACK POROSITY", 3(//)
2 2X, "GRAIN", 2X, "BOUNDARY", 2X, "SMOOTH", 2X, "SAMPLE", 2X, "CRACK WALL", 2X, "CRACK POROSITY", 3(//)
3 2X, "GRAIN", 2X, "BOUNDARY", 2X, "SMOOTH", 2X, "SAMPLE", 2X, "CRACK WALL", 2X, "CRACK POROSITY", 3(//)
4 2X, "GRAIN", 2X, "BOUNDARY", 2X, "SMOOTH", 2X, "SAMPLE", 2X, "CRACK WALL", 2X, "CRACK POROSITY", 3(//)
5 2X, "GRAIN", 2X, "BOUNDARY", 2X, "SMOOTH", 2X, "SAMPLE", 2X, "CRACK WALL", 2X, "CRACK POROSITY", 3(//)
6 2X, "GRAIN", 2X, "BOUNDARY", 2X, "SMOOTH", 2X, "SAMPLE", 2X, "CRACK WALL", 2X, "CRACK POROSITY", 3(//)
7 2X, "GRAIN", 2X, "BOUNDARY", 2X, "SMOOTH", 2X, "SAMPLE", 2X, "CRACK WALL", 2X, "CRACK POROSITY", 3(//)

```

CCCCC
WRITE POROSITIES, RELATIVE CRACK FREQUENCIES, ARITHMETIC
AND GEOMETRIC MEAN APERTURES, CRACK DENSITY AND NAME OF
THE ROCK SAMPLE ON TO TAPE2, AND END PROGRAM.
WRITE(2,*) (SMCP3(I),I=1,10), (CRKP3(I),I=1,10), CRKDS
1 WRITE(2,4) TITLE
STOP
END

```

APPENDIX III: HISTOGRAM PLOTTING PROGRAM

```

IPUTC,CN150000,T77,IO377,P2.  CHERNIS  5-5515
ACCOUNT(XXXXXX)
MOUSE(VSN=EMR130,SN=GMSM)
HUSE,CRACKFILE,PJC,XX,YYY,SN=GMSM.
HGET,TAPE2=SCRATCH.
FTN.
BFGIN,CISSPLA,,CALQ46,XSIZE=50,YSIZE=30,NAME=6CHERNISS,P1=NIB,P2=NIB.
*END
PROGRAM CRKPLT( INPUT,OUTPUT,TAPE2 )

THIS PROGRAM PLOTS HISTOGRAMS OF GRAIN BOUNDARY, INTRAGRANULAR
AND ROCK SAMPLE POROSITIES VS. CRACK WIDTH, USING DISPLA ROUTINES.
DATA IS READ FROM A FILE (TAPE 2) CREATED BY PROGRAM CRACKS.

VARIABLES IN CRKPLT ARE:
CLASS(10)= 10 CRACK WIDTH CLASSES AS IN PROGRAM CRACKS
SWCP(10)= SWATH WALL CRACK POROSITY OF THE 10 CLASSES
CRKP(10)= CRACK POROSITY OF THE 10 CLASSES
RELFRQ(10)= RELATIVE CRACK FREQUENCY OF THE 10 CLASSES
AVAP= ARITHMETIC MEAN APERTURE
GENTAP= GEOMETRIC MEAN APERTURE
DENSITY= CRACK DENSITY
DIMENSION CLASS(10), SWCP(10), CRKP(10), RELFRQ(10)
DIMENSION IWT(400), IPAK(100), TITL(7)
CALL CALCMP
CALL FLATRD
DO 12X=1,4
CALL RGNPL(10)

READ IN DATA FROM TAPE2
READ(2,*) (SWCP(I),I=1,10), (CRKP(I),I=1,10), (RELFRQ(I),I=1,10)
1, AVAP,GENTAP,DENSITY
PEAN(2,1) TITL
FORMAT(7A10)

SET CLASS LIMITS (XLIMIT), PAGE SIZE (YLENGTH, PAGEY), AND
LIMITS OF PLOT DIMENSIONS (C, O, F, F, G, PAO)

```

```

XLIMIT = -1.625
RIG = 0
TOTCRKP = C
TOTSWCP = C
YLENGTH = X
PAGEV = 11
C = 7.7
E = 7.5
G = 7.25
P = 0.048
Q = 0.043
R = 0.048

```

```

C C C
C CALCULATE TOTAL POROSITIES AND ADJUST SIZE OF PAGE TO SUIT PLOT

```

```

      DN 2 I=1,10
      TOTCRKP = TOTCRKP + CRKP(I)
      TOTSWCP = TOTSWCP + SWCP(I)
      CLASS(I) = 10 * XLIMIT
      XLIMIT = XLIMIT + 0.25
      IF(RIG.LE.CRKP(I) + 100) RIG = CRKP(I) + 100
      R = RELFREQ(I)/10
      IF(816.LE.R) RIG = R
      CONTINUE
      IF(RIG - 7) 3, 5, 4

```

```

2 C C C C
3 C REDUCE PAGE SIZE IF POROSITIES OR FREQUENCIES ARE SMALL

```

```

      R = 7 - RIG
      IF(R.GT.2) R = 2
      YLENGTH = YLENGTH - R
      C = C - R
      E = E - R
      G = G - R
      P = P - R
      Q = Q - R
      GO TO 5

```


INCREASE PAGE SIZE IF POROSITIES OR FREQUENCIES ARE LARGE

A=916-7
YLENGTH-YLENGTH + 8
PAGE-YLENGTH + 2.5
C=C + 8
D=D + 8
E=E + 8
G=G + (B / 100)
P=P + (R / 100)
Q=Q + (R / 100)
TOTCRP-TOTCRP - TOTSWCP

TOTCRP-TOTCRP - TOTSWCP

PRINT OUT INPUT DATA

PRINT 6, CRKP
PRINT 7, SWCP
PRINT 8, RELFREO
PRINT 9, TITL
FORMAT(1X, CRACK, GEODAP, DENSITY, "10(2X6.3)", "10(2X6.3)")
FORMAT(1X, SHODTH, WALL, CRACK, POROSITY, "10(2X6.3)", "10(2X6.3)")
FORMAT(1X, RELATIVE, "7A10")
FORMAT(1X, TITL, "7A10")
FORMAT(1X, AVERAGE, APERTURE, "F4.2", "1X"GEOMETRIC MEAN APERTURE=" F4.2", "1X"CRACK DENSITY=" F4.2")

BEGIN PLOT POUTINE

SET PRINT STYLE

CALL DUPLX
CALL MXIALF("STANDARD", "+")
CALL MX2ALF("L/CGREEK", "+")

```

CC      CALL XINTAX
CC
CC      TITLE AND AXIS LABELS
CC      CALL PAGE(8.5,PAGEY)
CC      CALL TITLE(TITL,100," S",0," S",0,4.0,VLENGTH)
CC
CC      DEFINE MAJOR AXES (SEMILOG) AND FRAME PLOT
CC      CALL BLNK1(-0.5, 0.0, -0.5, 0.0, 0)
CC      CALL XLG(0.01, 1.6, 0.0, 1.0)
CC      CALL XLGAXS(0.01, 1.6, 4.0, " CRACK WIDTH (*M+M)S", 100, -0.4, 0.
10)
CC      CALL RESET("BLNKS")
CC      CALL YSTAXS(0.0, 0.01, VLENGTH, "POROSITY (Z)S", 100, 0.0, 0.0)
CC      CALL FRAME
CC
CC      SET HISTOGRAM CLASS WIDTH AND SHADING PATTERN
CC      CALL BSHIFT(-0.4,0.0)
CC      CALL BARWID(0.4)
CC      CALL BARPAT(0)
CC
CC      PLOT CRACK WALL POROSITY (NO PATTERN)
CC      CALL VBARCLASS, SWCP, CRKP, 10)
CC
CC      RESET THE PATTERN AND PLOT THE SMOOTH WALL CRACK POROSITY
CC      CALL BARPAT(45141)
CC      CALL VBARCLASS, "BASE", SWCP, 10)
CC
CC      SET UP LEGEND INFORMATION
CC      CALL LINES("CM POROSITYS", IPAK, 1)
CC      CALL LINES("SWC POROSITYS", IPAK, 2)
CC      CALL LINES("REL. FREQUENCY", IPAK, 3)

```

```

PLOT AVERAGE APERTURES
CALL RLVEEC(AVAP, E, AVAP, P, 1201)
CALL RLVEEC(GEAP, G, GEAP, P, 1201)
CALL RLMESS(MGSM, 100, AVAP, Q)
CALL RLMESS(MGSM, 100, GEAP, Q)

DEFINE AND LABEL MINOR AXIS ON RIGHT SIDE OF PLOT
CALL YSTAXIS(10, YLENGTH, "RELATIVE FREQUENCY (Z)SM, -100, 4.4, 0)

RESET BAR WIDTH AND PATTERN, AND PLOT FREQUENCIES AS SOLID BARS
AGAINST THE MINOR AXIS

CALL BARPID(0.03)
CALL BARPAR(120100)
CALL VBARC(CLASS, "BASE", RELFREQ, 10)

PLOT LEGEND IN UPPER LEFT CORNER OF PLOT

CALL RESET ("SHIFT")
CALL REALND(TOTCMP, 3, 2.5, C)
CALL REALND(TOTSUP, 3, 2.5, D)
CALL MESSAGE("CRACK DENSITY=3%", 100, 0.2, E)
CALL REALND(DENSITY, 2, "ABUT", E)
CALL MESSAGE("MM", 100, 2.7, E)
CALL MESSAGE("2, 1)
CALL LEGEND(TPAK, 3, 0.2, F)
CALL ENDPL(1)
CONVTIME
CALL DONEPL
END

```

END

2 4 0 2 8 6

FIN