GEOLOGICAL RESULTS FROM THREE RESEARCH AREAS AND THEIR RELEVANCE TO THE NUCLEAR FUEL WASTE MANAGEMENT PROGRAM

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ABSTRACT

Geological data from three research areas indicates that fault-fracture systems were initiated shortly after emplacement and cooling of the plutons. These fracture systems have evolved through geologic time in response to major geologic-tectonic events. New fractures formed and existing fractures were reactivated. The effects of 'recent' geological activity appears to be largely restricted to the upper 200-300 m of the rock mass, and is constrained by the occurrence and distribution of pre-existing 'ancient' fracture systems. These results indicate that (i) stable geological environments may exist at depth, and (ii) an understanding of the 'ancient' fracture system is a basic requirement in order to develop an understanding the present day groundwater flow systems in these rocks.

INTRODUCTION

The safe of disposal of nuclear fuel wastes deep within plutonic rock of the Canadian Shield is, to a considerable degree, dependent upon the integrity of the plutonic rock formation. The rock mass is an important barrier for waste containment and the effectiveness of the barrier is controlled by the occurrence and properties of fault- fracture systems.

Geological investigations of plutons at AECL's three research areas, East Bull Lake, Atikokan and Whiteshell (Fig. 1) indicate that each area is quite distinctive in terms of pluton size, shape, composition, and tectonic history. In addition, each area has unique fracture style, fracture characteristics, and fracture filling materials. Despite these variations, all three areas have one thing in common;

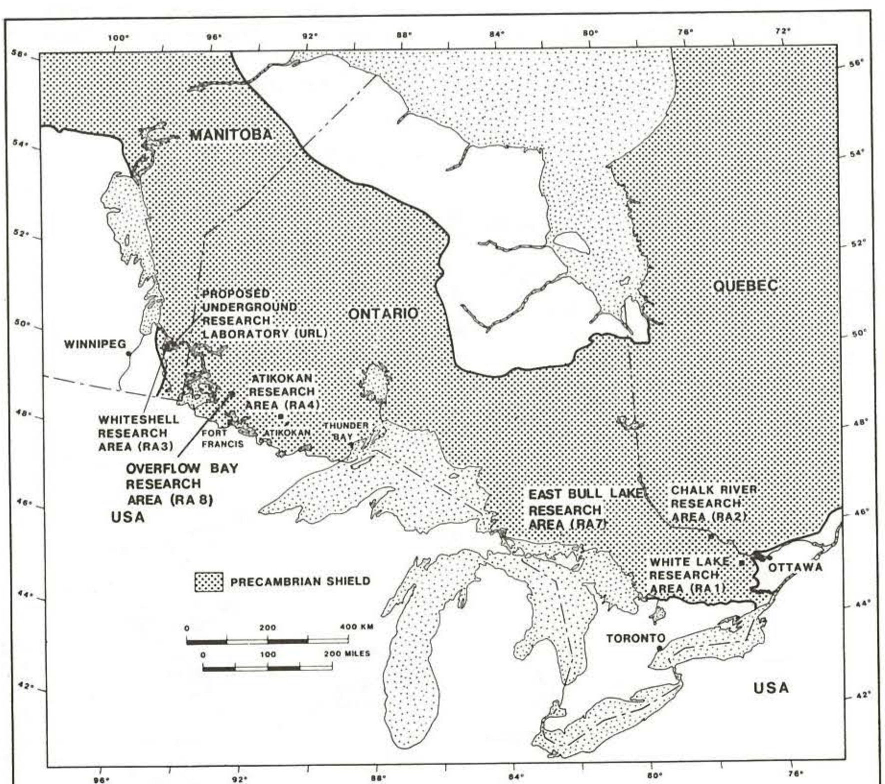

FIGURE 1: LOCATION OF EAST BULL LAKE, EYE-DASHWA PLUTON AND THE WHITESHELL RESEARCH AREA (URL) WITHIN THE CANADIAN SHIELD.

the fault-fracture systems record an evolution through geologic time. This evolutionary history, from pluton emplacement to present day, essentially 'controls' the physical-chemical characteristics of the existing fault-fracture networks. Understanding this evolutionary history is therefore considered a necessary prerequisite for any assessment of the integrity of the geological environment of these rocks.

EAST BULL LAKE

The East Bull Lake Gabbro-Anorthosite (Fig. 2) is an elongate layered, gabbro-anorthosite lopolith with anorthosite forming the basal, outer, layers and becoming progressively more mafic rich upwards and towards the centre of the pluton. (1) Extensive geological mapping, fracture mapping and geophysical surveys indicate that the pluton is cross cut by one major fault, the Folson Lake fault, and a number of smaller faults. In general the rock mass is highly fractured with a mean frequency of 2.5 fractures/m. (2) Four cored and oriented boreholes were drilled to investigate the shape, fracture characteristics, mineralogy, and geohydrological parameters of the pluton. The subsurface environment is apparently more highly fractured than the surface environment (3) i.e. 14.1 fractures/m vs. 2.5 fractures/m respectively. This discrepancy is due largely to a combination of (a) complete sampling of fracture zones in the subsurface and (b) the ability to define microfractures and hairline cracks in the core.

All of these fractures were found to contain a variety of filling minerals, the more common ones being calcic amphiboles, biotite, epidote, adularia, quartz, calcite, sphene, sulphides, serpentine, chlorite, prehnite, pumpellyite, laumontite, gypsum, iron hydroxides and clay (4). The mode of occurrence and relevant experimental data related to the stability of the filling minerals indicates that they formed under pressure-temperature conditions of i) epidote-amphibolite/greenschist facies ii) prehnite-pumpellyite facies, iii) zeolite facies, and iv) low temperature rock-water interaction (100°C). These data were used by Kamineni et al., (4) to outline decreasing P-T conditions with time from pluton emplacement (Fig. 3). Age dating of fracture filling minerals (specifically, mafic dykes) enabled these P-T conditions (as defined by the fillings) to be placed into a geological time frame and hence outline the evolutionary history of the fault-fracture system.

Emplacement of the pluton at 2472 $\pm$ 71 Ma, (samarium-neodymium isochron, A. LeHuray, personal communication), was followed by pervasive fracturing and hydrothermal metamorphism with growth of amphibole, epidote and biotite i.e. amphibolite-greenschist facies. Protracted tectonism in the region, from 2200 Ma to 1,700 Ma (5), was accompanied by the emplacement of mafic tholeiitic dykes (K-Ar, 1,800 Ma) and renewed fracturing and fracture controlled metamorphism (prehnite-pumpellyite facies). The associated filling materials (prehnite pumpellyite, chlorite, etc.) are confined to fractures and fracture zones. Renewed magmatism at 1,200 Ma (Sudbury type mafic dykes) and tectonism related to the Grenville Orogeny (1100-950 Ma) was accompanied by renewed fracturing and fracture controlled metamorphism (zeolite facies). This metamorphism is low grade, fracture controlled, and retrogressive, and is considered to represent fluid circulation along new fractures or reactivated old fractures. The gypsum, iron oxide-hydroxide and clay filled fractures occur in fracture zones throughout the rock mass and represent recent to

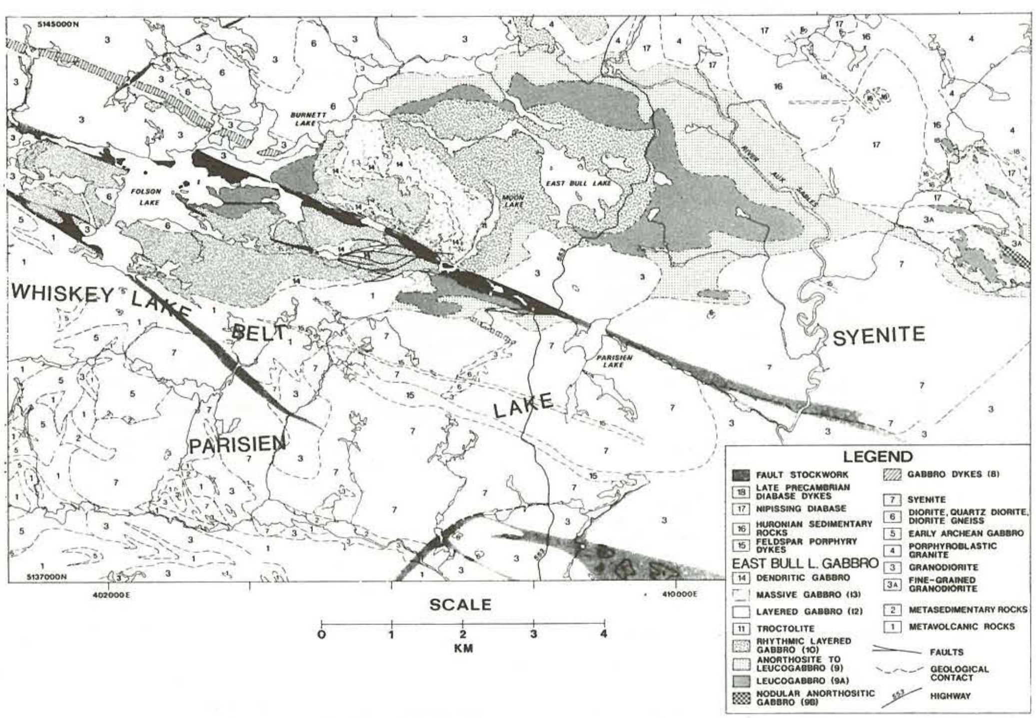

FIGURE 2: SIMPLIFIED GEOLOGICAL MAP OF THE EAST BULL LAKE GABBRO-ANORTHOSITE AND SURROUNDING COUNTRY ROCK

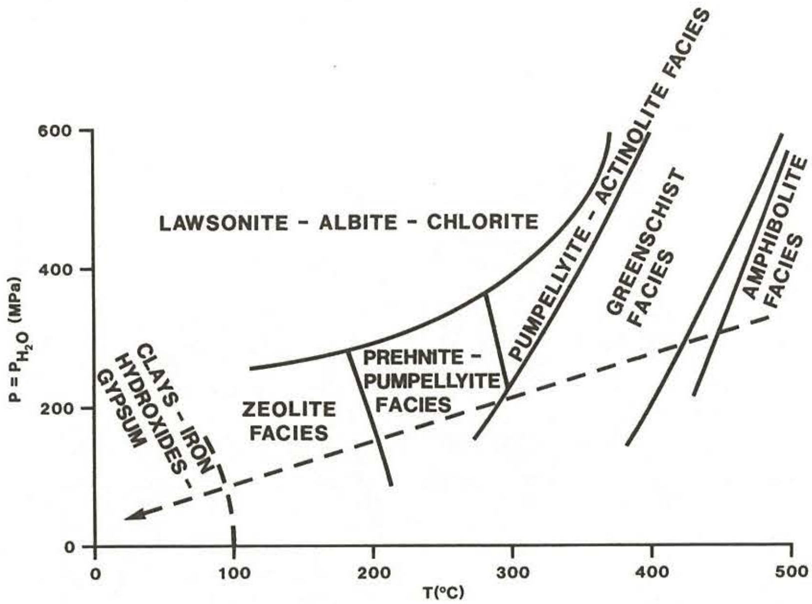

FIGURE 3: PRESSURE-TEMPERATURE CONDITIONS FOR THE FORMATION OF ALTERATION MINERALS WITHIN THE EAST BULL GABBRO-ANORTHOSITE (DASHED ARROW). WITH DECREASING P-T CONDITIONS THE ALTERATION MINERALS ARE PROGRESSIVELY RESTRICTED TO FRACTURES AND FRACTURE ZONES.

present day water-rock interaction processes (4). The limonite and goethite are restricted to the upper, near surface, part of the rock mass.

The evolutionary history of the fault-fracture systems within the East Bull Lake Gabbro-Anorthosite is therefore both protracted and complex. This is not unexpected since the pluton is located close to the Southern Province and the Grenville front. The repeated tectonism in this region of the Shield has had a direct effect on the fracture system within the pluton. With each new period of tectonic activity new fractures formed, old fractures were rejuvenated, and new filling materials emplaced. Thus, the fracture characteristics and the filling materials that they contain, are directly linked to the past geologic-tectonic history.

Of particular relevance to the Nuclear Fuel Waste Management Program is the fact that the most recent geological activity, as recorded by the low temperature rock-water interaction minerals such as limonite and goethite, is largely restricted to the near surface (0-300 m) part of the rock mass. Additional work is required to develop an understanding of the origins of these most recently 'open' fractures and fracture zones and to determine the controls on their orientation and depth extent.

EYE-DASHWA PLUTON, ATIKOKAN

The Eye-Dashwa pluton is an elliptical granite with a monzodiorite rim (Fig. 4) which diapirically intruded the tonalitic gneisses of the Wabigoon Subprovince at 2672 ± 24 Ma (U-Pb on zircons). (6) Major structural discontinuities within the pluton have been inferred from an analysis of aerial photographs and linear magnetic anomalies in conjunction with data from outcrop fracture mapping and ground geophysical surveys (7,8). The surface expression of one of these discontinuities was cleared of overburden and mapped in extreme detail, and found to be a fault (9). Subsurface data (from 5 boreholes drilled to a maximum depth of 1 km) indicated that this fault extends to at least 1 km depth. Detailed fracture mapping has also indicated that the fault-fracture system within the pluton is dominated by a conjugate pair of subvertical transcurrent faults (10,11), which have a characteristic sinusoidal trace and curved, splayed ends (9). All of these faults and fractures contain a variety of filling minerals, the most common of which are aplite, epidote, chlorite, calcite, gypsum, iron hydroxides and clay. (10)

Detailed analyses of these filling minerals in terms of (i) cross-cutting relationships, (ii) temperature of crystallization with respect to a modelled cooling curve of the pluton, and (iii) a variety of isotopic age determinations, led Kamineni and Stone (12) to outline the sequence and age of these fillings (Fig. 5). These results indicate that the time-temperature sequence of fracture fillings range in age from shortly after emplacement of the pluton, at 2672 ± 24 Ma to 20,000 years ago, or younger. The oldest fractures contain aplite and pegmatite, which are similar in composition to the host granite, and hornblende porphyry. These were probably emplaced before the granite core had solidified (10)(9) at temperatures as high as 600°C and welded the fracture walls together such that they have rarely been reopened. Structural analysis of this early fracture system has shown that it formed in response to internal stresses as the pluton cooled (11). With further cooling, from 500°C to 300°C, epidote and chlorite (derived from hydrothermal alteration of the wall rock) were emplaced in the newly forming subvertical conjugate fault system. These faults and fractures formed in response to a regional NW-SE compression (10,11). Data on the metamorphic conditions in the surrounding coun

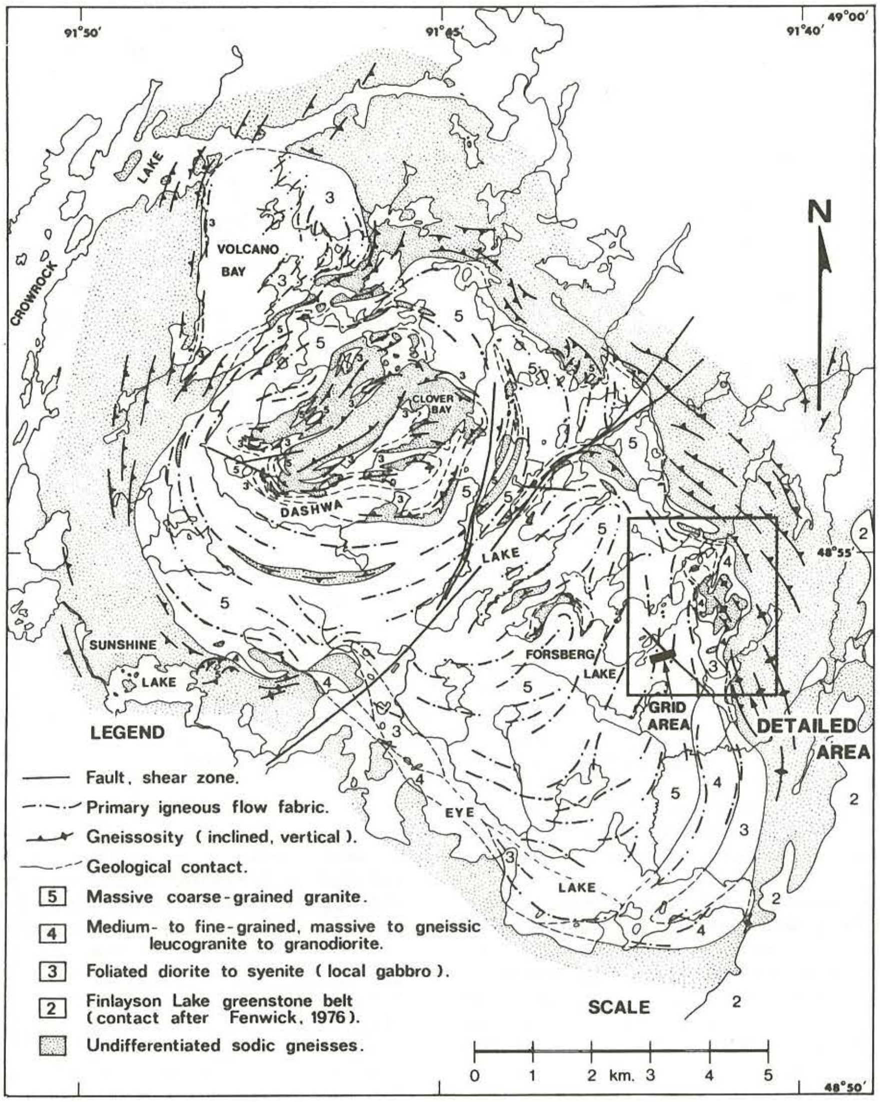

FIGURE 4: SIMPLIFIED GEOLOGICAL MAP OF THE EYE-DASHWA PLUTON, ATIKOKAN

try rock (13) and stability data from the fault-filling assemblages indicated that these faults formed within a few hundred million years of emplacement and cooling, while the pluton was at a depth of approximately 10 km. (14)

With the exception of a few diabase dykes, dated at 1132 $\pm$ 27 Ma, and emplacement of associated adularia and gypsum, the remaining fracture fillings (iron oxides, carbonate and clay) formed at temperatures below 100°C. Fractures containing these low-temperature fillings tend to be small and occur mainly as re-opened or reactivated segments of older fractures. This mode of occurrence and the recent age of these minerals (C14 on calcites yield 20,000 years) provides strong evidence that relatively few new fractures have formed in the recent geological past. Most of the recent geological activity appears to have resulted in a reopening of the ancient epidote-chlorite filled faults and fractures which formed when the pluton was at a depth of 10 km. Thus, the present day fluid pathways are controlled by the occurrence and distribution of the ancient fault-fracture network.

The depth distribution of 'recent' clay-filled fractures in boreholes ATK 1 to 5 and ATK-6 (Figure 6) shows that they are most abundant in the top 100-200 m of the boreholes and tend to die out with increasing depth. Boreholes ATK-1 to 5 intersect a fault-fracture zone at a number of different depths and has a much higher incidence, to greater depth, of clay filled fractures than ATK-6, which is drilled into a nonfault 'intrablock' environment (15). These differences may indicate that fault zones are preferentially reactivated or open to flow, to a greater depth, than nonfault environments.

These geological inferences are supported by the available hydrogeological data in that the upper 300-500 m of these boreholes contains zones of high hydraulic conductivity (16,17) whereas at depth (below 500 m) the boreholes are characterized by very low hydraulic conductivities (18)(17). Furthermore the upper 300-400 m is dominated by a 'recent' bicarbonate rich groundwater regime (17). At depth the groundwaters become saline in composition (40 g/L TDS) with low Na/Ca and high Br/Cl ratios suggesting a fluid inclusion-mineral alteration origin

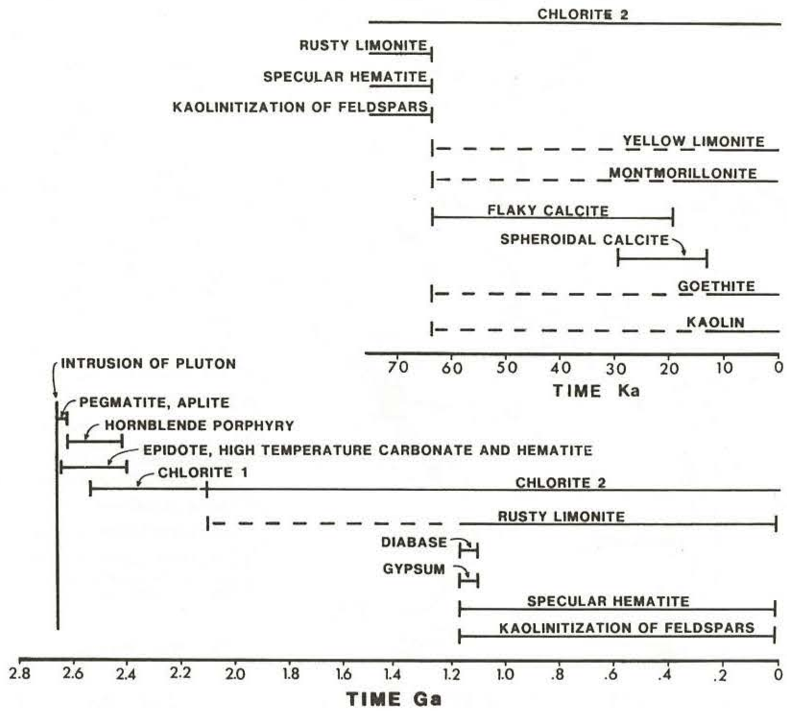

FIGURE 5: SEQUENCE AND AGE OF FRACTURE FILLING MINERALS WITHIN THE EYE-DASHWA PLUTON, ATIKOKAN

(19). Thus, within the Eye-Dashwa Pluton, the evolutionary history of the fracture system indicates that: (i) the basic fault-fracture (pathways) system formed 2600-2200 Ma ago while the pluton was at a depth of 10 km. (ii) subsequent geological activity, and uplift, resulted in a reactivation of this ancient system rather than the development of new fracture systems. (iii) the most recent geological activity has resulted in low-temperature fillings and 'open' fractures, which are most abundant in the upper 200 m of the rock mass but may extend to greater depths in fault zones. (iv) the present 'open' pathways system appears to be constrained and controlled by the occurrence and distribution of the ancient fault-fracture network.

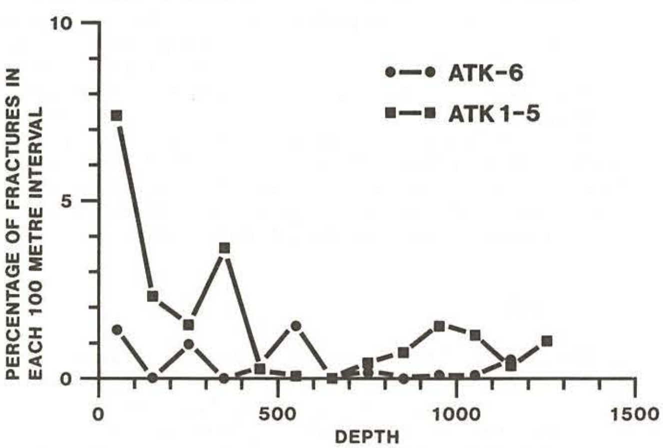

FIGURE 6: DISTRIBUTION OF CLAY-FILLED FRACTURES IN BOREHOLES ATK 1-5 AND ATK-6 SHOWING DECREASING ABUNDANCE WITH INCREASING DEPTH

An understanding of the ancient fracture system, how and when it formed and under what pressure-temperature conditions, and the subsequent evolution through geologic time is considered a necessary prerequisite to develop an understanding of the occurrence and distribution of these present-day fluid- flow pathways.

LAC DU BONNET BATHOLITH, WHITESHELL

The Lac du Bonnet Batholith (Fig. 7) is a 1500-km^2 northeast-trending granite, which intruded the greenstones and gneisses of the English River Subprovince 2680 $\pm$ 91 Ma ago. The dominant phase is a pink porphyritic granite-granodiorite, with subordinate biotite rich and gneissic phases, xenolith-bearing granite, grey granite-quartz monzonite and gneissic granite (20). Two older phases, a foliated biotite granite and porphyritic hornblende-biotite granite, outcrop at the east end of the batholith (20,21). Linear magnetic anomalies, which have been intepreted to represent major discontinuities, transect the batholith. Only one of these anomalies is known, from observation, to be associated with a fault. The regions between these linear magnetic anomalies are, in general, characterised by few vertical fractures, and by low-dip fractures, which tend to control the outcrop surface. The mean fracture frequency is 0.3 fractures/m (20), i.e. an order of magnitude lower than either the Eye-Dashwa Pluton or the East Bull Lake gabbro-anorthosite.

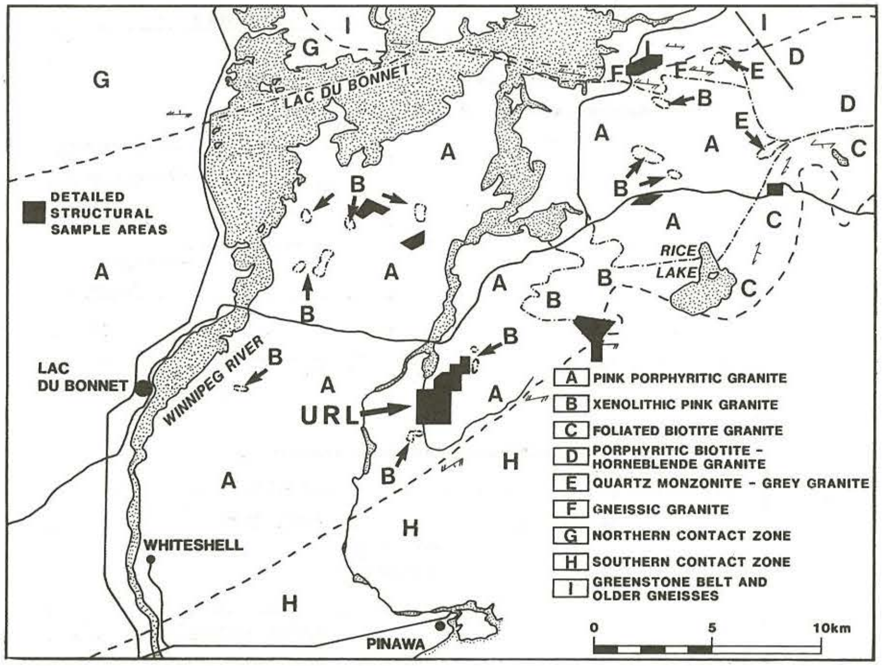

FIGURE 7: SIMPLIFIED GEOLOGICAL MAP OF THE LAC DU BONNET BATHOLITH, AND THE LOCATION OF THE URL LEASE SITE AND OTHER AREAS IN WHICH SOME DETAILED GEOLOGICAL STUDIES HAVE BEEN UNDERTAKEN.

A number of cored and oriented boreholes (mostly within the Underground Research Laboratory (URL) lease area shown in Fig. 7) indicate that the subsurface environment is dominated by low-dip fractures. In addition, the subvertical fractures that are present tend to be restricted to the upper 100 m - 200 m of the rock mass. Below these depths, the rock mass at the URL is, except for local low-dip reverse-movement zones, largely unfractured and unaltered.

Detailed analyses of fractures and their relationship to the compositional banding and foliation in the rock mass at the URL lease area has allowed the formation of fractures and their evolution through geologic time to be outlined in considerable detail (21). (1) Intrusion, cooling, and crystallisation of the batholith at 2680 $\pm$ 91 Ma under a regional stress field with σ_1 oriented approximately N-S (subhorizontal). Development of a gross E-W trending compositional banding and a conjugate pair of cataclastic zones at 150° and 030°. (2) Rotation of σ_1 to 020° accompanied by intrusion of pegmatites (020°) and development of a foliation fracture cleavage at 170° and a weak but pervasive foliation at 065°. (iii) Local development of a conjugate pair of epidote-filled fractures at 170° and 100° indicating σ_1 orientation at 135°. (iv) Chlorite filled low to intermediate dip fractures and reverse fault zones oriented at 020°/15°-30° and, very locally, 110°/15°-30°, suggesting an increase in horizontal stresses relative to the vertical stresses. General NW thrusting movements are indicated. (v) Subvertical fractures trending 030°-035° filled with low-temperature fillings such as iron hydroxides, carbonate and clays. These fractures are parallel to present day σ_1, tend to die out with depth, and are interpreted to have formed in the most recent geologic past and are presently forming at the URL excavation site (21)(22).

The hydrogeological regime at the URL lease area is dominated by the low- angle reverse-fault zones ((iv) above) with 'recent' bicarbonate waters near surface and saline waters at depth (20). The saline waters are characterised by low Br/Cl and high Na/Ca ratios and may be due to mixing with adjacent Western Canada sedimentary basin brines(19). Recent age dating (Ar-Ar) of minerals within these low angle thrusts suggests that they are at least 700 Ma old (Kamineni, personal communication), i.e., as at the two other research areas, the present-day fluid pathways are largely constrained and controlled by the occurrence of pre-existing ancient fracture pathways.

Although few age dates on fracture-filling minerals are presently available most of the structures are interpreted to have formed during the early to late crystallisation and deuteric alteration stages of batholith emplacement and cooling. Subsequent brittle fracturing episodes are restricted to the epidote and chlorite events and, of course, the recent, near-surface fracturing. This general reduced level of pervasive brittle fracturing is in accord with the quiescent geologic-tectonic history of this part of the Canadian Shield (24).

DISCUSSION

Plutons at three research areas, East Bull Lake, Atikokan and Whiteshell, are completely dissimilar in terms of size, shape, composition and tectonic history. The East Bull Lake gabbro-anorthosite is a small elongate lopolith which has been subjected to a considerable number of tectonic-orogenic events from emplacement at 2472 $\pm$ 71 Ma to present. It is highly fractured and contains an abundance of filling materials which were emplaced during the various tectonic-orogenic events. Recent activity is recorded by low temperature filling materials, which are most abundant in the upper 300 m of the rock mass, but also occur in discreet fracture zones throughout the rock mass.

The Eye-Dashwa Pluton at Atikokan is an oval shaped granite, which was deformed in a regional stress field shortly after emplacement and cooling at 2672 ± 24 Ma. Subsequent tectonism, related to Lake Superior rifting at 1100 Ma, resulted in emplacement of diabase dykes and reactivation of the existing fracture system. Recent activity is recorded by low-temperature filling materials which are most abundant in the upper 200 m of the rock mass.

The Lac du Bonnet Batholith is a large granite body whose structures were formed during and shortly after emplacement and cooling at 2680 ± 91 Ma. Subsequent brittle deformation is restricted to the sparse development of low- angle chlorite-filled fault zones and local subvertical epidote-filled fractures. Recent activity is recorded by low-temperature fillings within fractures which are most abundant within the top 100-150 m of the rock.

Despite these differences in size, composition and tectonic history, the fault-fracture systems in all three plutons have been shown to undergo an evolution through geologic time. This involves: (i) development of the basic fault-fracture system shortly after emplacement and during cooling of the pluton, (ii) emplacement of a sequence of filling materials that record decreasing pressure-temperature conditions with increasing time to present. These fillings record a periodic reactivation of the existing fracture system and the development of new fractures, and can be correlated with specific regional geologic-tectonic events that are known to have occurred in the Canadian Shield.

The low temperature, recent, fracture fillings and unfilled, new, fractures tend to be restricted to the upper, near surface, part of the rock mass, indicating that the effects of 'recent' geological activity are most pronounced near surface (at East Bull Lake low-temperature fillings also occur in discrete fracture zones throughout the rock mass). This decrease in abundance of recent fillings is accompanied by a decrease in hydraulic conductivity values and an increase in salinity with depth.

These results provide substantial evidence to suggest that stable fracture environments (i.e. those not reactivated by recent geologic events) are present at depth within plutonic igneous rocks. This stability is a very positive finding in terms of the concept of disposal of used nuclear fuel within these environments.

The results also indicate that the present day fluid pathways in these rocks are largely constrained and controlled by the occurrence and distribution of the ancient, pre-existing, fracture system. At the Lac du Bonnet Batholith (URL lease area) the preexisting low angle thrust zones, which are at least 700 Ma old, form the major controls on the present day groundwater systems. At the Eye-Dashwa Pluton the basic fault-fracture system was formed between 2,600 Ma and 2,200 Ma. Localised reactivated parts of that system comprise the present day groundwater flow paths. This re-activation appears to occur to greater depths within faults than in non-fault areas. At East Bull Lake the complexity of the fracture history precludes, at present, a definitive assessment of the controls of formation of the ancient fracture system. However, the fact that younger fillings always occur in reactivated segments of older fractures indicates that similar constraints are equally applicable in this area.

This apparent control and constraint by the ancient fracture system indicates that in order to develop an understanding of the present day groundwater flow systems within these rocks it is necessary to define the occurrence and distribution of the ancient fracture systems. The development of these ancient systems is manifestly different in each of the three areas studied. These differences cannot be attributed to age, i.e. all three plutons are essentially Archean. It is possible that the differences may be partly due to variations in size, composition, and emplacement mechanism of the plutons. (25) The most likely cause is, however, considered to be the distinctly variable geologic-tectonic history undergone by each pluton. This variable tectonism has imprinted quite distinct fracture-fracture flow and fracture filling-geochemical conditions at each of the three areas.

The safe disposal of nuclear fuel waste deep within plutonic rocks requires an assessment of the physical-chemical-hydrogeological conditions within the rock mass. Because these present conditions are largely constrained and controlled by the ancient fracture systems it is suggested that any such assessment should be based on a full understanding of the evolutionary structural-geochemical history of the basic fracture framework within the rock mass.

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