# CHARACTERIZING FRACTURED PLUTONIC ROCKS OF THE CANADIAN SHIELD FOR DEEP GEOLOGICAL DISPOSAL OF CANADA'S RADIOACTIVE WASTES

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## Abstract

Since 1978 AECL has been investigating plutonic rocks of the Canadian Shield as a potential medium for the disposal of Canada's nuclear fuel waste. During the last two years this study has been continued as part of Ontario Hydro's used fuel disposal program. Methods have been developed for characterizing the geotechnical conditions at the regional scale (500 to 1000 km$^2$) of the Canadian Shield as well as for characterizing conditions at the site scale (~25 km$^2$) and the very near-field scale needed for locating and designing disposal vault rooms and waste emplacement areas. The Whiteshell Research Area (WRA) and the Underground Research Laboratory (URL) in southeastern Manitoba have been extensively used to develop and demonstrate the different scales of characterization methods.

At the regional scale, airborne magnetic and electromagnetic surveys combined with LANDSAT 5 and surface gravity survey data have been helpful in identifying boundaries of the plutonic rocks, overburden thicknesses, major lineaments that might be geological structures, lithological contacts and depths of the batholiths. Surface geological mapping of exposed rock outcrops, combined with surface VLF/EM, radar and seismic reflection surveys were useful in identifying the orientation and depth continuity of low-dipping fracture zones beneath rock outcrops to a depth of 500 to 1000 m. The surface time-domain EM method has provided encouraging results for identifying the depth of highly saline pore waters.

The regional site scale investigations at the WRA included the drilling of twenty deep boreholes (> 500 m deep) at seven separate study areas. Geological core logging combined with borehole geophysical logging, TV/ATV logging, flowmeter logging and full waveform sonic logging in these boreholes helped to confirm the location of hydrogeologically important fractures, orient cores and infer the relative permeability of some fracture zones. Single-hole radar and crosshole seismic tomography surveys were useful to establish the continuity of fracture zones away from the boreholes up to distances of 50 to 400 metres. Single-hole hydraulic tests using straddle packer methods, testing in multiple-interval casing systems and large-scale crosshole pumping tests provided estimates of the in-situ permeability. Crosshole tracer tests were performed in several of the major fracture zones to estimate the solute transport properties and to provide information to scale up the properties to the regional modeling scale. Geochemical and hydrogeochemical characterization of host rock, fracture-infilling minerals, groundwaters and porewaters have provided data for flow modelling and safety assessment as well as obtaining supporting information such as groundwater ages, sources of salinity and rock-water interactions.

# 1 Introduction

AECL has been conducting detailed geological/geotechnical investigations in plutonic rocks at several Research Areas in the Canadian Shield since 1978 (Dormuth and Nuttall 1987). The main focus of the work was on developing and testing site evaluation and site characterization methods to investigate progressively larger volumes of plutonic rocks to depths of 1000 m. Major studies were conducted at Atikokan, Ontario (granite-granodiorite), Chalk River, Ontario (ortho- and paragneisses), East Bull Lake, Ontario (layered gabbro-anorthosite), and Whiteshell, Manitoba (granite-granodiorite). AECL has also conducted brief field studies of about 30 other plutonic rock bodies on the Shield. One of the objectives has been to study the character and distribution of fracturing, at all scales, in several types of rock. A second objective has been to develop ways to analyze this information to infer conditions at depths of 500 - 1000 m to aid in the future siting of a nuclear fuel waste disposal vault. Both objectives help define rock conditions and characteristics for hydrogeological modeling. In this process, extremely detailed fracture and lithologic logging(including geophysical logging), and hydrogeological monitoring and testing of over 75 inclined boreholes (some drilled to depths up to 1 km) have been performed in the research areas. The 450 m-deep Underground Research Laboratory (URL) excavated in the Lac du Bonnet granite and boreholes in the associated Whiteshell Research Area have provided extensive opportunities to develop and demonstrate the area scale, site scale and local scale characterization methods. The results from the Lac du Bonnet Batholith (with twenty deep boreholes) are discussed in this paper. These results have been obtained by appropriate use of the disciplines of geology, geophysics, hydrogeology and hydrogeochemistry as described below. In the last two years this work has become integral part of Ontario Hydro's used fuel disposal program.

# 2 Geology

The Lac du Bonnet Batholith lies in the southern part of the English River Subprovince, the Winnipeg River batholith zone. The batholith is in sharp contact with the Bird River Greenstone Belt to the north and in gradational contact with foliated tonalite- granodiorite gneisses and migmatite. The batholith trends east-northeast, with about 1500 $km^2$ exposed east of the Paleozoic rock cover. The initial fault/fracture identification shown in figure 1 is partly based on several types of satellite data, airborne geophysical data, airphoto data and available bedrock geology maps. This is followed by detailed surface geological mapping, ground geophysics, surface hydrological and associated studies. The geology of the URL site is representative of the batholith as a whole. The gross structure, the variations in its large-scale litho-structural components, and the orientation of smaller scale fabric elements affect the distribution of some of the fractures and large low-dipping fault zones. AECL mapped the batholith for category, lithology and fracture frequency at a scale of 1:50,000 (Brown and Thivierge 1981 and McCrank 1985) and the URL site for lithology and fracture characteristics and distribution at a scale of 1:1000 (Stone et al. 1984). Detailed geological work at URL site and five other smaller areas 'A', 'B', 'D', 'G' and 'J' shown in figure 1 has continued (Davison et al. 1994).

## 2.1 Lithology

The component granite phases of the batholith are pink, porphyritic granite- granodiorite, xenolith-bearing granite and grey granite. A pink, medium to coarse-grained, porphyritic granite underlies most of the lease site near surface at URL, site 'A', 'B' and 'D'. The site 'G' is at the southern contact of the batholith with tonalite the gneisses and site J is entirely in the gneissic belt. A grey granite that is commonly homogeneous and equigranular underlies much of the lease area below the sites exclusively in batholith. This grey granite is also found outcropping south of the shaft.

The alteration of the granite has been divided into five types: (*i*) three major, partially coinciding with petrologic units; and (*ii*) two minor, largely coincident with fracture zones (Brown et al. 1989). At the URL lease site and sites 'A', 'B' and 'D' the gross sequence from deep to shallow level is (1) grey granite, (2) green-grey granite, and (3) pink granite. Discrete zones of deep-red granite and clay rich granite occur in both units in association with fracturing in fault or other heterogeneous zones. Grey granite represents the mass of the batholith, with almost unaltered microcline, plagioclase, and biotite. The green-grey granite is similar, but epidote partially replaces plagioclase and biotite and the granite contains microscopic, chlorite filled fractures.

At the URL site shown in figure 2, pink granite is present from surface to a depth of 260 m. Grey granite underlies most of the pink granite away from fault zones. The intensity of pink coloration increases both towards individual fractures and also as the total number of fractures increases, suggesting that pink granite has further altered to dark red granite in the highly fractured zones and that the hydrothermal flow through these zones involved a large component of meteoric water. The compositional layering on a scale of 0.25 m to several tens of metres is common and is shown by variation in the contents of plagioclase, potassium feldspar, quartz and above all, biotite. The western half of the URL lease is underlain by a series of domes trending north-northeast in a long antiform and outlined by bands of xenolith-bearing granite and associated pegmatodial granite.

## 2.2 Structure

The formation of faults and mesoscopic fractures that are not filled by magmatic material appears to have been initiated immediately following the formation of the foliations, dykes, and quartz veins. At the URL site, fractures either are subvertical or dip 10-30°. Subvertical fractures, described in more detail are grouped into those striking north-northeast (015-020°), those striking east-southeast-southeast (110-130°) and those striking south-southeast (160-170°). The overall observations suggest a north-northeast trending maximum compressive stress and a vertical intermediate compressive stress axis at the time of fracturing, similar to the stress field during the formation of the later pegmatite dykes and quartz veins. Except in the vicinity of low-dip fault zones, subvertical joints striking east-southeast largely die out around 100 to 150 m from the surface, implying that they are only due to near-surface general extension, from whatever cause.

Low-intermediate-dipping (10-30°) fractures are common at surface and are associated with fault zones in the subsurface. There is a general tendency throughout the batholith for two pairs of thrust-movement fractures to form about north-north-east and southeast strikes. At the URL site three reverse faults, important in controlling groundwater flow, have been encountered by drilling. Fracture zone 3 (FZ3) and a splay zone off fracture zone 2 (FZ2) were intersected in the URL shaft. FZ2 which was initially defined by drilling only was indicated in surface seismic reflection (Kim et al. 1994) and crosshole seismic tomography surveys (Wong et al. 1985). In characteristics these faults studied in detail at URL are typical of faults in the entire batholith.

## 3 Geophysical Investigations

Airborne magnetic data have been very effective in mapping the boundaries of granite rock masses and their contact with adjoining gneisses in the entire Superior Province. The Lac du Bonnet Batholith boundaries are clearly marked by the transition from a high total magnetic field, associated with granite/granodiorite mass, to a low magnetic field, mapped over gneisses to the north and south (Soonawala et al. 1990). In addition, the vertical magnetic gradient derived from the total field map has identified steeply dipping lineaments and lateral displacements along north north-east trending faults. The east south-east trending gradient anomalies are indicative of granodiorite dykes and near-surface concentration of xenolith-rich trends. Near-surface outcrops of FZ2 and FZ3 at URL study area are marked by magnetic lows on the total field map and identified in surface VLF-EM anomaly maps. Multi-frequency airborne EM data has been very useful in producing an overburden thickness map over the entire batholith (Dvorak 1988). In general most of the batholith is covered with thin overburden of 2 to 5 m thickness. One north-north-east 60 m thick sediment filled valley (the Dead Creek lineament) runs along a magnetic displacement anomaly. The Lee River is identified as another parallel magnetic lineament and supported by increased thickness of sediments in the airborne EM overburden map. The Lac du Bonnet and Rice Lakes have also been interpreted to have 15 to 60 m thick sediments. The surface gravity surveys have a mapped negative anomaly of up to 7 mgal associated with the batholith with a steeper gradient towards its southern contact with gneisses. The combined gravity and magnetic modeling along a few northwest- southeast cross sections (utilizing density and magnetic susceptibility values determined from a large number of surface samples from different rock units) indicate that the root of this batholith extends up to a depth of 15 to 18 kms (Tomsons et al. 1995).

Localized ground penetrating radar surveys over exposed outcrops have been very useful in mapping low dipping fracture zones to depths of 10 to 70 m. The regional seismic reflection profiles have identified scattered reflectors in depth range of 250 to 1200 m. However, in view of the increased ground noise in shallow surface seismic reflection data over crystalline rocks, the reflectors identified are at times ambiguous. Recent tests with time domain electromagnetic methods at the WRA (Maris et al. 1998) suggest that properly planned surface surveys can be used to identify the depth and lateral extent of regions of highly saline pore water saturated granitic rocks in the Canadian Shield environment.

The conventional geophysical logging tools and development of dedicated new logging tools like borehole radar and crosshole seismic tomography surveys have been extremely useful in detailed fracture mapping and lithologic logging (in association with the oriented cores) from many boreholes drilled to depths of up to 1 km. The conventional single-hole geophysical logging, supplemented by full waveform sonic, TV/ATV and core logging from all the 40 boreholes in this batholith (of which 20 are deep boreholes varying between 500 to 1000 m) has demonstrated that the upper 150 to 300 m of rock was a pink, fractured granite. Below the upper pink layer, the rock is a sparsely fractured grey granite. The transition zone from the upper, moderately fractured rock matrix to deeper sparsely fractured rock may extend from few tens of meters to one hundred meters and more depending upon the locations of low dipping fractures and local lithological variations. Discrete, low- to intermediate-dipping fracture zones (10-75 m thick) have been encountered at depths of 200 to 1000 m. Epidote fillings have been found in a steeply-dipping fracture zone extending from the surface to at least 700 m depth in the grey granite at the B-site.

Conventional geophysical logging has been able to map fractures in a radius of 15 to 30 cm around the borehole walls. The reflections mapped by single-hole radar surveys were able to trace open fractures (identified in boreholes from core log or conventional logs) up to a radial distance of 60 m in the pink granite section of the borehole walls. The effective radius of investigation at greater depths (beyond 150 to 200 m) was found to decrease exponentially due to the reduced resistivity of grey granite caused by saturation of pore space by saline water.

Cross hole radar tomography surveys were able to map continuity of an intermediate-dipping fracture up to a distance of 100 m between boreholes WB1 and WB2 to a depth of 190 m. In the same pair of boreholes, the crosshole seismic tomography survey at a frequency of 4500 Hz shown in figure 5 was able to map two regions of low P-wave velocity (5400-5700 m/s) between depths of 150-220 m and 280-310 m (Lodha et al. 1991). The upper low-velocity zone mapped a fracture zone within pink granite. The lower, low-velocity zone represents another low-dipping fracture zone and the transition from pink to grey granite. Crosshole hydraulic testing demonstrated these fracture zones to be connected with the transmissivity values varying between $1.5 \times 10^{-8}$ to $1.3 \times 10^{-5}$ $m^2$/sec. Below these two fracture zones the average P-wave velocity was 5850 m/sec which based on the core logs from these two boreholes and an understanding of velocity measurements at the nearby URL represents sparsely fractured, grey granite. A geologically-extrapolated epidote dyke exists between the two boreholes. However this feature did not produce any velocity anomaly in the seismic tomography panel and it showed no evidence of hydraulic conductivity in crosshole testing.

The crosshole seismic tomography tool developed in the CNFWMP/ UFDP to use in properly planned co-planner boreholes, has the potential of mapping the continuity of fracture zones and the volume of sparsely fractured rock to distances ranging from 200 to 400 meters up to 1000 metres depth. At the other extreme the small scale high frequency (10,000 to 20,000 Hz) crosshole seismic transducers, have been successfully used to measure excavation damage of 10 to 50 cm from the excavated walls at depths of 400 m in URL. The single hole radar, crosshole radar and crosshole seismic tomography techniques have been used in many small scale to intermediate scale experiments in the URL to characterize moderately and sparsely fractured rock, map fracture geometry behind excavated rooms, and to understand excavation damage zone in underground openings of different shapes (Hayles et al. 1995a, 1995b).

## 4 Geochemical Characterization

It is important to obtain an indication of the residence times ('ages') of groundwaters and get a semi-quantitative insight into rock-water interactions, rates of groundwater flow and the locations of modern and ancient flow paths. This, in turn, is used to provide qualitative support for the predictions of radionuclide-transport models.

In addition to siting requirements, for performance assessment modelling it is important to know the groundwater chemistry of the site because:

1. the total dissolved solids (TDS) content affects the density and viscosity of the groundwater;
2. the performance of the used fuel container and surrounding buffer materials is influenced by groundwater composition; and,
3. the retardation or migration of radionuclides with respect to buffer, backfill and various rock minerals is affected by varying pH, Eh and ionic strength conditions, and the presence or absence of specific dissolved components (e.g., $HCO_3$, F, $SiO_2$).

The parameters that were determined in characterizing the groundwater composition in Canadian program are shown in Table 1. In general, the pH, Eh and elemental concentration data were used in determining rock-water interactions that have occurred. The isotopic data were used to further delineate rock-water interactions and to determine the relative 'age' of the groundwater. Some typical rock-water interactions that were recognized as occurring in felsic igneous rocks were the carbonic acid attack and hydrolysis of plagioclase and orthoclase feldspars to produce kaolinite, illite and $Ca^{2+}$, $Na^+$, $K^+$, $SiO_2$ and $HCO_3^-$ in solution, carbonic acid dissolution of biotite to give kaolinite and $K^+$, $Mg^{2+}$, $SiO_2$ and $HCO_3^-$ and oxidation of accessory pyrite to produce ferric oxyhydroxides and $SO_4^{2-}$. In addition, secondary minerals in fractures in the rock, such as gypsum and calcite may have been dissolved to give $Ca^{2+}$, $SO_4^{2-}$ and $HCO_3^-$ in solution.

The composition of groundwater in most rocks of the Canadian Shield evolves from a dilute (TDS < 0.3 g/L) Ca-$HCO_3$ water in shallow bedrock in recharge areas to a highly saline (TDS ~ 50 g/L) Na-Ca-Cl or Ca-Na-Cl water at a depth of about 1 km. The variation in type and concentration of the major dissolved species in these groundwaters in the Canadian program in general and in particular at the URL lease area are shown in figures 3 and 4 respectively.

The process of chemical evolution of these groundwaters is complicated by mixing with deeper, more saline groundwater and rock pore fluids, whose composition may not be derived entirely from reaction with the granitic host rock. For instance, to the west of the Lac du Bonnet Batholith, in the Paleozoic sedimentary rocks of western Manitoba, are Na-Cl formation brines which may have penetrated eastwards into the granite under past hydrogeological regimes (Gascoyne et al. 1989). Isotopic analyses have helped to resolve the origin and residence times of these types of groundwater. Shallow, fresh groundwaters are essentially post-glacial in origin (less than about 8000 years old) whereas the intermediate-depth brackish waters contain pockets of cold-climate recharge which are probably of Late Pleistocene age. Underlying, saline groundwaters appear to be recharge that occurred under warm climate conditions and are probably pre-Pleistocene (>2 million years) in age (Gascoyne 1994).

**Table 1 Summary of categories of samples taken and analyses made for groundwaters collected in AECL's hydrogeochemical program.**

| Category | Species/Element | Category | Species/Element |
|---|---|---|---|
| Anions | $HCO_3$, $SO_4$, Cl, Br, F, $NO_3$, I | Sulphate Isotopes | $S^{18}O_4$, $^{34}SO_4$ |
| Cations | Na, Ca, Mg, K, Sr, Si, B | Halogen Isotopes | $^{36}Cl$, $^{129}I$ |
| Trace Elements | Li, Fe, Mn, V, Al + Others | Strontium Isotopes | $^{87}Sr/^{86}Sr$ |
| Dissolved Organic Carbon | Organic C | Uranium and Radium Isotopes | U, $^{234}U/^{238}U$, $^{226}Ra$ |
| Colloids | Colloidal Fractions | Radon | $^{222}Rn$ |
| Environmental Isotopes | $^{2}H$, $^{3}H$, $^{18}O$, | Dissolved Gases | $H_2$, He, $O_2$, $N_2$, $CO_2$, $CH_4$, Ar, $H_2S$ |
| Carbon Isotopes | $^{13}C$, $^{14}C$ | Dissolved Inert Gas Isotopes | He, $^{3}He/^{4}He$, $^{22}Ne/^{21}Ne$ |

## 5 Hydrogeological Characterization and Modelling

The rate, direction and chemical characteristics of groundwater flow through plutonic rocks of the Canadian Shield is controlled by the fracture networks that exist in the rock, their geometry and interconnections, and how the fractures connect to the surface topography. AECL has studied groundwater flow in plutonic rocks to depths of about 1 km at various geologic research areas on the Shield. These studies reveal that the degree of fracturing is the main distinguishing feature between domains of rock that have different groundwater flow characteristics. These domains comprise: zones of intensely fractured rock; regions of moderately fractured rock; and, low-permeability, sparsely fractured areas (figure 2) where the rock contains few, if any permeable fractures (Davison et al. 1990).

Field investigations show that the fracture zones are the most important pathways for the large-scale movement of groundwater and solutes through the rocks. These are narrow zones of intense fracturing that can be hydraulically continuous over relatively large distances and to great depths in the rock. These zones are often more permeable than the rest of the rock mass, although significant spatial variations in permeability can occur within them. In some cases the permeability range has been as much as six orders of magnitude ($10^{-12}$ to $10^{-18}$ $m^2$) over distances of a few metres and long interconnected channels of high permeability have been observed (Davison and Kozak 1989, Davison et al. 1990).

The regions of moderately fractured rock occur adjacent to the fracture zones as well as at shallow depths in the rocks. The frequency of permeable fractures associated with these domains of moderate fracturing decreases with depth and the rocks below a few hundred metres contain very few permeable fractures aside from the fracture zones.

Rock with very low permeability (less than $10^{-19}$ $m^2$) has been encountered below depths of 300 m to 800 m at all the geologic research areas examined so far. Studies at the Whiteshell Research Area reveal that domains of extremely low permeability, sparsely fractured rock greater than 500 m thick occur in the granitic Lac du Bonnet batholith below depths of only a few hundred metres (figure 6). Permeabilities as low as $10^{-22}$ $m^2$ have been determined from hydraulic tests and abnormally high fresh water equivalent fluid pressures are recorded in piezometers that isolate these regions of rock. The high fluid pressures appear to be related to extremely high salinity pore fluids (up to 200 g/L TDS) that reside in the very low permeability rock (Stevenson et al. 1996a, 1996b).

Modelling studies were performed during construction of the revised groundwater flow model of the WRA to determine if the high fluid pressures in the domains of massive, sparsely fractured grey granite could be accounted for by the presence of dense, saline pore fluids. The modelling showed that if highly-saline $CaCl_2$ brine (up to 200 g/L TDS) occupied the pore spaces in these domains, most of the high fluid pressures could be explained. This explanation is supported by independent evidence from the URL site where samples of very slow seepage into boreholes drilled into domains of low permeability, sparsely fractured grey granite at the 420 m level show that the pore fluids are of $CaCl_2$ composition and have a salinity of at least 90 g/L (Gascoyne et al. 1996).

The results of modelling (Ophori et al. 1996) using the calibrated flow model were also analyzed and used to define boundaries for a smaller local model surrounding the selected, hydraulically-favourable location for a hypothetical disposal vault. In this analysis, several hydraulic cross sections were constructed across the flow model. Zones in which flow was either divergent or convergent were identified and assumed to be natural flow divides. Some of the divides were then connected to demarcate an area of about 75 $km^2$ for the revised local model around the selected, hydraulically-favourable location for a hypothetical vault. Groundwater flow in this local model region would need to be analyzed in much more detail as part of any process of developing a geosphere model for use in evaluating the overall performance of a hypothetical disposal vault at this location.

## 6 Summary

The entire geoscience/geotechnical process of site screening, evaluation and characterization of the disposal site is shown in figure 7. The integrated geological, geophysical, hydrological, hydrogeological and hydrogeochemical process begins with regional scale site screening-evaluation of a 500 to 1000 $km^2$ area selected from other considerations (volunteerism, socio-economic, geotechnical etc.). This process progresses with little overlap, between site screening and site evaluation activities, to site scale evaluation of smaller grid blocks (5 to 25 $km^2$) within the candidate area. This site scale evaluation involves more detailed investigations, such as drilling, in addition to surface-based investigations. The surface and subsurface information is integrated to produce a regional hydrogeological model with a depth of one to four kilometers. This regional model is then used to select a technically preferred location for the disposal vault.

The preferred vault location (about 5 $km^2$) is then characterized in detail to develop a three-dimensional subsurface structural and groundwater flow model in preparation for vault design and performance assessment. All this information will ultimately be required to obtain a license for shaft sinking, underground excavation and vault characterization.

The detailed geoscience/geotechnical investigations completed at WRA and experiences from other studies provide enough support to suggest that reasonably large volumes of sparsely fractured plutonic rocks are present in the Canadian Shield. The knowledge gained in the WRA and URL clearly demonstrates that these sparsely fractured rocks, enveloped by low-dipping and occasional vertical fracturing, can have very low permeabilities (< $10^{-20}$ $m^2$). The hydrogeochemistry studies of groundwater from fracture zones and the rock matrix provide evidence of high salinity (> 50 g/L) fluids and, both late to pre-Pleistocene origin (> 2 million years in age) for these waters. This demonstrates that a long residence time of ground water in sparsely fractured volumes of plutonic rock can potentially provide a suitable environment for siting a safe repository.

The examples provided from WRA studies also demonstrate that geoscience/geotechnical application methods have enough resolution to identify saline water-saturated, sparsely fractured rock volumes and associated major fracture zones in plutonic rocks. The detailed site characterization methods are sufficiently advanced to develop subsurface structure and groundwater flow models for performance assessment and safety analysis for vault design. Any future developments in site characterization technology will provide additional enhancement for siting a nuclear fuel waste repository.

## 7 Acknowledgements

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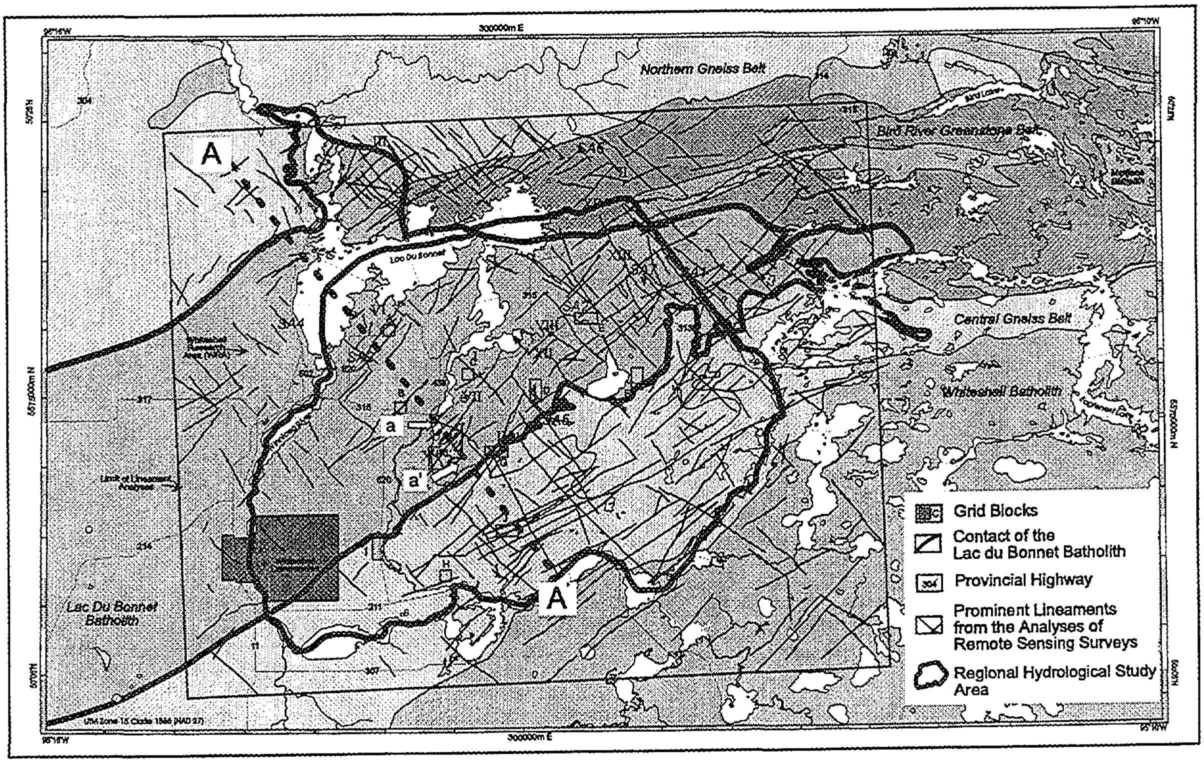


FIGURE 1. Prominent Composite Lineaments from Remote Sensing Data (Airphoto, Aeromag and LANDSAT), Boundary of Regional Hydrological Study and Individual Smaller Site Evaluation Grid Blocks in the Whiteshell Research Area

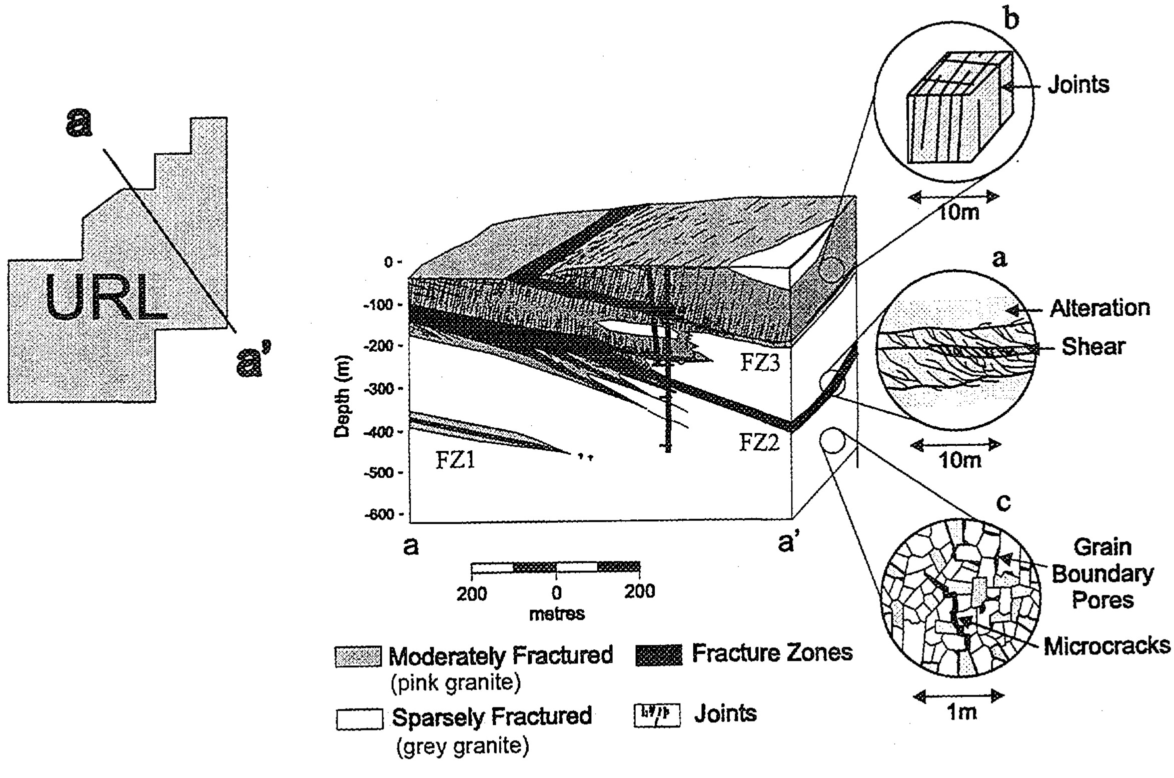


FIGURE 2: The Three Main Fracture Domains in the WRA; a) Fracture Zones (faults), b) Moderately Fractured Rock, and c) Sparsely Fractured Rock

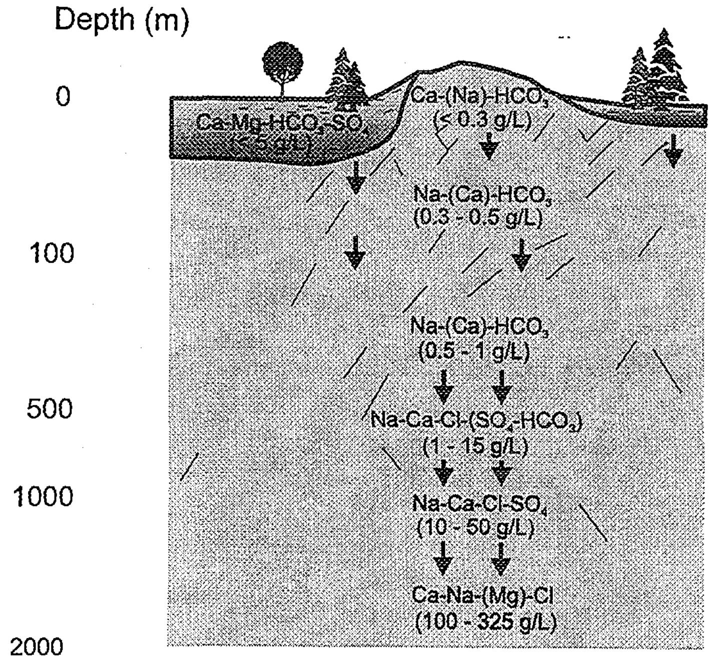


FIGURE 3: Generalized Evolution of Groundwater Chemistry with Flow Through Crystalline Rock Showing Typical Ranges of Salinity (TDS) Encountered at Depth

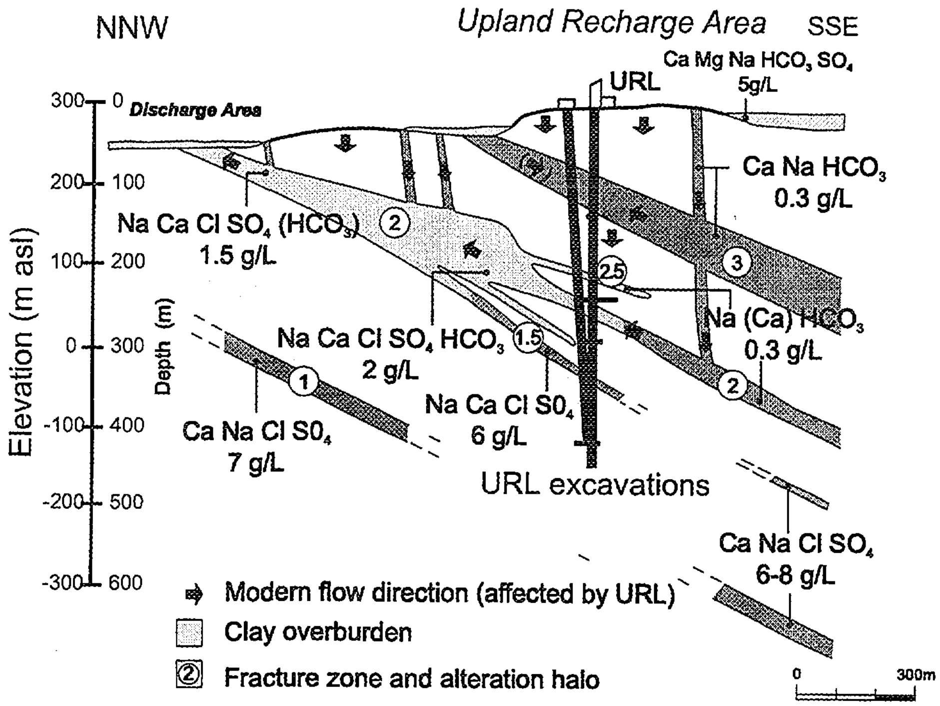


FIGURE 4: Schematic Cross-section Through the URL Area Showing Inclined Fracture Zones and Groundwater Chemistry in the Fracture Zones. Flow directions from pre- and post-excavation head distributions.

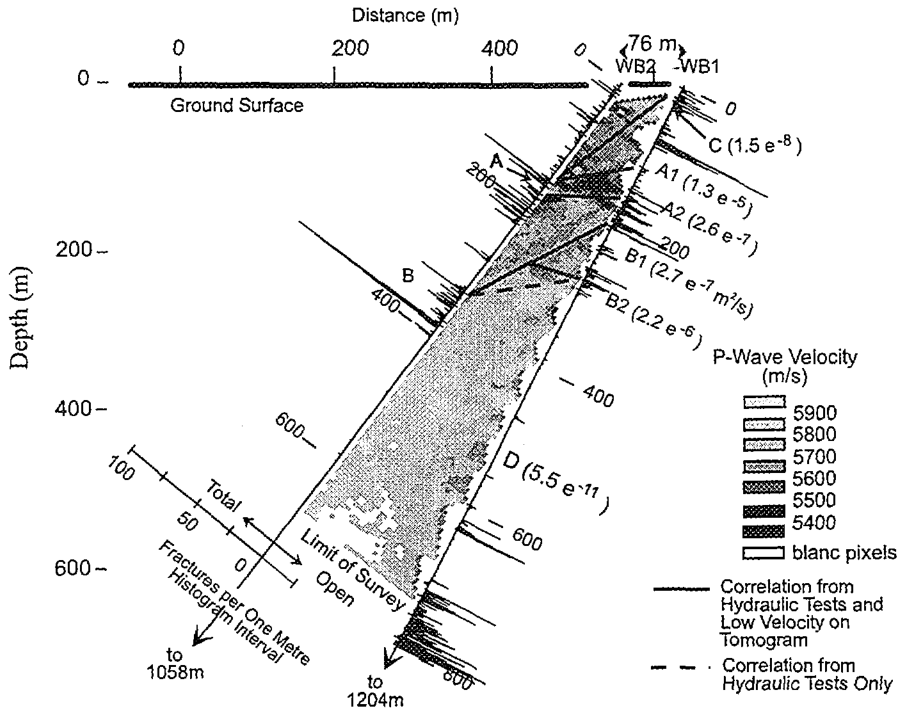


FIGURE 5: Cross-Hole Seismic Image of the P-Wave Velocity Between Boreholes WB1 and WB2 with Hydraulic Test Correlation. Histograms of the fractures observed in the core log are also shown. Low Velocity zones A1, A2, B1, B2, and C have increased hydraulic transmissivity ($m^2/s$) compared to sparsely fractured rock transmissivity (D).

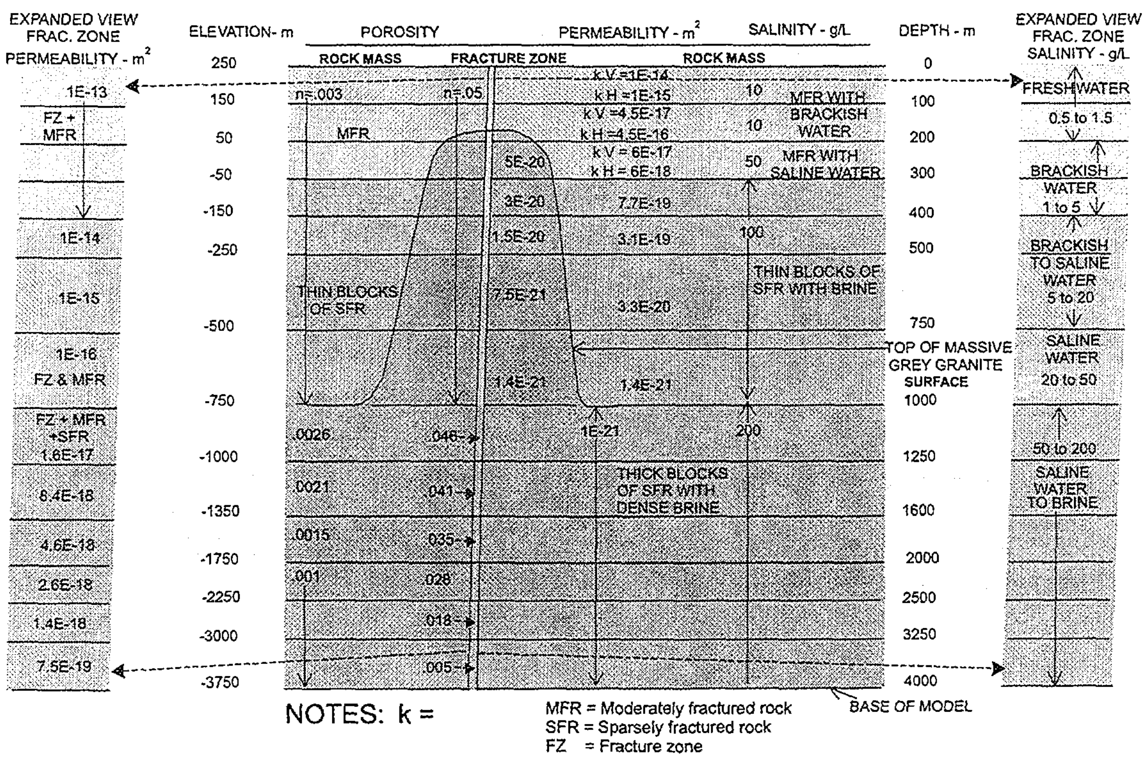


FIGURE 6: A Schematic Section of the Permeability, Porosity and Salinity Distributions in the Fracture Zones, Moderately and Sparsely Fractured Rock with Depth at WRA

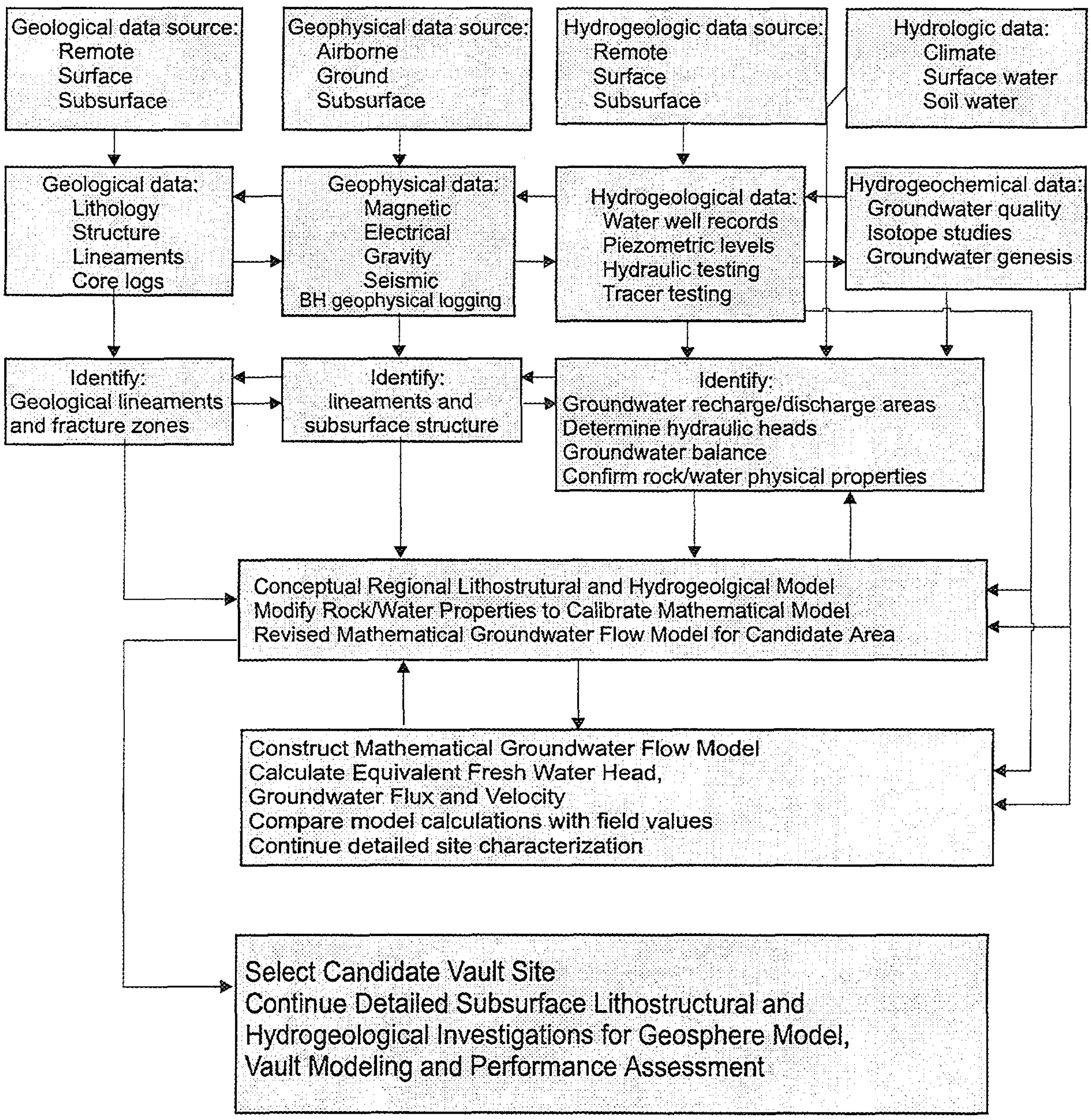


FIGURE 7: Site Evaluation and Characterization Procedure for Constructing the Regional Conceptual Hydrogeologic Model and Selecting Preferred Vault Site. Detailed subsurface lithostructural and hydrogeological models are needed at selected site for ultimate vault design and performance assessment.