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Chapter 15

Region 12, Precambrian Shiela

R. N. Farvolden
Department of Earth Sciences, University of Waterloo, Waterloo, Ontario NL2 3G1, Canada
O. Pfannkuch
108 Pillsbury Hall, University of Minnesota, Minneapolis, Minnesota 55455
R. Pearson
Golder Associates Incorporated, 3772 Pleasantdale Road, Suite 165, Atlanta, Georgia 30340
P. Fritz
Department of Earth Sciences, University of Waterloo, Waterloo, Ontario NL2 3G1, Canada

INTRODUCTION

The Precambrian Shield represents the largest petrologically homogeneous and contiguous province of the North American continent. Crystalline metamorphic rocks underlie most of the Shield, and structural provinces are defined on the basis of age, lithology, and structural features. In places, relatively unmetamorphosed igneous rocks or indurated sedimentary rocks are predominant, but all have more or less the same hydrogeologic characteristics in that fractures control the occurrence and flow of ground water.

The extent of the Precambrian Shield Hydrogeologic Region is shown on Figure 1. The boundaries are defined on Fig. 3 and Table 2 of Heath (this volume). In general, the boundaries are rather easy to determine, and this portion of the Precambrian Shield is a well-defined ground water region.

PHYSIOGRAPHY AND CLIMATE

The physiography of the region is a direct consequence of the bedrock and surficial deposits and their interaction with the climate through weathering and erosional processes, including glaciation, during long intervals of geologic time. For the most part the landscape is rolling and monotonous, with relief less than 50 m. Locally, however, differential erosion along structural and lithologic lineaments has resulted in steep cliffs and rugged topography, and greater relief. Surficial deposits have smoothed the surface by filling in many deep bedrock depressions (mostly lineaments), and some end moraines are prominent features. Ground surface elevations are about 200 to 300 m in the south and 50 to 100 m at the northern boundary of the region.

The drainage is mostly into Hudson Bay and to the Great Lakes–St. Lawrence River system. Drainage patterns are controlled by differential erosion along major structural features such as folds, faults, and intrusive contact zones. Glacial erosion and deposition disrupted preglacial drainage systems forming many lakes and swamps and causing the poor drainage of most of the region (Fig. 2). In localities such as this the preponderance of surface water tends to mask or obscure ground-water phenomena such as dry-weather flow, springs, seeps, and phreatophytes. In other areas, undrained flatlands underlain by glacial lake deposits support extensive wetlands. One of the largest contiguous peatlands in the world, the Red Lake patterned peatlands, is located in the Precambrian Shield region of northern Minnesota.

Climatic zonation is more or less along lines of latitude with the mean annual temperature decreasing from 11°C in the south to about 1°C in the north. The climate can be classified as humid continental, with mesoscale local effects caused by the Great Lakes and Hudson Bay. Precipitation ranges from 1,200 mm in the south to less than 500 mm in the extreme northwest, about 25 percent of which is snow. Evaporation increases from 200 mm in the north to about 750 mm in the southwest. Mean annual runoff increases from about 25 mm in the west to 500 mm in the east (Pfannkuch and others, 1983; Fisheries and Environment Canada, 1978). Quality of surface water is generally excellent—the water is low in dissolved solids and slightly acidic. Organic color is common in many poorly drained catchments.

Hydrographs of observation wells show that ground-water recharge is mostly caused by the annual spring snowmelt and infiltration from cyclonic and frontal rainfall. Sporadic convective summer storms are of lesser importance. On the other hand, isotope data show the ground water to be the same as a composite sample of annual precipitation.

GENERAL GEOLOGY

The Precambrian Shield Hydrogeologic Region includes the Southern structural province and parts of Churchill, Superior,

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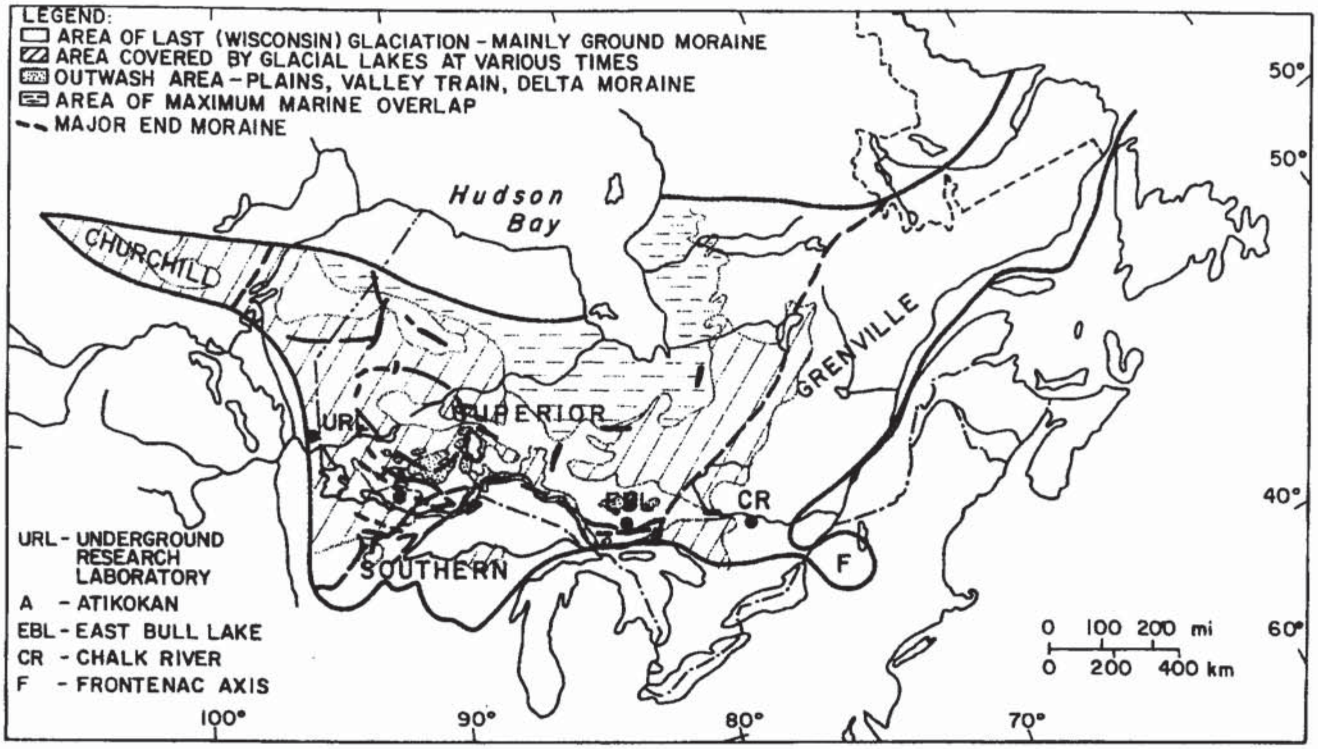

Figure 1. The Precambrian Shield Hydrogeological Region with structural provinces, and locations cited in text.

and Grenville structural provinces (Fig. 1). Each province and subprovince of the Shield is identified by lithology, age, and characteristic structural features. Most of the information in the following paragraphs is from Stockwell and others (1970).

Churchill Province (Fig. 1) is underlain by Archean rocks comprising mainly metamorphosed volcanic flows and pyroclastics with lesser amounts of flysch-type sediments. Extensive areas of granitic terrain are probably metamorphosed equivalents of these ancient volcanics and sediments. These Archean rocks are intruded by granite and overlain by conglomerates, sandstones, siltstones, shales, and dolomites. The entire sequence has been folded and metamorphosed. Sedimentary facies changes suggest a geosynclinal environment. Granite intrusions of the Hudsonian orogeny are dated at 1,650 to 1,850 Ma. In the southern portion of Churchill Province, diabase rocks dated at 1,200 Ma intrude into these older rocks. Numerous faults, some major, cut all the rock types. Brecciated zones are commonly associated with these faults.

The history of Superior Province is similar to that of Churchill Province, but stratigraphic correlation between these provinces is not possible. Superior Province may be described as a granite gneiss terrain engulfing elongated pods of highly metamorphosed volcanic and sedimentary strata, commonly referred to as greenstone belts. The greenstones represent Archean volcanic rocks and associated flysch-type sediments. The granitic gneisses are from the Kenoran orogeny (about 2,500 Ma). Younger intrusions in the form of alkaline plutons and diabase dikes have ages ranging from 2,200 to 1,000 Ma. As in Churchill Province, many faults with brecciated zones or shear zones appear to be associated with the intrusions and sedimentary basins.

The main distinctive feature of Grenville Province is the tight, complex folding, on a small scale, of a wide range of lithologic types. Many varieties of volcanic flows and pyroclastics are represented. Metamorphic equivalents of sandstones, graywackes, shales, and carbonate rocks are common in sequences perhaps 6,000 m thick or more. The soluble marble units are of special interest with respect to hydrogeology.

Major amounts of mafic rock (anorthosite) and minor amounts of other rock, including felsic, mafic, and intermediate types, were intruded prior to the major deformations caused by the Grenvillian orogeny (1,000 Ma). The Adirondack outliner in northern New York State is directly connected to the main part of Grenville Province, by the Frontenac Axis (Fig. 1).

Southern Province is characterized by sedimentary rocks of Aphebian age or younger, lying unconformably on older rocks of Archean age. The Aphebian rocks are relatively undeformed in Canada, and moderately folded in the U.S. The sediments range from basal conglomerates and sandstones to shales, limestones, and tillites. All are moderately metamorphosed and intruded. Gabbroic intrusions in the Sudbury region and elsewhere are 1,700 to 2,150 Ma. The sills that intrude the Aphebian sedimentary rocks in the Lake Superior region are about 1,000 Ma and may be related to the Keweenawan basalts that lie unconformably on Aphebian and Archean rocks. They are the youngest major rock type of the region.

POST—PRECAMBRIAN WEATHERING

Large parts of the Precambrian Shield were previously covered by Paleozoic and Cretaceous strata. These strata were subsequently removed by erosion, and tectonic stability surely allowed the development of a deeply weathered regolith on the basement surface during the long interval preceding the onset of Pleistocene glaciation. Extensive weathering must have taken place over the entire Precambrian Shield, but the regolith was almost entirely removed by the continental glaciers, except for the southernmost extension in Minnesota. There, the regolith is as much as 20 m thick and preserved under glacial cover. Similar occurrences can be expected elsewhere but have not been described. Extensive surface sands over the extreme western portion of Churchill Province may have been derived from this regolith but have clearly been transported or disturbed by glacial action.

PLEISTOCENE DEPOSITS

The glacial deposits overlying the Precambrian Shield region are all products of the Laurentide ice sheets and their different advances. In particular, the multiple glaciation in four major glacial episodes during the Pleistocene Epoch resulted in erosion of the regolith and differential erosion of the bedrock and then deposition of eroded material by the ice sheet and by associated meltwater streams and lakes (Fig. 1).

Over a wide area of central Minnesota, discontinuous patches of Cretaceous shales and sandstones overlie Precambrian rocks and are in turn overlain by thick Pleistocene deposits. These Cretaceous outliers do not warrant being considered as a distinct hydrogeologic unit because they exert little hydrologic influence. They react hydraulically with the regolith and are appropriately grouped with these materials. From a hydrogeochemical point of view, however, their influence is strong, in that they dominate ground-water quality. The western margin of the ground-water region is placed just east of the Red River of the North, where the Cretaceous and Mesozoic sedimentary rocks thicken to more than 100 m, and form a distinct hydrogeologic unit.

Of the four glacial episodes, only the deposits of the latest, the Wisconsinan, will be discussed because earlier drift was either eroded or buried. Wisconsinan deposits constitute virtually all of the surficial material of the region.

An interesting interplay exists between the bedrock and the drift in that the Shield materials—bedrock and regolith—provided the source material for the glacial deposits. Furthermore, the configuration of the bedrock topography, especially the location and trends of broad lowlands, controlled the pathways of lobate advances and the intricate pattern of lobe movement and interaction. This interaction is especially the case near the Great Lakes where bedrock topography controlled the direction of ice advances from the northwest, the north, and the northeast. Repeated advances and retreats from these different directions, plus the deposition of end moraines, created intricate drainage patterns by mutual blocking and diversion. One of the important results was the creation of large outwash regions and glacial lakes. The deposition of moraines by glaciers overriding each other from different directions resulted in some of the greatest thicknesses of glacial deposits—in central Minnesota they are as much as 200 m thick over a large area. Locally, drift thickness over buried bedrock valleys is even greater, but the areal extents of these features are limited (Wright and others, 1983).

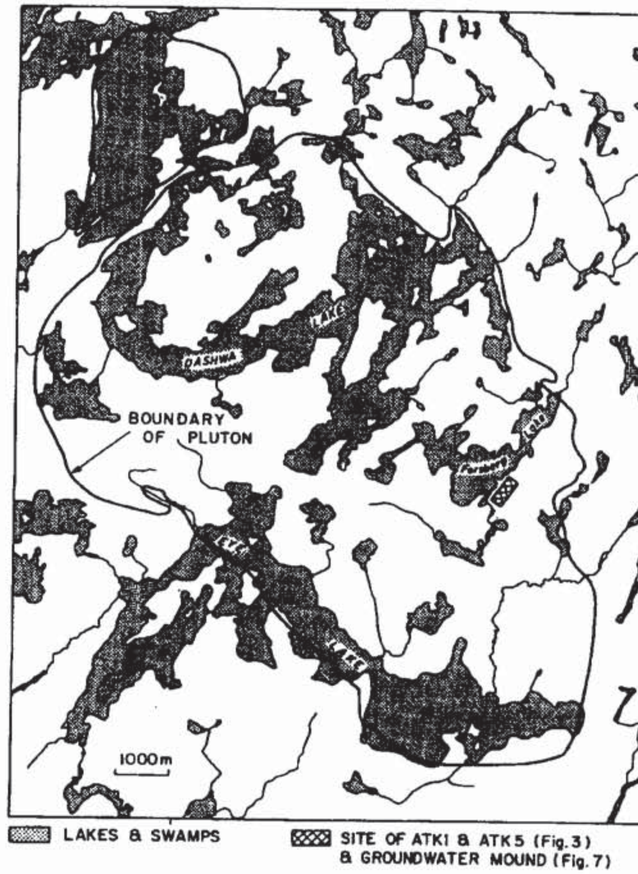

Figure 2. Drainage network in the vicinity of the Eye-Dashwa Lakes Pluton, near Atikokan, Ontario.

Major terminal moraines in northern Ontario are locally important features of the landscape. Some end moraines northwest of Lake Superior are 30 m high and over 100 km long in places (Fig. 1). Most of the material is locally derived, so it is granular and coarse and rather permeable. These features appear to be local recharge zones, though little detailed hydrogeologic information is available. Some terminal moraines were deposited at ice fronts in proglacial lakes.

Extensive proglacial lakes such as Lake Ojibway were a feature of ice retreat on the Precambrian Shield (Fig. 1). Deposits of glacial Lake Agassiz cover an area of almost 500,000 km^2, albeit much of this is not on the Shield region. However, the extensive wetlands along the boundary of the Shield region in northwestern Minnesota and southeastern Manitoba are related to the occurrence and properties of Lake Agassiz clays. In some sectors of the Shield, notably the southwestern part of Superior Province, glaciofluvial sands are an important hydrogeologic unit. Outwash sand underlies many swamps, shallow lakes, and streams, in places to depths of more than 50 m.

This sand is an important factor in the hydrologic response of the drainage systems in the region because of its high storage capacity and high hydraulic conductivity relative to the rock. In some channels a considerable portion of runoff is by means of underflow.

Geophysical soundings indicate that the bedrock topography under some lakes has been significantly modified. Here, too, deeply eroded fracture zones and depressions in incompetent rock have been filled, and smoothed or partially obscured by outwash and lake sediments.

For the most part, uplands or interstream areas are bare rock, or have only a thin cover of till or outwash. The hydrologic role of this surface cover is not known, but Bredehoeft and Maini (1981) suggest that if a cover is more permeable than underlying rock, the flow pattern in the upper unit will govern that in the medium below.

GROUND-WATER OCCURRENCE ON THE PRECAMBRIAN SHIELD

Ground-water occurrence on the Precambrian Shield has not been studied except in a very general way because the region is sparsely populated and bountifully endowed with surface water of good quality. Charron (1967) reports that of the 112 communities on the Canadian portion of the Shield with a population of more than over 1,000, 27 use ground water at the rate of 50,000,000 liters per day (L/day). Much of this is from aquifers in surficial deposits.

Charron (1967) provides abundant evidence for the sporadic occurrence of ground water in the rocks of the region. Some 53 mines on the Canadian part of the region pump an average of about 1,500,000 L/day from depths generally between 600 and 1,000 m. He notes remarkable evidence of the low permeability of some crystalline rocks; extensive underground workings only 30 m below a lake bottom produce only 1,000,000 L/day. This low rate of flow may be in part owing to sediments of low permeability on the lake bottom.

For the U.S. portion of the Shield, conditions of ground-water occurrence in the crystalline rocks are quite similar. No major ground-water withdrawals from the bedrock are made. The few wells in bedrock serve domestic needs, and extensive aquifer testing has not been done. The only data of any hydrogeologic significance available are well yields and specific capacity. In general, these are less than 0.5 1/sec and 0.2 1/sec/m, respectively (Pfannkuch and others, 1983).

Mineral deposits on the Precambrian Shield are commonly associated with geologic anomalies, in particular, contact zones, faults, or fracture zones and greenstone belts. Many of the communities on the Precambrian Shield are near mines and consequently near geologic anomalies, so the scant information that is available is highly biased and does not represent ground-water conditions generally. The iron mines of the Mississabi Range and quarries for building stone are perhaps exceptions in that the ore body is representative of the country rock.

LAKES AND WETLANDS

Numerous lakes and extensive wetlands are the most striking hydrographic features of many parts of the Shield. Two basic types of lakes are recognized: bedrock scour lakes and lakes on glacial deposits. The first are found predominantly in the northern part of the Shield region. They have a somewhat radial orientation around Hudson Bay, aligned with the general drainage direction of the streams.

The role of so-called seepage lakes on glacial drift and their interconnection with the ground-water flow field has been the subject of many studies in Minnesota and elsewhere over the last decade (Winter, 1976; Pfannkuch and Winter, 1984; Lee, 1977; Frape and Patterson, 1981). Ground water is one of the most important components in sustaining these lakes, which in turn are important boundary conditions for the ground-water flow field and profoundly influence the boundaries and geometry of flow systems defined by Tóth (1963).

The most important finding for single lakes is that seepage into and out of the lake is concentrated in a fairly narrow near-shore zone, so that a large fraction of the total volumetric exchange with the ground-water reservoir takes place over a very small fraction of the lake bottom (Lee, 1977). The interactions depend on the geometry of the flow field, specifically the ratio of the lake width to the thickness of the aquifer with which the lake is interacting, and on the anisotropy of the aquifer.

In settings with multiple lakes at different elevations on a regional slope, local ground-water flow systems that discharge to the lakes may be superimposed on a regional flow system. In this case, stagnation points and other relations between hydraulic head and depth, as described by Tóth (1963), can be expected.

The conditions required for wetlands to form are (1) poor drainage and (2) a close balance between all inflow (direct precipitation, surface water, and ground water) and all abstractions (evapotranspiration and perhaps slow surface-water drainage), so that water depth remains low. Two basic types of wetlands are those that have formed by infilling or terrestrification of modern lakes or ponds and those on extensive ancient lake beds. The latter are usually very extensive, perhaps associated with open water, as for example the Upper and Lower Red Lakes in Minnesota and Lake of the Woods. These ancient lake beds are characterized by a flat surface and low surface gradients. They are underlain by lacustrine clays of low permeability, and are poorly drained. Near the ancient shorelines, where the gently sloping shield surface breaks to join the flat lake bed surface, conditions are created that cause the upward seepage of regional ground-water flow that sustains the wetland condition. Siegel (1981) has shown that under conditions of such low hydraulic gradient, intermediate and even regional flow systems are extremely sensitive to small topographic changes and concomitant changes in the configuration of the water table and in distribution of hydraulic head.

FIELD RESEARCH AT ATIKOKAN

During the past several years (1976–1985), research related to the Canadian Nuclear Fuel Waste Management Program (CNFWMP) has provided important new insight into the hydrogeology and hydrochemistry of the Shield region, with emphasis on rocks of low hydraulic conductivity, particularly massive plutons and granitic terrain.

Extensive field studies have been made to find the best way of identifying individual fractures, fracture patterns, and their role in ground-water flow.

An example is provided by research on and around the Eye-Dashwa Lakes Granitic Pluton in the Superior Structural Province near Atikokan, Ontario (Fig. 1). The pluton is located toward the northern edge of an east-west, elongated, regional drainage basin. Several small catchment basins drain the pluton area (Fig. 2), locally to the south but eventually to Hudson Bay.

The pluton trends north–west; it is an elliptical body, 13 by 8 km, composed of medium- to coarse-grained, hornblende-biotite granite of Archean age, that intrudes tonalite-granodiorite gneisses (Brown and others, 1980). It is generally undeformed, except for joints, faults, dikes, and veins, collectively called fractures. Large gneissic inclusions occur within the pluton. Secondary foliations, lineations, folds, and evidence of penetrative ductile deformation are rare in the pluton but are prevalent within the surrounding gneissic country rock.

Ground-water flow in the area occurs through both the granitic and metamorphic bedrock and the overburden deposits. The near-surface bedrock has low primary hydraulic conductivity ($<10^{-10}$ ms^{-1}), but zones of localized, relatively high, secondary hydraulic conductivity (10^{-6} to 10^{-8} ms^{-1}) and low interconnected porosity (10^{-1} to 10^{-3}), are associated with the rock-mass fracture system. In contrast, the surficial deposits, mostly of glacial origin, have low (clay) to high (sand) primary hydraulic conductivity (10^{-11} to 10^{-3} ms^{-1}) but high primary porosity (2×10^{-1} to 5×10^{-1}).

A thin (<1 m) veneer of bouldery sand till covers a large portion of the area. The till appears fissured in many places and probably possesses enhanced secondary permeability in the order of 10^{-8} ms^{-1} (Grisak and Cherry, 1975). Typically, the lowlands contain sandy outwash and other sediments (Ridgway and Pearson, 1985). The Eagle-Finlayson and Steep Rock moraines of gravelly sand and till form prominent east-west–trending ridges across the study area. Some lake beds are underlain by sediments exceeding 50 m in thickness, which rest on fractured eroded rock and mask the irregularities of the bedrock surface (Ridgway and Pearson, 1987).

GROUND-WATER FLOW SYSTEMS

Considerable research has been done on the nature of recharge and discharge and on identification of ground-water flow systems at several sites on the Canadian Shield, selected as research areas in the CNFWMP. They include the Underground Research Laboratory (URL) and the Atikokan, East Bull Lake, and the Chalk River research areas (Fig. 1).

Near Atikokan on the Eye-Dashwa Lakes Pluton, hydrogeological testing of deep boreholes (Lee and others, 1983; Fig. 3), fracture analysis (Dugal and others, 1981; Fig. 4), and monitoring of specific fracture zones have revealed the presence of three regimes. A local, shallow, fresh-water regime to depths of 150 m and possibly deeper, is controlled by the hummocky surface topography, local lakes and swamps, and a locally intense network of fracturing. Discrete, high-permeability, flat-lying, and high-angle sheared fracture zones act as controls on the scale of the local flow systems. An intermediate, or transition, regime is related to the discrete shear zones mentioned above at depths from 150 m to 600 m. A zone below 600 m, with generally higher hydraulic head values than the intermediate regime (Dickin and tohers, 1984; Black and Chapman, 1981; Fig. 4), has been identified in several deep test holes.

The ground-water regimes identified in the studies on the Eye-Dashwa Lakes Pluton are very similar to those found at the three other research areas (Fig. 1). At all test sites, strong structural control of flow patterns exists, owing to flat-lying shear zones or dikes (Raven and others, 1985; Bottomley and others, 1984; Davison and Guvanasen, 1985; Fig. 5). Extensive and detailed testing of individual fractures and fracture systems has indicated strong anisotropy within the planes of fractures and fracture systems (Davison and Guvanasen, 1985; Fig. 6). The causes for this can be attributed to shear movement, to the intersection of fractures, and to chemical deposition within the fracture planes.

At Atikokan, shallow observation wells, completed to identify the water-table configuration on a small bedrock upland, show a ground-water mound typical of a recharge zone (Fig. 7). Shallow minipiezometers (Lee and Cherry, 1979) in surficial sand indicate that vertical ground-water gradients are present, and suggest recharge and discharge zones. Multilevel piezometers set at depths as much as 60 m into the bedrock prove that these vertical gradients are manifestations of a flow system in the bedrock rather than merely phenomena related only to ground-water flow within the surficial deposits. Of some 100 such piezometers, each isolated by packers to measure hydraulic head over several meters of the borehole, more than 90 function well enough to provide good data on hydraulic head and good samples for geochemical and isotope analyses (Wingrove and others, 1984).

The evidence is clear that shallow flow systems such as those described by Tóth (1963), Meyboom (1966), and Freeze and Witherspoon (1966, 1967, 1968) occur in these crystalline rocks

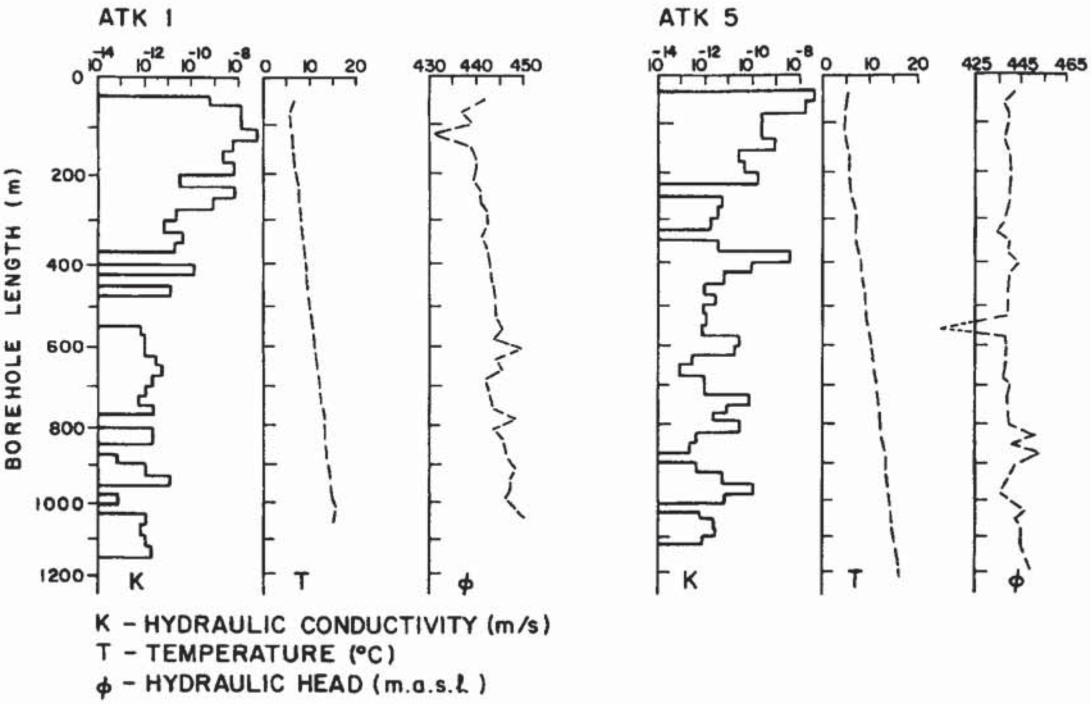

Figure 3. Hydrogeologic logs of two test-holes on the Eye-Dashwa Lakes Pluton near Atikokan, Ontario (from Lee and others, 1983).

and that, as for porous media environments, the water table is a subdued replica of the topography. Vertical fracturing in the near-surface bedrock is an important factor in recharge and ground-water flow.

Steep gradients suggest that hydraulic conductivity is low, even though fractures appear to be ubiquitous. Effective porosity must also be very low because in most places not enough ground water is discharged to be recognized by surface observations.

Further evidence of water-table configuration was obtained from ground-water investigations on the URL (Fig. 1) being constructed for research on nuclear-waste disposal. Here, too, the water table is a subdued replica of the surface topography. Recharge and discharge zones are evident; once again, this suggests an active flow system and hydraulic continuity. During controlled ground-water pumping to dewater the URL shaft for construction, measurements in observation wells reveal a drawdown cone that is similar in terms of size and geometry to that expected in a porous medium (Davison, 1984).

Before about 1977, when detailed testing began in the Canadian Shield log-linear decrease of hydraulic conductivity with depth was inferred (Davis and Turk, 1964; Snow, 1968). The inference was based on data from relatively shallow (<400 m) randomly drilled water wells and construction site boreholes and was attributed to a general tightening of fractures due to increasing vertical stress. Testing for the CNFWMP and studies of deep mines in the Canadian Shield together with information from elsewhere, including Swedish, Swiss, and USSR sources, has modified this picture somewhat.

While a case can be made for a log-linear decrease in hydraulic conductivity with depth in the upper 100 to 400 m at a particular site, the flat-lying fracture zones mentioned above are the major controls on regional flow. These zones have been encountered at various depths between surface and at least 1,000 m, with a generalized vertical spacing of one to 300 m and a thickness of 10 to 50 m. Within these zones, permeability is highly anisotropic; distinct flow channels in the fracture plane are a controlling feature (Davison and Guvanasen, 1985). Some 10 to 30 percent of a given fracture zone can have permeabilities several orders of magnitude greater than the background fracture zone and the intact bedrock.

In the research areas (Fig. 1), the flat-lying fracture zones are associated with steep fault zones that penetrate to great depth and often appear as long lineaments at the surface (Raven and Gale, 1986). These zones also appear to be highly anisotropic, with permeability controlled by both fracture fillings and regional stresses. The spacing of these steep fault zones varies from less than 1 km to greater than 5 km. Regional stresses are important in the hydraulic properties of these faults. Where the maximum horizontal compressive stress is normal to the strike, these faults tend to be closed or tight and chemically filled. The opposite has been observed where regional stresses are parallel to the zone. A similar correlation of regional stress and permeability has been

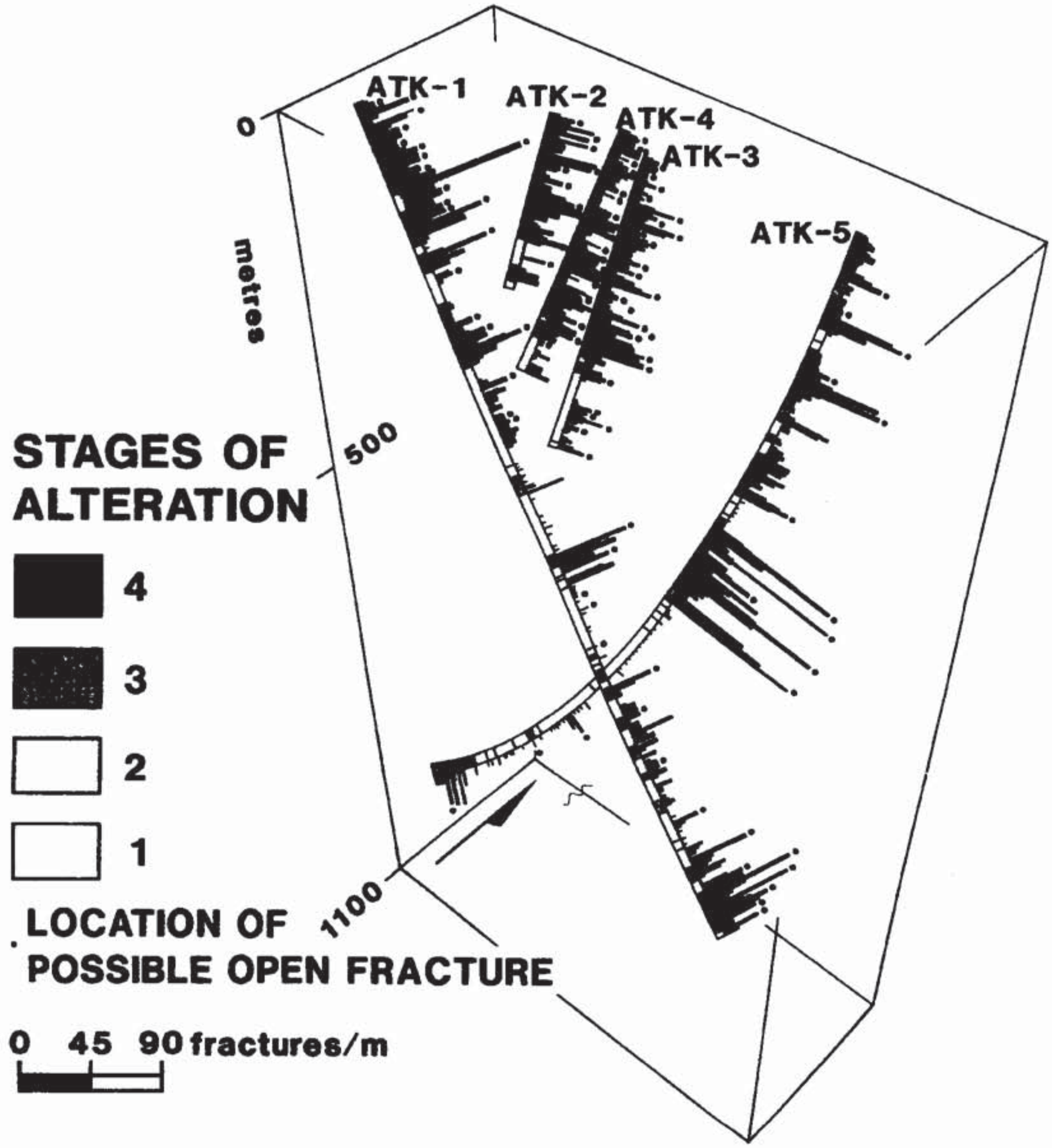

Figure 4. Borehole fracture logs from test holes near a fault on the Eye-Dashwa Lakes Pluton.

noted in work at the Stripa Mine in Sweden (Doe, personal communication, 1985).

On the other hand, in the relatively intact rock blocks between major fault zones, the rock is tight. All fractures are chemically filled and, except for the deep semihorizontal zones of high permeability mentioned above, ground-water flow is minimal and no systematic flow pattern has been measured or observed.

The evidence to date from CNFWMP research indicates that, other than for horizontal exfoliation sheeting joints probably produced by glaciation, in the upper 100 m or so, all fractures were formed congruent with or shortly after the emplacement of the plutonic rock. Since that time these fractures have been rejuvenated many times (Brown and others, 1980). The implication is that deep flow systems are controlled by these structures, with perhaps some influence by regional slope but little influence by local topography.

GROUND-WATER QUALITY

Surface waters and shallow ground waters of the Canadian Shield region are generally very low in dissolved constituents. Surface water is typically soft, neutral to slightly acidic, colored but not turbid. In the western portion of the region, glacial deposits contain carbonate clasts from the area of provenance and these carbonate materials have a local influence on water quality. Similarly, where glacial-lake sediments occur, ground water tends to carry more Na^+, Ca^{2+}, and HCO_3^- and is harder.

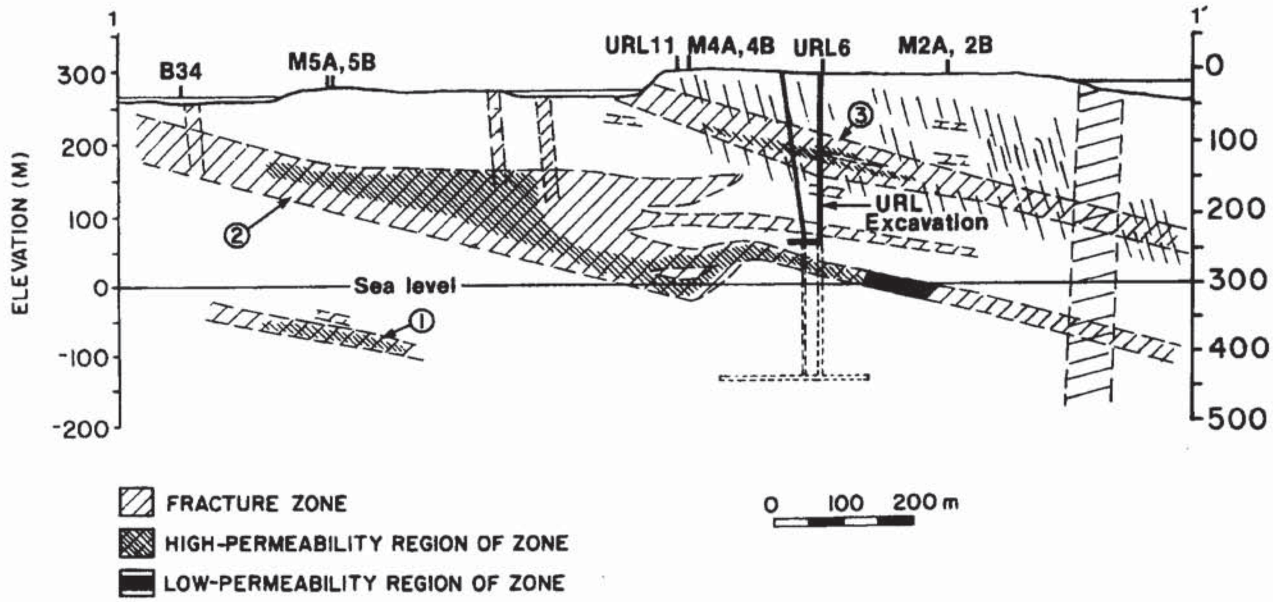

Figure 5. Schematic cross section through part of the Lac du Bonnet Batholith at the URL site illustrating the presence of flat-lying fracture zones (from Davison and Guvanasen, 1985).

Shallow ground water is similar to the surface water, but Frape and Fritz (1982) show that the average composition of several hundred samples increases in dissolved constituents within the first 150 m and increases by an order of magnitude within the first 300 m of depth (Fig. 8). Fewer samples are available from greater depths, but trends are rather clear. Ground waters below about 800 m are Ca-Na-Cl brines with dissolved solids exceeding 100,000 mg l^{-1}. The waters are depleted in HCO_3^- and SO_4^{2-} and, to a lesser degree, in Mg^{2+}.

Brackish water is generally encountered at intermediate depths. Kameneni and others (1982) believe that the minerals in fracture fillings and fracture walls react with ground water to produce the chemistry observed in boreholes in the Eye-Dashwa Lakes Pluton. They account for the trends in Na^+ and Mg^{2+} content by exchange with clay minerals. Low Ca^{2+} concentrations in shallow ground water are attributed to lesser abundance of calcite fillings in fractures in shallow zones than at depth.

In the Lake Nipigon–Lake Superior area, some small springs and seeps discharge ground water of high salinity—up to 10^4 mg/L. They are known locally as "moose licks" and have been reported elsewhere on the Shield. The origin of the highly saline water is not clear, but may be caused by solution of Precambrian evaporites such as the Sibley Formation. However, some "moose licks" are found in regions where these rocks do not occur. Also, geochemical considerations preclude major contributions from evaporite solution (Blackmer and others, 1987).

Instead, isotope data suggest that these waters are depleted in ^{18}O and ^2H (deuterium) and are distinct from other local ground waters, indicating that these are "old" waters recharged under cooler climatic conditions. The salinity of these waters may be due to either mixture of surface water with deep saline ground waters encountered at depth across the Shield or derived through rock-water interaction, perhaps involving leakage of fluid inclusions, dissolution of grain boundary salts, and highly saline pore fluids—the residuals of former brines permeating these rocks. Strontium isotope data suggest that rock-water interaction dominates their geochemical history.

Ground waters from depths exceeding 650 m are fluids that are distinct chemically and isotopically from those in the shallower zones. These deep ground waters are exceedingly saline and are either enriched in deuterium, depleted in ^{18}O, or both, if compared to normal meteoric waters. These characteristics and the fact that the subdued relief of this part of the Canadian Shield is thought to be insufficient to establish deep, active flow systems strongly suggest that these fluids are old and have undergone substantial rock-water interactions.

Chemical data for Canadian Shield ground waters have been summarized by Frape and others (1984). The most salient feature of these brines is not their high salinity but their chemical composition, which is Ca-Na-Cl dominated. Much higher salinities are known for sedimentary basin brines, but the strong Ca dominance is rarely encountered.

This difference is documented in Figure 9 where Na-Ca-Mg molar percentages are compared on a triangular diagram. Little or no overlap exists between the compositions of these Shield brines and those of evaporated ocean waters or other natural saline systems.

It is also noteworthy that for the most concentrated brines, this Ca dominance is independent of the type of host rocks, which range from very mafic to felsic. On the other hand, magnesium

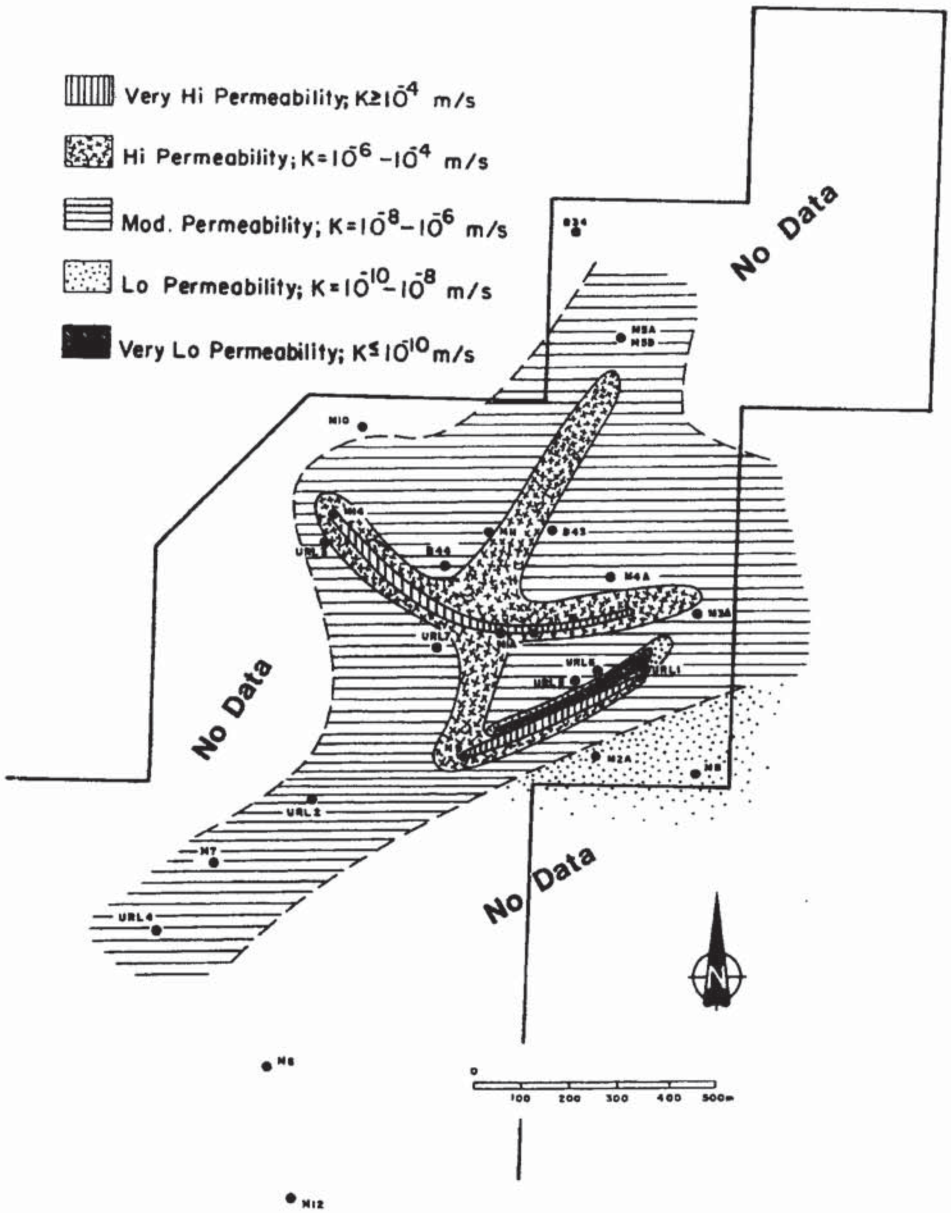

Figure 6. Variations in permeability in a flat-lying fracture zone at the URL site (from Davison and Guvanasen, 1985).

concentrations in these brines are more independent of salinity (and thus chlorinity) and rather closely linked to rock type. For example, the elevated magnesium concentrations in brines from a mine at Thompson, Manitoba, are most likely related to magnesium-rich ultramafic rocks with which those fluids had interacted (Frape and others, 1984).

A strong relationship between host rock and brine is also seen in the strontium data. Strontium isotopic composition suggests that "equilibration" between solid and aqueous phases has occurred in most of these very saline systems.

However, isotope data, and specifically ^{18}O and ^{2}H concentrations, indicate that brine samples collected to date may not represent the most saline fluids. Figure 10 shows increasing salinities with increasing ^{2}H contents and, to a lesser degree, ^{18}O contents. These relationships most certainly reflect mixing of brine fluids with local, nonsaline ground waters. In addition, in disturbed environments such as those created by operating mines and where deep cones of depression result from mine dewatering, local surface waters can penetrate to great depth. Water from the surface has been found in discharges in exploration boreholes

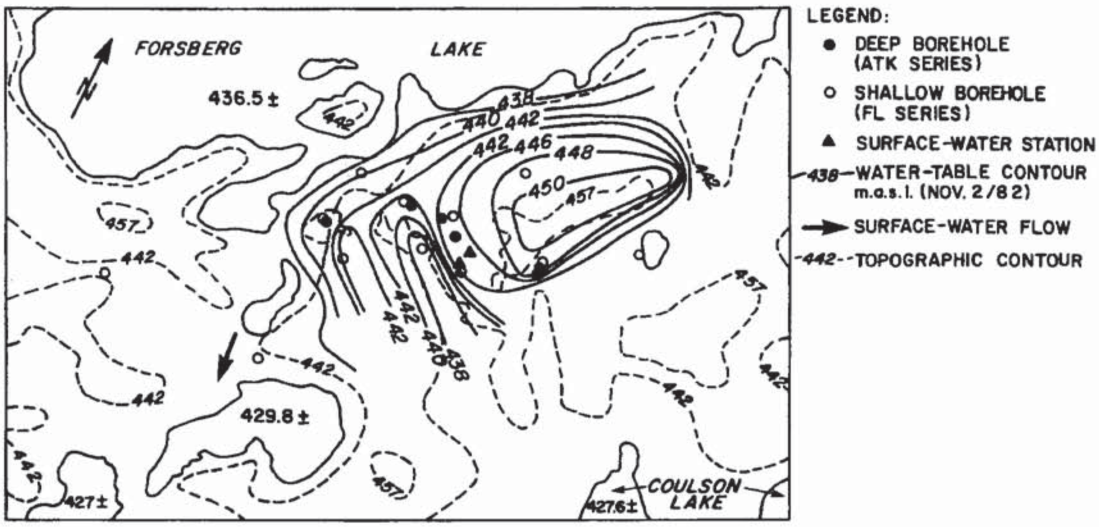

Figure 7. Ground-water mound under a rock knoll on the Eye-Dashwa Lakes Pluton near Atikokan, Ontario. Note the apparent influence of the faults (from Lee and others, 1983).

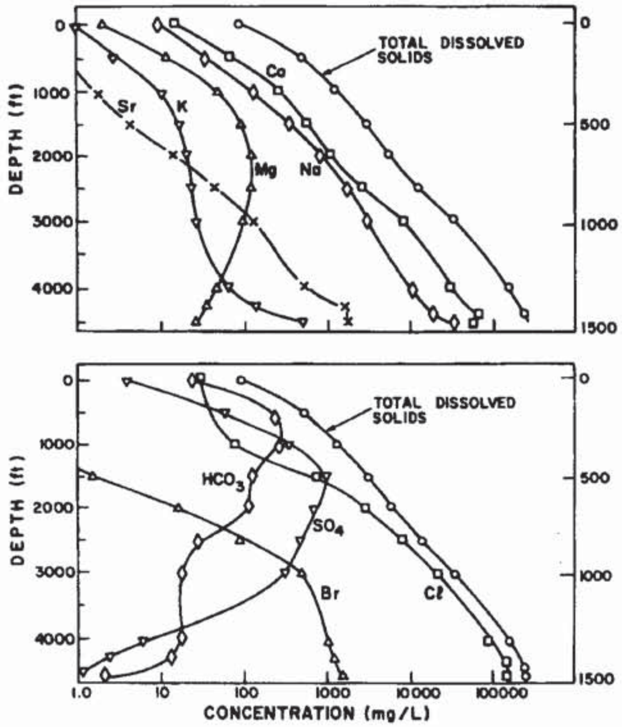

Figure 8. Average values for the concentrations of major ions in ground waters of the Canadian Shield.

drilled from mine levels, at depths exceeding 1,500 m. Thus hydraulic continuity does exist in many vertical "fracture" systems and cannot necessarily be attributed to man's activities (Frape and others, 1984; Gascoyne, personal communication, 1985).

The salinity-isotope regression lines can be extrapolated for each site and, if combined with geochemical considerations, permit the "definitions" of the isotopic composition of a "source" brine as it may exist across the Canadian Shield. The shaded area in Figure 10 shows the results; note that the extrapolated composition indicates somewhat higher ^{18}O and ^{2}H concentrations than measured values. Yet this extrapolation agrees with estimates based on brine chemistries and where it was assumed that the source brines would be at halite saturation (Pearson, 1986). Halite is a common fracture mineral and is frequently present in fluid inclusions of fracture minerals in crystalline rocks.

Isotope and geochemical data clearly show that the genesis of the deep brines in the Canadian Shield cannot be discussed in terms of the "origin" of the fluids. Rock-water interactions have almost certainly obliterated most primary characteristics. These brines should be viewed as fluids that are directly linked to the geochemical (and hydrologic) evolution of deep crystalline rocks. As such, the brine would have to be called "crustal fluids" whose primary origin cannot be uniquely defined.

TECHNIQUES FOR HYDROGEOLOGIC STUDIES ON PRECAMBRIAN TERRAIN

Techniques for ground-water studies of Precambrian terrain are similar to those developed for other terrain in terms of the overall approach. They differ in some details since, for most applications, the prime targets in exploration are fractures and fracture zones and associated dikes and sills of various sizes

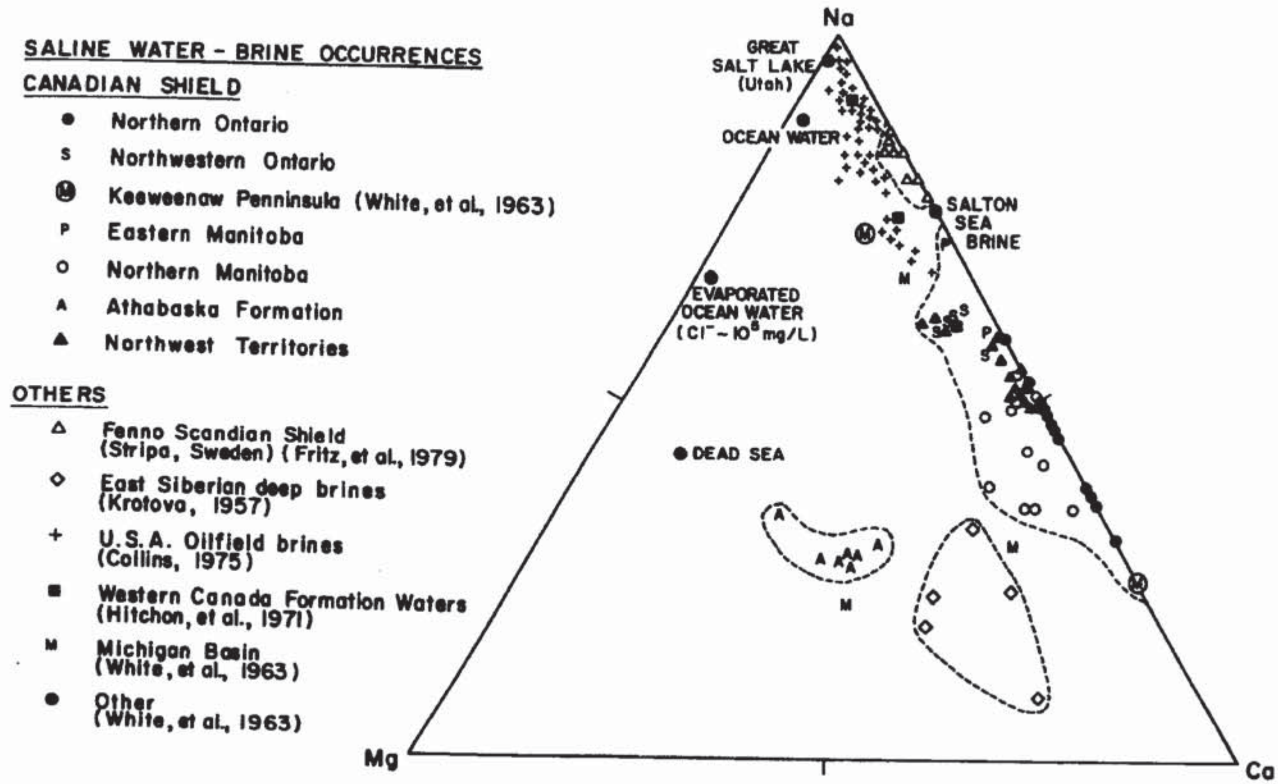

Figure 9. Comparison of chemical characteristcs (mole percent) of brines (>10^4mgl^{-1} TDS) with brines and saltwater from other environments (from Frape and Fritz, 1982).

within the rock mass. Some are very costly and unlikely to be used in water-resource projects. Topography, surface drainage, overburden, vegetation, and lake coverage are generally controlled by rock structure and/or surficial deposits and so may provide important hydrogeologic information.

Airborne techniques are invaluable as the first tools for investigating the regional scale. Satellite imagery and airphoto coverage, including infrared analyses (Lee and Tracey, 1984), can delineate not only vegetation cover and rock/overburden type but potential zones of discharging ground water and high velocity flow or potential discharging ground water in lakes and rivers.

Geophysical airborne surveys such as gravimetric, gamma spectrometry, and very-low-frequency electromagnetic (VLF-EM) surveys can be used to delineate rock type, major structural features, and areas of thick overburden (Soonawala, 1984). Gravity surveys provide an initial indication of the shape and possible depth of rock bodies. Gamma spectrometry can delineate plutonic rock from country rock due to the higher thorium, uranium, and potassium content of the former. Aeromagnetic techniques (Hood and others, 1976) not only aid in distinguishing plutonic from country rock and in identification of dikes and weathered zones, but also in identification of linear conductors that may be related to steep fractures and faults.

As is the case everywhere, a first-order surface description of the lithological and structural framework, including surficial deposits and consequent vegetation and surface-water drainage patterns, together with adequate topographic control at the scale of interest, are required as basic information in a hydrogeological assessment.

Useful land-based techniques include all standard methods developed for geological, geophysical, and hydrological assessments with major emphasis on structure and regional stress assessments. Geophysical methods that have been used successfully are seismic reflection, VLF-EM, sonar, and radar tools. Seismic reflection holds great promise for detecting major flat-lying fracture zones (Green and Mair, 1983), while VLF-EM can help in interpretation of clay-based overburden materials. Sonar methods, when used from boats on lakes, are extremely valuable in determining depth of lakes and depth of sediments in lakes and thus in confirming the shape of water bodies and continuity of major lineaments (Holloway, 1983). Radar is useful in determining overburden thickness on land.

Seasonal analyses of surface-water body temperature and chemistry can be useful in identifying recharge and discharge zones and in detecting perennial and ephemeral surface discharge events (Ridgway and Pearson, 1987). Included in this work should be analysis for major ions and natural radioactivity (Larocque and Gascoyne, 1986) from potential discharge areas and

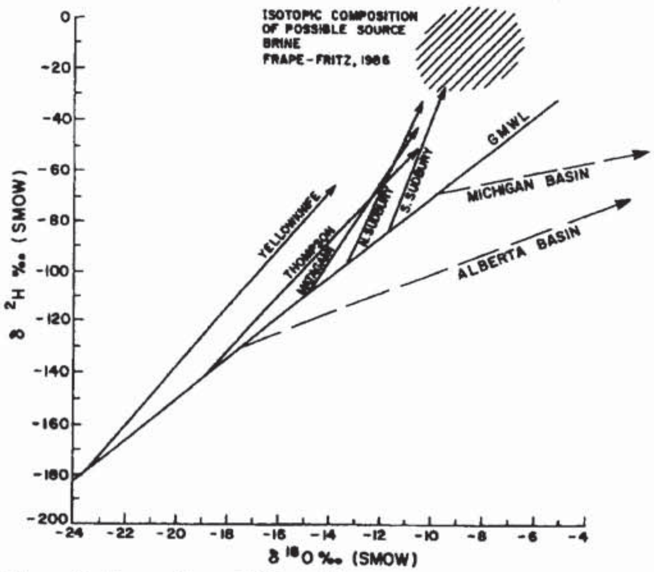

Figure 10. Composition of ^{18}O and ^{2}H contents in ground waters and brines of the Canadian Shield and representative adjacent sedimentary basins. Arrows are regression lines for data points and indicate direction of increasing salinity.

for tritium in both recharge and discharge areas. Other considerations include attempting to find effluent and influent conditions in rivers and streams focussing on the intersection of structural controls, since, although most base flow and stream flow is from overburden and lake storage, there have been strong indications of discrete deeper bedrock discharges. Related to this work is the need, in conjunction with lake sonar work, to examine the beds of lakes at structurally controlled points for submarine discharge. Here scuba diving and lake-bed drags fitted with temperature and conductivity measurement instruments are useful (Lee, 1985).

Techniques used in borehole assessment include identification of permeable fracture zones and chemical variations using many borehole techniques. They include through-the-bit hydraulic testing during drilling with single-packer systems, borehole television, acoustic television, core, gamma, neutron, fluid resistivity, temperature, sonic and radar logging, and straddle-packer testing and sampling of selected borehole zones (Lau, 1983; Lee and others, 1983; Davison and others, 1982; Davison, 1984; Paillet and others, 1985; Bottomley and others, 1984). In addition, several methods to establish continuity of permeable zones are useful. These include interborehole hydraulic (Black and Kipp, 1981) and tracer tests (Novakowski and others, 1985; Webster and others, 1970) over distances of 10s to 100s of meters in conjunction with geophysical techniques such as cross-hole seismic (Wong and others, 1982) and down-hole radar (Olsson and others, 1982; Holloway and others, 1985) and geological assessment of continuity (McEwan and Hillary, 1985). Two important considerations in this work are isolation of all test sections in boreholes used in hydrogeological work soon after drilling to stop intraborehole flows along the length of the borehole, and proper completion of the borehole in terms of extracting all drilling fluids and ensuring that boreholes (and fractures) are "clean."

The first of these considerations is met by installation of borehole isolation systems such as multilevel piezometers or multipoint casings (Wingrove and others, 1984; Davison, 1984). The second is a matter of correct borehole test procedures and includes the requirement that zones of interest are pumped long enough to remove drilling fluids.

When these devices are installed, time and effort can be expended on establishing both ground-water chemistry and hydraulic-head values and fluctuations. In ground-water sampling it is important that the pumping or bailing be sufficient to ensure the obtaining of formation fluid. On the other hand, care must be taken that the radius of influence of the test does not tap other systems.

CONCLUDING REMARKS

It should be clear from this paper and the recent dates on most references that knowledge of the hydrogeology of the Precambrian Shield region is in a state of very rapid growth. We have tried to present some of the important observations made during the past decade or so because these have provided information not available in earlier publications.

As is common in a review paper, we have presented mainly our interpretations and those of colleagues without much basic data. Supporting data are to be found in the references.

REFERENCES CITED

Black, J. H., and Chapman, N., 1981, In search for nuclear burial grounds: New Scientist, v. 91, p. 402–404.

Black, J. H., and Kipp, K. L., 1981, Determination of hydrogeological parameters using sinusoidal pressure tests; A theoretical appraisal: Water Resources Research, v. 17, no. 3, p. 686–692.

Blackmer, A. J., Frape, S. K., Fritz, P., and McNutt, R. H., 1987, Geochemistry and hydrogeology of two salt-water springs in the Nipigon regon: Canadian Journal of Earth Science (in press).

Bottomley, D. J., Ross, J. D., and Graham, B. W., 1984, A borehold methodology for hydrogeochemical investigations in fractured rock: Water Resources Research, v. 20, no. 9, p. 1277–1300.

Bredehoeft, J. D., and Maini, T., 1981, Strategy for radioactive waste disposal in crystalline rocks: Science, v. 213, no. 4505, p. 293–296.

Brown, P. A., Kameneni, D. C., Stone, D., and Thivierge, R. H., 1980, General geology of the Eye–Dashwa Lakes Pluton, northwest Ontario; Current Research Activities, Part A: Geological Survey of Canada Paper 80-1A, p. 379–384.

Charron, J. E., 1967, The Canadian Shield hydrogeological region, *in* Brown, I. C., ed., Groundwater in Canada: Geological Survey of Canada Economic Geology Report no. 24, p. 120–130.

Collins, A. G., 1975, Geochemistry of oilfield waters: Amsterdam, Elsevier, 485 p.

Davis, N., and Turk, L. S., 1964, Optimum depth of wells in crystalline rocks: Groundwater, v. 2, no. 2, p. 6–11.

Davison, C. C., 1984, Hydrogeological characterization at the site of Canada's Underground Research Laboratory, *in* Proceedings of the International Groundwater Symposium on Groundwater Resources Utilization and Contaminant Hydrogeology: Atomic Energy Canada, v. 2, p. 310–335.

Davison, C. C., and Guvanasen, V., 1985, Hydrogeological characterization, modelling and monitoring of the site of Canada's underground research laboratory: Atomic Energy of Canada Limited Paper 8676, 26 p.

Davison, C. C., Keyes, W. S., and Paillet, F. L., 1982, Use of borehole-geophysical logs in hydrologic tests to characterize plutonic rock for nuclear waste storage: Atomic Energy of Canada Limited Report, WNRE-7810, 103 p.

Dickin, R., Frape, S. K., Fritz, P., Leach, R.E.J., and Pearson, R., 1984, Groundwater chemistry to depths of 1,000 m in low permeability granite rocks of the Canadian Shield, *in* Proceedings of the International Groundwater Symposium on Groundwater Resource Utilization and Contaminant Hydrogeology: International Association of Hydrogeologists, p. 357–371.

Dugal, J.J.B., Pearson, R., and Stone, D., 1981, Hydrogeological testing and fracture analysis of the Eye–Dashwa Lakes granitic pluton at Atikokan, Ontario: Atomic Energy of Canada Limited Paper TR-7363, p. 8.4.1–8.4.16.

Fisheries and Environment Canada, 1978, Hydrogeological atlas of Canada.

Frape, S. K., and Fritz, P., 1982, An initial summary of the major-minor element chemistry of the groundwaters from the Canadian Shield: Atomic Energy of Canada Limited Report TR-210, p. 43–46.

——, 1986, Geochemical trends for ground waters from the Canadian Shield, *in* Fritz, P., and Frape, S. K., eds., Saline waters and gases in crystalline rocks: Geological Association of Canada, Special Paper 33, p. 19–38.

Frape, S. K., and Patterson, R. J., 1981, Chemistry of interstitial water and bottom sediments as indicators of seepage patterns in Pearch Lake, Chalk River, Ontario: Limnology and Oceanography, v. 26, p. 500–517.

Frape, S. K., Fritz, P., and McNutt, R. H., 1984, Water-rock interaction and chemistry of groundwaters from the Canadian Shield: Geochimica et Cosmochimica Acta, v. 48, p. 1617–1628.

——, 1985, Water-rock interactions and the percipitation of gypsum fracture fillings in the Canadian Shield: Atomic Energy of Canada Limited Report TR-299, p. 315–333.

Freeze, R. A., and Whitherspoon, P. A., 1966, Theoretical analysis of regional groundwater flow; 1. Analytical and numerical solutions to the mathematical model: Water Resources Research, v. 2, p. 641–656.

——, 1967, Theoretical analysis of regional groundwater flow; 2. Effect of water-table configuration and subsurface permeability variation: Water Resources Research, v. 3, p. 623–634.

——, 1968, Theoretical analysis of regional groundwater flow; 3. Quantitative interpretations: Water Resources Research, v. 4, p. 581–590.

Fritz, P., and Frape, S. K., 1982, Saline groundwaters in the Canadian Shield—A first overview: Chemical Geology, v. 36, p. 179–190.

Fritz, P., Barker, J. F., and Gale, J. E., 1979, Geochemistry and isotope hydrology of groundwaters in the Stripa granite. Swedish-American Co-operation Program on Radioactive Waste Storage in Mine Caverns in Crystalline Rock: Lawrence-Berkeley Laboratory Publication 8285, 135 p.

Green, A. G., and Mair, J. A., 1983, Sub-horizontal fractures in a granitic pluton; Their detection and implications of radioactive waste disposal: Geophysics, v. 48, p. 1428–1449.

Grisak, G. E., and Cherry, J. A., 1975, Hydrogeologic characteristics and response of fractured till and clay confining a shallow aquifer: Canadian Geotechnical Journal, v. 12, p. 23–43.

Hitchon, B., Billings, G. K., and Klovan, J. E., 1971, Geochemistry and origin of formation waters in the western Canada sedimentary basin—II, Factors controlling chemical composition: Geochemica et Cosmochimica Acta, v. 35, p. 567–598.

Holloway, A. L., 1983, Sonar profiling in lakes near the Atikokan Research Area, Ontario, *in* Proceeding of the 17th Information Meeting of the Canadian Nuclear Fuel Waste Management Program: Atomic Energy of Canada Limited Report TR-299, v. 2, p. 622–633.

Holloway, A. L., Soonawala, N. M., and Collett, L. S., 1985, Three-dimensional fracture mapping in a granitic excavation using ground-penetrating radar, *in* Proceedings of the 87th Annual General Meeting of the Canadian Institute of Mining, Vancouver, p. 14.

Hood, P., Kornick, L. J., and McGrath, P. H., 1976, The aeromagnetic gradiometer; A new geophysical took for geophysical mapping programs [abs.]: International Geological Congress, v. 2, p. 391–392.

Kameneni, D. C., and Dugal, J.J.B., 1982, A study of rock alteration in the Eye–Dashwa Lakes Pluton, Atikokan, northwest Ontario, Canada: Chemical Geology, v. 36, p. 35–57.

Kameneni, D. C., Stone, D., Dugal, J.J.B., and Brown, P. A., 1982, Geochemistry of the Eye–Dashwa Lakes Pluton, Atikokan, northwestern Ontario: Atomic Energy of Canada Limited Technical Record 201, p. 21–41.

Krotova, V. A., 1957, Conditions of formation of calcium chloride waters in Siberia: Petroleum Geology, v. 2, p. 545–552.

Laroque, J.P.A., and Gascoyne, M., 1986, A survey of the radioactivity of surface water and groundwater in the Atikokan area, northwestern Ontario: Atomic Energy of Canada Limited Report, TR-379, 12 p.

Lau, J.S.O., 1983, The determination of true orientations of fractures in rock cores: Canadian Geotechnical Journal, v. 20, p. 221–227.

Lee, D. R., 1977, A device for measuring seepage flux in lakes and estuaries: Limnology and Oceanography, v. 22, p. 140–147.

Lee, D. R., and Cherry, J. A., 1979, A field exercise on groundwater flow using seepage metres and mini-piezometers: Journal of Geological Education, v. 27, no. 1, p. 6–10.

Lee, D. R., and Tracey, J. P., 1984, Identification of groundwater discharge locations using thermal infrared imagery: Proceeding of the 9th Canadian Symposium on Remote Sensing, p. 301–308.

Lee, P. K., Pearson, R., Leech, R.E.J., and Dickin, R., 1983, Hydraulic testing of deep fractures in the Canadian Shield: International Association of Engineering Geologists Bulletin, no. 26–27, p. 461–465.

McEwan, J., and Hillary, E., 1985, Early fracture evolution within the Eye–Dashwa Lakes Pluton, Atikokan, Ontario, Canada: Journal of Structural Geology, v. 7, no. 5, p. 591–603.

Meyboom, P., 1966, Unsteady groundwater flow near a willow ring in hummocky moraine: Journal of Hydrology, v. 4, p. 38–62.

Novakowski, K. S., Evans, G. V., and Raven, K. G., 1985, Field experiments investigating radionuclide migration in plutonic rock, *in* Hydrogeology of rocks of low permeability: International Association of Hydrogeologists, 17th International Congress Proceedings, p. 345–357.

Olsson, O., Duran, O., Jamtlid, A., and Stenberg, L., 1982, Geophysical investigations for the characterization of a site for radioactive waste disposal, *in* Proceedings of a Workshop on Geophysical Investigations in Connection with Geological Disposal of Radioactive Waste: Paris, France, Nuclear Energy Agency, Office of Economic Cooperation and Development, p. 45–56.

Paillet, F. L., Keyes, W. S., and Hess, A. E., 1985, Effects of lithology on televiewer-log quality and fracture interpretation: Transactions of the Society of Petroleum and Well Loggers 26th Annual Logging Symposium, 30 p.

Pearson, J. F., 1986, Models of mineral controls on the composition of saline groundwaters of the Canadian Shield, *in* Fritz, P., and Frape, S. K., eds., Saline waters and gases in crystalline rocks: Geological Association of Canada Special Volume 33, p. 39–51.

Pearson, R., 1984, Geoscience research activities in 1983, *in* Proceedings of the 16th Information Meeting of the Canadian Nuclear Fuel Waste Management Program: Atomic Energy of Canada Limited Report TR-218, p. 30–50.

Pfannkuch, H. O., and Winter, T. C., 1984, Effect of anisotropy and groundwater system geometry on seepage through lakebeds; 1. Analog and dimensional analysis: Journal of Hydrology, v. 75, p. 213–237.

Pfannkuch, H. O., Edgar, D., Van Luik, A., and Harrison, W., 1983, Hydrology, *in* Harrison, W., ed., Geology, hydrology, and mineral resources of crystalline rock areas of the Lake Superior region, United States: Argonne, Illinois, Argonne National Laboratory, ANL/ES-134, pt. 1, p. 184–302.

Raven, K. G., and Gale, J. E., 1986, A study of the surface and subsurface structural and groundwater conditions at selected underground mines and excavations: Atomic Energy of Canada Limited Report TR-177, 81 p.

Raven, K. G., Smedley, J. A., Sweezey, R. A., and Novakowski, K. S., 1985, Field investigations of a small groundwater flow system in fractured monzonitic gneiss, *in* Hydrogeology of rocks of low permeability: International Association of Hydrogeologists, 17th International Congress Proceedings, p. 72–86.

Ridgway, W. R., and Pearson, R., 1987, Regional hydrogeological characterization studies at Atikokan, northwest Ontario: Atomic Energy of Canada Limited Paper (in press).

Siegel, D. I., 1981, Hydrogeologic settings of the Glacial Lake Agassiz Peatlands, northern Minnesota: U.S. Geological Survey Water Resources Investigation 81-24, 33 p.

Snow, D. T., 1968, Hydraulic characterization of fractured crystalline rocks of the Front Range and implications to the Rocky Mountain Arsenal Well: Golden, Colorado School of Mines Quarterly, v. 63, no. 1, p. 167–199.

Soonawala, N. M., 1984, An overview of the geophysics activity within the Canadian nuclear fuel waste management program: Geoexploration, v. 22, p. 149–168.

Stockwell, C. H., and 7 others, 1970, Geology of the Canadian Shield, *in* Stockwell, C. H., ed., Geology and economic minerals of Canada: Geological Survey of Canada Economic Geology Report no. 1, p. 43–150.

Stone, D., 1984, Sub-surface fracture maps predicted from borehole data; An example from the Eye–Dashwa Lakes Pluton, Atikokan, Ontario, Canada: International Journal of Rock Mechanics, Mining Science, and Geomechanics Abstracts, v. 21, no. 4, p. 183–199.

Toth, J., 1963, A theoretical analysis of groundwater flow in small drainage basins: Journal of Geophysical Research, v. 68, p. 4795–4812.

Webster, D. S., Proctor, J. F., and Marine, I. W., 1970, Two-well tracer test in fractured crystalline rock: U.S. Geological Survey Water Supply Paper 1544-I, 26 p.

White, D. E., Hem, J. D., and Waring, G. A., 1963, Geochemical composition of subsurface waters: U.S. Geological Survey Professional paper 440-F, 67 p.

Wingrove, T. R., Rudolph, D. L., and Farvolden, R. N., 1984, Field evidence for groundwater flow in Precambrian terrain near Atikokan, Ontario, *in* Proceedings of the International Groundwater Symposium on Groundwater Resource Utilization and Contaminant Hydrogeology: International Association of Hydrogeologists (Canadian chapter), v. 2, p. 580–593.

Winter, T. C., 1976, Numerical simulation analysis of the interaction of lakes and groundwater: U.S. Geological Survey Professional Paper 1001, 45 p.

Wong, J., Hurley, P., and West, G. F., 1983, Crosshole seismology and seismic imaging in crystalline rocks: Geophysics Research Letters, v. 10, no. 8, p. 686–689.

Wright, H., Jr., Goldstein, B., Harrison, W., Pfannkuch, H. O., Edgar, D., and Van Luik, A., 1983, Physiograph and surficial deposits, *in* Harrison, W., ed., Geology, hydrology, and mineral resources of crystalline rock areas of the Lake Superior region, United States: Argonne, Illinois, Argonne National Laboratory, ANL/ES-134, pt. 1, p. 167–183.

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