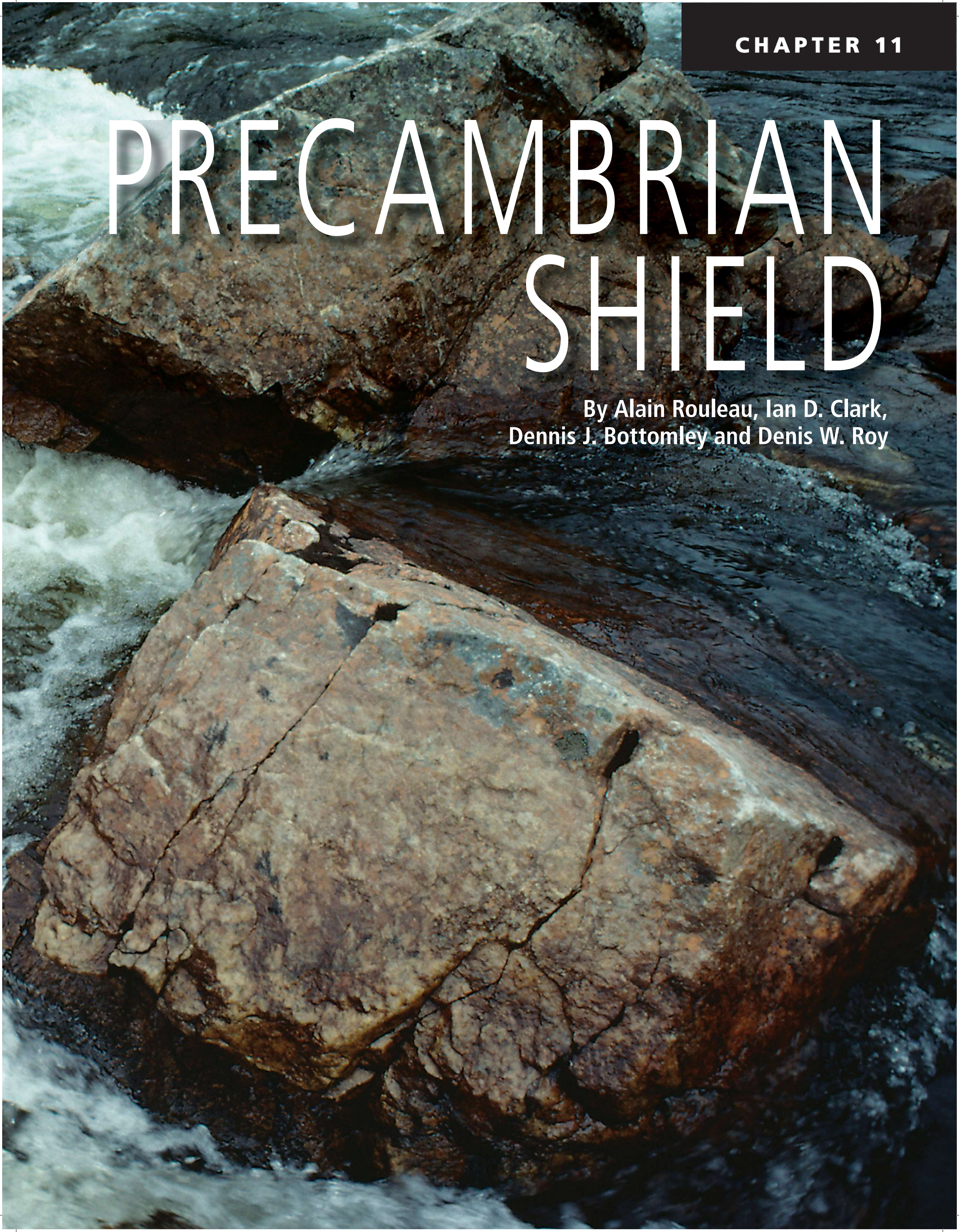
CHAPTER 11

PRECAMBRIAN SHIELD

By Alain Rouleau, Ian D. Clark, Dennis J. Bottomley and Denis W. Roy



11.1 INTRODUCTION

11.1.1 Physiography

The Precambrian Shield region extends from the Northwest Territories to Labrador, across northern Saskatchewan, and constitutes most of the surface area of Manitoba, Ontario and Québec. The general physiography of this region is that of a peneplain at an elevation typically ranging from 500 to 1,000 m. This region has been subjected to many erosional cycles following the Precambrian orogenies. It is underlain almost entirely by Precambrian igneous and metamorphic bedrock and minor areas of sedimentary rock. The bedrock is typically covered by thin layers of glacial and post-glacial sediments.

11.1.2 Population

Most of the largest cities in Manitoba (Winnipeg), Ontario (Toronto and Ottawa) and Quebec (Montreal and Quebec City) are located immediately south of the Shield region. Nevertheless, major population centres are located within the southern part of the Shield, including Sault-St-Marie, Timmins, Sudbury, Rouyn-Noranda, Gatineau, and Saguenay. Mining and forest-based industries, particularly lumbering and paper-making, constitute important groups whose economic activities are scattered over many areas of the Shield. Hydroelectric power generation is also important in some areas, as well as some industries requiring high energy input such as aluminium manufacturing in Quebec's Saguenay region. Tourism, as well as agriculture in lowland areas, are other important activities in a number of areas of the region.

11.1.3 Climate and hydrography

Canada's Shield region includes a large surface area embracing 6 of the 15 different ecozones set out in the Ecological Framework for Canada (Environment Canada, 2005): these are the Boreal Shield, the Hudson Plains, the Taiga Shield, the Southern Arctic, the Northern Arctic, and the Arctic Cordillera. The last three ecozones are located in the Arctic and are discussed in Chapter 15 as the permafrost groundwater region. The Boreal Shield ecozone is further described in Urquizo et al. (2000), including its ecological and the socioeconomic settings. These ecozones are further subdivided in a number of ecoregions. The portion of the Shield region covered in this chapter experiences a moderate moisture regime; with precipitation and temperature decreasing significantly from south to north. At a given latitude, temperatures are lower near and across Hudson Bay. The northern half of the region is underlain by a sporadic or discontinuous superficial layer of permafrost.

11.1.4 Groundwater and human activities

Even in the most populated areas, groundwater is not used in large quantities because of the wide availability of surface water (i.e., lakes and streams). Groundwater is mostly drawn from permeable glacial and proglacial deposits, and is used by municipalities and industries. Mine drainage constitutes the main groundwater withdrawal from the crystalline basement formations in the Canadian Shield (Rouleau et al., 1999). As a result, mine drainage creates the characteristic hydrogeological problem in the bedrock basement formations of the Shield (Charron, 1967; Brown, 1970). The problem of radioactive waste disposal has also motivated a number of hydrogeological studies, particularly in Manitoba and Ontario's plutonic rocks (Farvolden et al., 1988).

Prior to about 1980, few detailed investigations had been conducted into the hydrogeology and geochemistry of groundwaters in crystalline rocks of the Canadian Shield. Most information on groundwater in the Shield is found in water-well records on file with the provincial Ministry of the Environment or the Ministry of Natural Resources, various consultants' reports on groundwater potential for communal or private wells (for potential rural residential subdivisions or light industry, for instance), and occasional reports on groundwater quality of inflows at various mine sites. This situation began to change dramatically in the late 1970s when Atomic Energy of Canada Ltd. (AECL) became interested in the Shield as a potential geologic repository for the subsurface disposal of fuel waste from nuclear power generating stations, waste that is presently being stored on surface. At that time, however, little information was available on the hydrogeological suitability of the Shield for the storage of such material. AECL established research sites at its nuclear facilities at Whiteshell in southeastern Manitoba, and at Chalk River in eastern Ontario. It also set up sites near the community of Atikokan in northwestern Ontario, and at East Bull Lake in central Ontario (35 km east of Elliot Lake). Furthermore, AECL constructed an underground research laboratory at a depth of about 400 m at the Whiteshell site. The lab was constructed to collect more detailed information on the subsurface conditions than data provided from borehole drilling and geophysical testing on the surface. AECL also supported various studies into the collection of information on the hydrogeological conditions at several operating mines on the Shield. This type of work was also done by the Canadian Nuclear Safety Commission in order to independently verify the geologic safety of AECL's disposal concept.

11.2 GEOLOGY

Compilations of the geology of Canada's Precambrian Shield have been provided by Lucas and St-Onge (1998), and by Thurston et al. (1991) for Ontario, and Hocq (1994a) for Quebec. A comprehensive thematic review of Precambrian research over the World is presented in Eriksson et al. (2004); the work includes many papers discussing parts of the Canadian Shield.

11.2.1 Bedrock geological provinces

The Canadian Shield is subdivided into geological provinces according to deformation style and age (Stockwell, 1962), a subdivision which has been reinterpreted in a plate tectonic framework by Hoffman (1988, 1989; Figure 11.1). Every province generally comprises belts of stratified or banded rocks that have been metamorphosed and deformed to various degrees, as well as bodies of intrusive and highly metamorphosed rocks. Most provinces of the Canadian Shield host *greenstone belts* composed of volcano-sedimentary rocks that have been submitted to many deformation phases and are metamorphosed to the greenschist facies (and lower amphibolite facies). These belts are normally bounded by intrusive bodies, mainly granitic in composition, and various types of gneisses. Minor amounts of alcaline rocks, including carbonatites, occur throughout the Shield. The two principal geological provinces south of the discontinuous permafrost line are Superior (Archean in age) and Grenville (Middle Proterozoic in age) Provinces (Figure 11.2). The former provides a good example of the distribution of greenstone belts within an Archean Province, while the latter, being the youngest in the Canadian Shield, may herald the present-day mountain ranges with deep crustal roots in the Earth mantle.

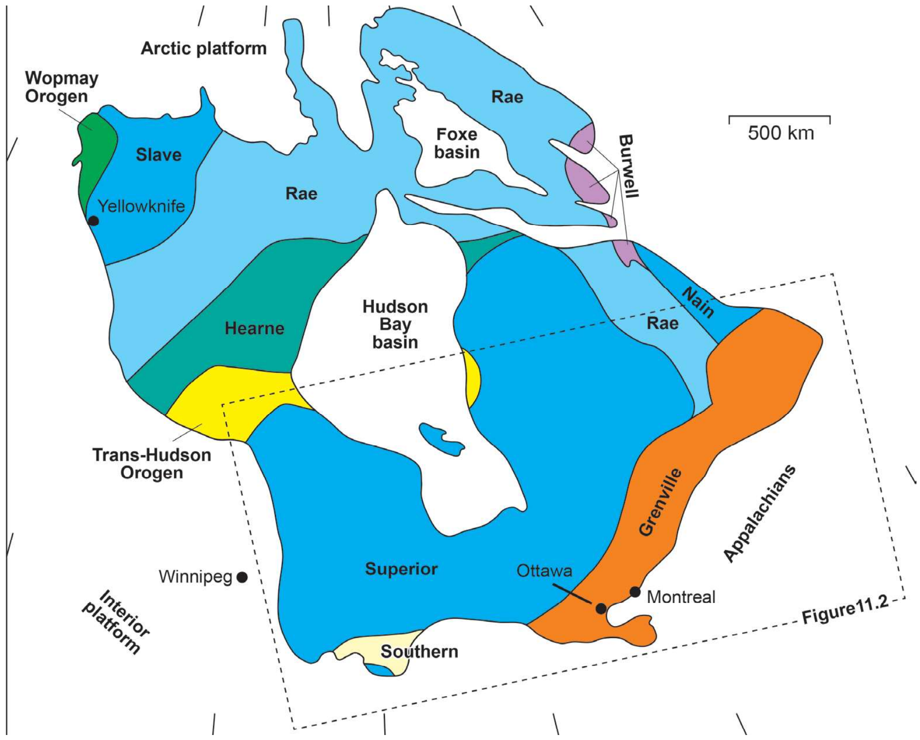


Figure 11.1 Schematic pre-drift restoration of the principal geological provinces of the Canadian Shield (adapted from Hoffman, 1989).

The Superior Province is Late Archean in age (2.85 to 2.5 Ga) and occupies the central part of the Canadian Shield (Hocq, 1994b; Card and Poulsen, 1998). This geological province is further divided into sub-provinces based on various contrasts concerning rock type, metamorphism, structure and age (Card, 1990; Figure 11.2). Numerous metal mines (Cu, Zn, Ni, Fe, Ag, Au) are located within the Superior Province, particularly in the Abitibi Subprovince (Hocq and Verpaelst, 1994). Most of these mines contain gold-bearing quartz veins or volcanic massive sulphides deposits (Chartrand, 1994).

The Grenville Province (Rivers et al., 1989; Easton, 1992; Hocq, 1994c; Davidson, 1998) is the latest Precambrian geological province accreted to the Canadian Shield, in its southeastern part (Figure 11.2). The surface of this geological province features highly deformed rocks that were metamorphosed (upper amphibolite and granulite facies) at more than 25 km deep in the crust. They were first intruded by large quantities of magmatic rocks (such as the anorthosite and charnockite suite) that crystallized under high temperature, and secondly by late grenvillian granites.

Subhorizontal layers of sedimentary rock, Paleozoic and Mesozoic in age, cover the Canadian Shield platform on its border, e.g., the St. Lawrence and Hudson Bay Lowlands, and the Interior platform to the west. Metamorphic and plutonic bedrock within the Canadian Shield itself is covered unconformably in places by subhorizontal outliers of sedimentary rocks. These are remnants of stratigraphic units of a much larger extent which have been deposited unconformably over the crystalline bedrock during a number of distinct episodes of sea invasion during the Proterozoic and Paleozoic eras. Proterozoic sedimentary rock includes the Cobalt Group (part of the Huronian Supergroup; Bennet et al., 1991) in the Lake Timiskaming area, as well as the Otish and the Mistassini Basins, all in the southeast side of the Abitibi Subprovince (Hocq, 1994b). Paleozoic rock outliers are found within the tectonic depression of the Saguenay graben (Avramchev, 1993; Desbiens and Lespérance, 1988), as well as in the Lake Timiskaming area on top of the Huronian Supergroup (Johnson et al., 1992), and in most parts of the Hudson Bay Basin.

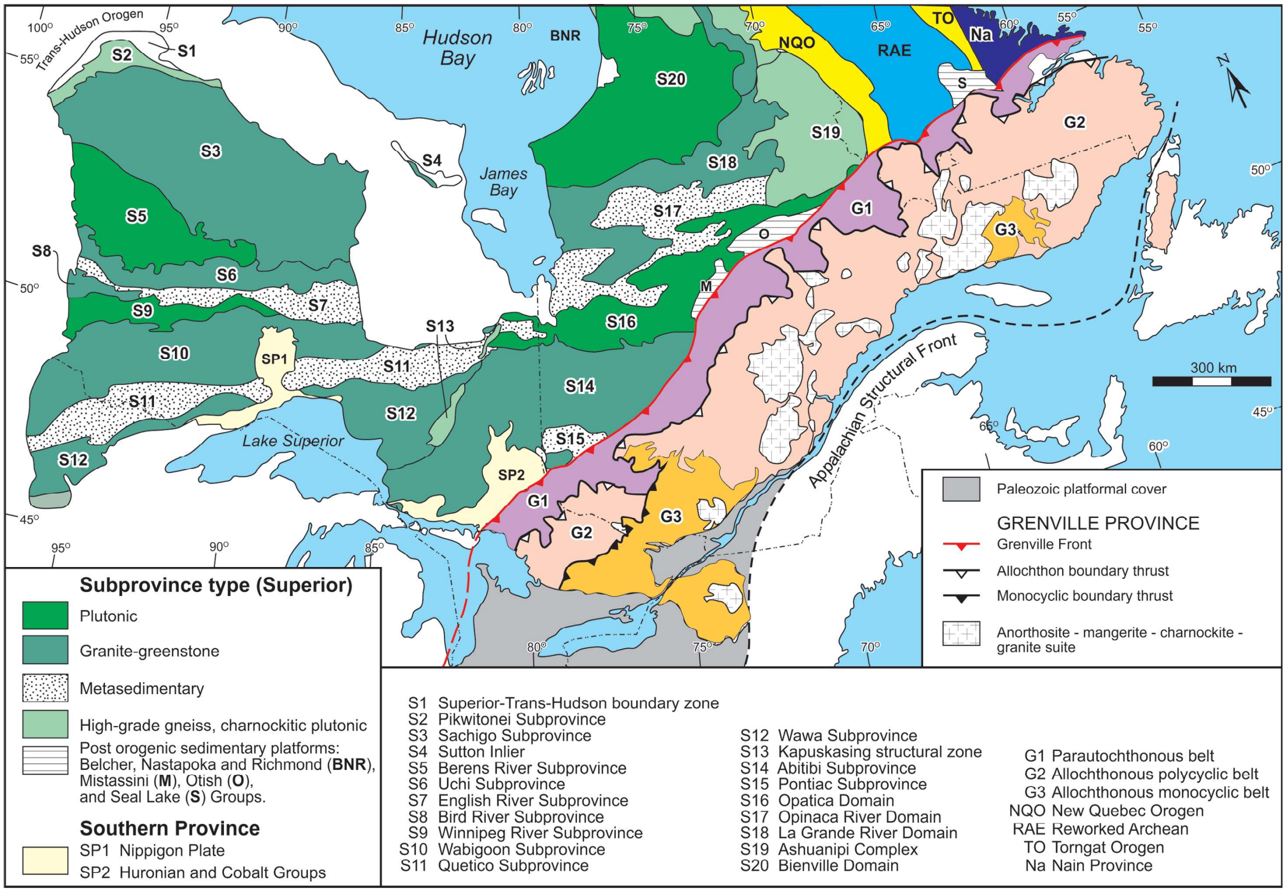


Figure 11.2 The Grenville and the Superior geological Provinces and their subdivisions based on structure, lithology, and metamorphism (adapted from Card and Poulsen, 1998; Rivers et al. 1989).

11.2.2 Quaternary deposits

The bedrock here is covered in most parts by Quaternary sediments. Quaternary overburden deposits over most of the Canadian Shield, except along stream and river valleys, are generally relatively thin and often absent. Moreover, where present, the overburden is predominantly glacial till which is typically too low in permeability to be a potential aquifer for a municipal water supply. Glacial and proglacial deposits also include moraines and eskers, as well as fluvial deposits and sediments left by glacial lakes or post-glacial seas. Extensive glaciofluvial sand and gravel deposits are present in some areas of Quebec and northern Ontario. More recent deposits include alluvia and organic sediments (peat) in wetlands (Vincent, 1989).

As described by Roy et al. (2006), eskers could be located in flat-lying uplands, such as in Abitibi (Veillette, 1986) and the Larder Lake area, but also in valley bottoms, as along the Peribonka River, which drains into Lake Saint-Jean (LaSalle and Tremblay, 1978)

Large outwash deposits are found at many locations in the southern margin of the Precambrian Shield. Deltaic systems have been formed by rivers that discharged to seas that invaded parts of the southern margin of the Shield at the end of the last glaciations. These seas include the Champlain Sea in the St. Lawrence Lowlands, and the Laflamme Sea in the Saguenay-Lake-Saint-Jean area.

11.3 HYDROGEOLOGICAL CONTEXTS

Simard and Des Rosiers (1979) have subdivided the

Precambrian Shield in southern Quebec into four hydrogeological units, mostly based on geographical location and geology, but also on the specific capacity of wells estimated from the *Système d'information hydrogéologique* (SIH) database (MDDEP, 2006). Table 11.1 summarizes water well data from the Precambrian bedrock; the statistics on well depth, yield and specific capacity are estimated for a total of 708 wells from the SIH data base, whereas the groundwater quality is based on a total of 20 water samples from as many wells. All of these hydrogeological units are qualified as low-permeability by Simard and Des Rosiers (1979), since the water wells generally yield less than 2.7m^3/hr. The statistics on well yield shown in Table 11.1 are biased toward high values because of the presence of overlying permeable granular deposits frequently encountered in valleys.

Many different hydrogeological units have been defined by Roy et al. (2006) for the southern part of Quebec, including the Precambrian Shield area, both for the bedrock and for the surficial unconsolidated deposits. Many of these units are applicable to the overall extent of the Shield. For the bedrock in the Precambrian Shield, Roy et al. (2006) have defined three other types of possible hydrogeological unit (types E, F, and G), in addition to those mentioned in Table 11.1 (types A, B, C, and D). Type E corresponds to faults or fault zones that are present at numerous locations in the Precambrian Shield. These zones are often expressed at surface by linear topographic depressions and lineaments; and they are often characterized by a high fracture density and increased permeability. Moreover, permeable granular deposits are often present in the bottom of valleys corresponding to fault zones. Many authors (Simard and Des Rosiers, 1979; Sylvestre, 1981; McCormack, 1983) have suggested that the presence of these deposits induces a better groundwater recharge and contributes to a higher yield of wells in valleys, even those wells in the fractured bedrock.

Mapping of faults and fault zones has been carried out mostly as part of tectonic studies. Card and Poulsen (1998) presented a map showing many of the major fault zones in the Superior Province. A map in DuBerger et al. (1991) depicts many lineaments in a large portion of the Grenville Province surrounding the epicentre of the Saguenay 1988 earthquake. A number of examples of lineament

TABLE 11.1 CHARACTERISTICS OF WATER WELLS IN THE PRECAMBRIAN BEDROCK IN SOUTHERN QUEBEC GROUPED IN FOUR HYDROGEOLOGICAL UNITS (AFTER SIMARD AND DES ROSIERS, 1979)

GEOGRAPHIC AREA	TIMISKAMING	ABITIBI	SAGUENAY-LAKE-SAINT-JEAN	ELSEWHERE
Hydrogeological unit	A	B	C	D
Rock types	Metasedimentary	Metavolcanic Metasedimentary Acidic intrusive	Anorthosite Acidic intrusive	Acidic intrusive gneiss
Number of wells	48	267	41	352
Mean yield (m^3/hr):	5.4	5.9	2.8	4.1
Mean depth (m)	67	69	62	39
Mean specific capacity (m^3/hr/m)	0.278	0.343	0.123	0.326

analysis, using remote sensing over the Canadian Shield, are discussed in Short (2002). Roy et al. (2006) have compiled data for many set of large structural discontinuities in the Precambrian Shield (including dyke swarms and faults) with their age and orientation. Not all lineaments, however, correspond to structures that are efficient groundwater conduits. A study by Gleeson and Novakowski (2009) in the Tay River watershed in southern Ontario suggests that structures corresponding to lineaments often act as watershed-scale hydraulic barriers. The low-gradient Tay River flows over exposed and fractured bedrock of the Grenville Province or a thin veneer of coarse-grained sediments; groundwater discharge rates to the river are low, indicating that the groundwater and surface water system may be largely decoupled in this watershed when compared to watersheds underlain by porous media (Gleeson et al., 2009).

The type F of Roy et al. (2006) corresponds to metamorphosed Proterozoic carbonate rock units found in many places in the Precambrian Shield, e.g., southwest part of the Grenville Province. Karstic networks have developed in places within these marble and crystalline carbonate units, creating highly permeable flow channels. Finally the type G hydrogeological unit defined by Roy et al. (2006) corresponds to remnants of a subhorizontal platform cover of sedimentary rock.

11.3.1 Context 1: Greenstone belts, metasedimentary, gneissic and intrusive crystalline rock (most of the Shield)

The hydrogeological units of types B, C, D, E and F defined above are included within the hydrogeological context 1 (Figure 11.3) described in this section.

Greenstone belts, gneissic basement and plutons are comprised of plutonic and metamorphic rocks often termed crystalline rocks. An important characteristic of crystalline rocks is their relatively low primary porosity and rock matrix permeability, except where weathered (Trainer, 1987). These rocks, unless fractured, commonly yield only a small supply of water to wells. The hydrogeology of crystalline rocks in the Canadian Shield is known mostly at mining sites and hydroelectric power plants, and at a few sites where field research has been conducted in relation to radioactive waste storage.

Studies conducted at these sites indicate that the rock is fractured more or less extensively, with fracture spacing ranging from metres to tens of metres or more (e.g., Raven 1986; Raven and Gale, 1986; Stevenson et al., 1996, among others). If the fractures are connected within a network, then this connectivity will allow groundwater circulation even though the rock matrix has very low permeability.

Although groundwater flow in Shield bedrock is highly restricted, fracture permeability can represent an important aquifer for rural water supply. The Quaternary aquifers at the AECL Chalk River Laboratories (CRL) in Eastern Ontario are underlain by granitic gneiss doming the 1.4 Ga Algonquin Batholith in the Central Gneiss belt of the Grenville Province. Here, regional bedrock relief is on the order of 100 m. Raven (1986) demonstrated a highly complex and non-homogeneous fracture network in the upper 100 m with bulk vertical hydraulic conductivities up to 4.4×10^{-5} m/s, and over 100 times greater than the radial hydraulic conductivity.

Many authors have observed that the degree of fracturing generally decreases with depth from surface. In most geological settings, including the Precambrian Shield, this decrease occurs in parallel

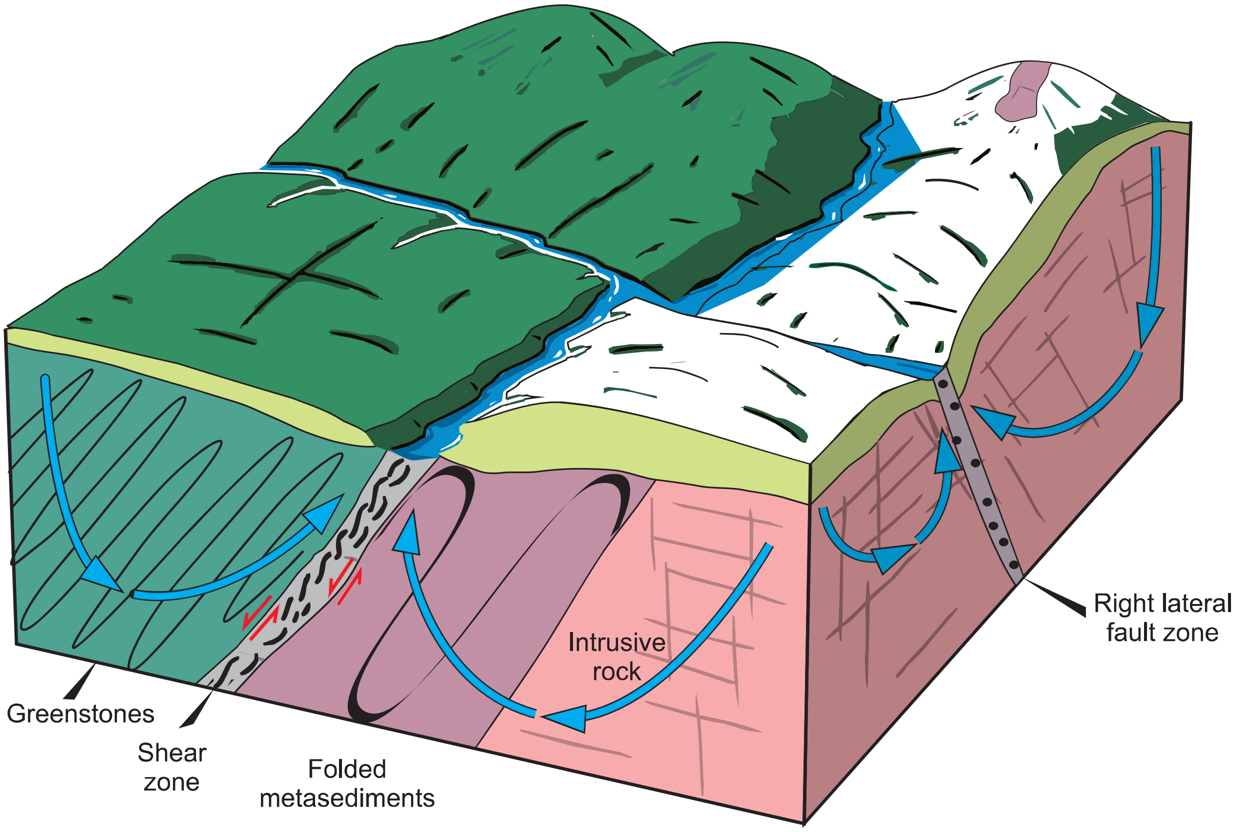


Figure 11.3 Hydrogeological context in the Precambrian Shield consisting of greenstone belt , metasedimentary and intrusive rocks, showing a shear zone offset by a fault zone, and surface lineaments.

with a decrease in rock mass permeability. (Gale et al., 1982; Gustafson and Krásný, 1994). A higher permeability near the surface can be due to a higher fracture density related to stress release, or to weathering and mineral dissolution in fracture planes. Farvolden et al. (1988) and Lemieux et al. (2008b) point out that a log-linear decrease can usually be observed in the first 400 m and that the deeper hydraulic conductivity values tend to be variable depending on the fractures or faults intercepted. Additionally, a progressive increase in effective stress results in fracture closure with depth.

The hydrogeological properties of a structural discontinuity may vary considerably along its plane (Raven and Gale, 1986) even at the same depth. One example is provided by data from the Underground Research Laboratory at Pinawa (Manitoba), where detailed characterization of the in situ geomechanical stress and the hydrogeological properties of the rock mass along a major subhorizontal fault zone allowed the identification of a significantly lower-permeability segment of that structure, corresponding with higher values of normal stress; that location constituted a better emplacement for a future excavation in order to reduce groundwater inflow (Davison et al., 1993).

11.3.2 Context 2: Same as context 1, with a platform cover of Proterozoic or Paleozoic age

The areas of crystalline bedrock in the Canadian Shield covered by subhorizontal remnants of sedimentary rock units constitute a distinct

hydrogeological environment. Hydrogeological units of types A of Simard and Des Rosiers (1979; Table 11.1) and G of Roy et al. (2006) are both included in the hydrogeological context no. 2 defined here. These sedimentary rock units may constitute valuable aquifers provided their saturated zone is sufficiently thick. In any case, the presence of a relatively permeable sedimentary rock cover favours groundwater recharge to deeper aquifer systems. As an example, a water well installed in a remnant of an Ordovician carbonate unit provides an important supply of drinking water to the town of Saint-Félicien near Lake Saint-Jean (Verreault, 2003).

11.3.3 Context 3: Quaternary aquifers of granular material

In lowlands areas of the Canadian Shield, and at its southern border, Quaternary sediments deposited during and after the Wisconsinian glaciation include significant units of granular material which constitute major aquifer systems. Various types of Quaternary granular aquifers are illustrated schematically in Figure 11.4, using the Saguenay-Lac-Saint-Jean (SLSJ) region as an example. The regional physiography, deeply affected by the Saguenay graben, has controlled the placement and formation of these granular deposits in lowland areas.

The Quaternary granular aquifers includes glacial and glaciofluvial as well as post-glacial prograding alluvial and delta plains sediments deposited in lowlands, and on bedrock uplands and plateaus. Figure 11.4 illustrates important glaciofluvial aquifers located at the border of the

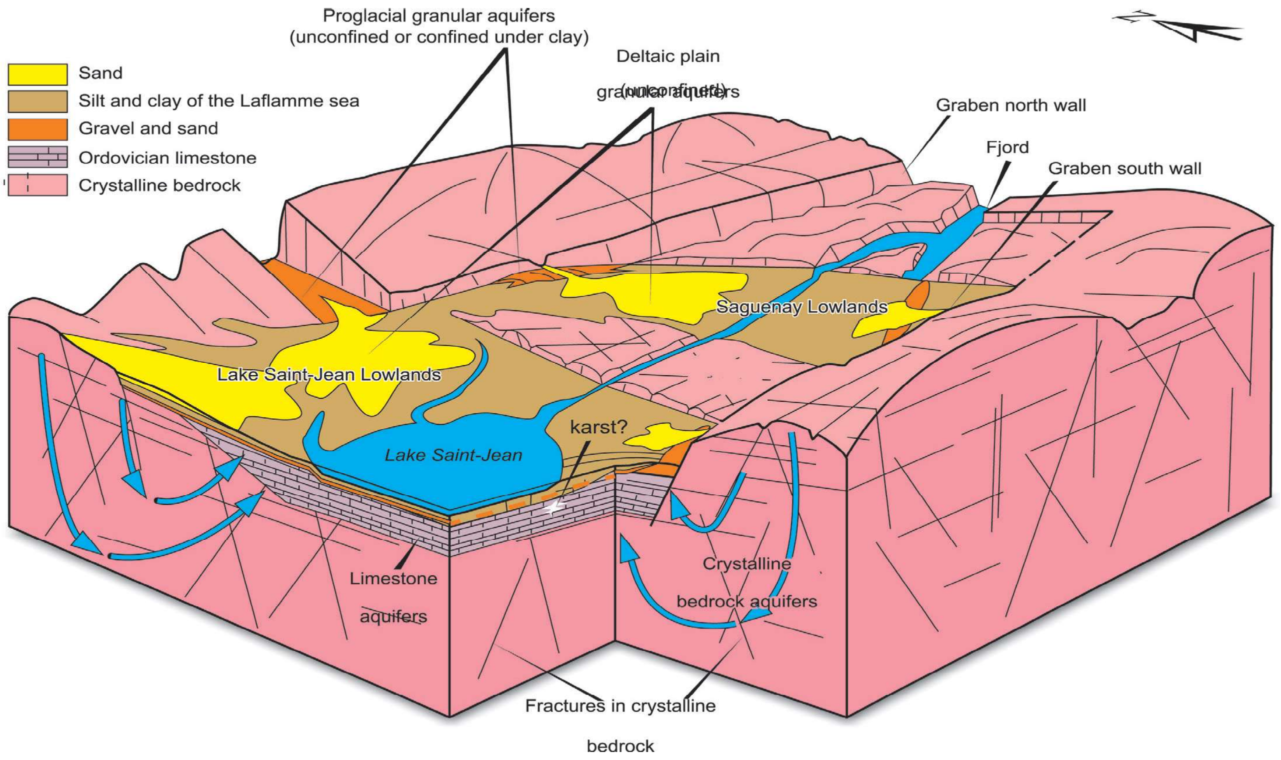


Figure 11.4 Schematic block diagram of aquifer types identified in the Saguenay-Lac-Saint-Jean region (modified from Rouleau et al., 2011).

Saguenay lowlands, near the east-west oriented northern and southern graben faults. In glaciofluvial deposits such as eskers and kames, fine particles have been washed out in many places during the sedimentation process, resulting in permeable granular aquifers. Extensive glaciofluvial sand and gravel deposits are present in some areas, such as the Larder Lake esker in northern Ontario, and the Berry-Saint-Mathieu esker near Amos, Quebec. Fine particle washing has also taken place locally in other glacial deposits, such as moraines, producing complex aquifer systems. These granular units are either unconfined, or confined by extensive units of silt or clay deposited at the bottom of glacial lakes or seas.

A second type of Quaternary granular aquifer is comprised of post-glacial deposits such as large outwash plains and deltaic systems, particularly along Shield margins. In the SLSJ region (Figure 11.4), rivers discharging from both sides of the graben into the invading Laflamme Sea after the last glaciation have deposited granular sediments in their deltas or deltaic plains. These deposits constitute relatively productive unconfined aquifers. The Saint-Honoré aquifer, described by Tremblay (2005), and Tremblay and Rouleau (2004), constitutes an example of a paleodeltaic aquifer that has been put in place by a river flowing to the south and discharging into the Laflamme Sea.

Water wells in these types of Quaternary aquifers provide an important municipal drinking water supply because of their high yield. Most of the rural communities in the SLSJ region, for instance, are pumping groundwater from these granular aquifers for their municipal water distribution system. Also, these permeable granular deposits facilitate groundwater recharge, increasing groundwater flux within underlying bedrock aquifers.

11.4. CURRENT KNOWLEDGE ON GROUNDWATER IN THE CANADIAN SHIELD

11.4.1 Hydrology and climate

Total annual precipitation (P) over the Canadian Shield decreases from about 1400 mm in the south (Proulx et al., 1987) to about 400 mm at the northern tip of the Ungava peninsula (Lapointe, 1977). The percentage of total precipitation falling as snow varies from about 25% in the south to more than 50% in the northern part of Quebec (Gagnon and Ferland, 1967).

Evapotranspiration (ET) also decreases with latitude (van Everdingen, 1987), even more notably than precipitation. As a result, the ratio of runoff (Q) to precipitation, i.e., the runoff coefficient (Q/P), is often higher to the north. As an example, Q/P is estimated at 80% in the Nastapoka and the Grande-Baleine Rivers, both discharging into Hudson Bay near Kuujjuarapik (Hydro-Québec, 1993). Q/P is around 65% in the southern part of the Canadian Shield (Ferland, 1969; Proulx et al., 1987), and about 50 to 60% at the southern limit of Quebec (Simard and Des Rosiers, 1979).

Analysis of stream baseflow, in relation to factors such as precipitation, geology and topography, provides a first assessment of groundwater resources in areas with a temperate or cold climate (Gustafson and Krásný, 1994). This is particularly valuable in a region with a low population density such as the northern half of the Canadian Shield, since baseflow is often the only hydrogeological data available there.

Water budget calculations with an emphasis on the groundwater component have been carried out by Singer and Cheng (2002) on watersheds of five major rivers discharging into Hudson Bay and James Bay (Severn, Winisk, Attawapiskat, Albany and Moose Rivers, Figure 11.5), as well as the Ontario part of the Upper Ottawa River. The bedrock geology of these watersheds is composed mostly of Precambrian basement, with sedimentary rocks of the Phanerozoic Hudson Bay Platform on the downstream part of those northern flowing rivers. The bedrock is covered in large part by a generally thin layer of Quaternary deposits, which can, however, exceed 100 m in thickness in some bedrock valleys of the Canadian Shield (Dredge and Cowan, 1989). These unconsolidated deposits can be more than 200 m thick in places over the Hudson Bay Lowlands. The long term mean annual precipitation in that region varies from 471.4 to 796.6 mm, and Singer and Chen (2002) have estimated that the long-term mean annual groundwater recharge ranges from 33.6 to 44.0 mm.

The northern half of the Canadian Shield is covered more or less continuously by permanently frozen ground (the permafrost). The presence of a perennial or seasonal frozen layer reduces water infiltration and groundwater recharge considerably, both in surficial deposits and in the bedrock (van Everdingen, 1987). The reduction of groundwater recharge in permafrost terrains is reflected by a one order of magnitude decrease in stream baseflow (expressed in $m^3/s/km$) with increasing latitude, from about 5×10^{-3} in the southern part of discontinuous permafrost, to about 5×10^{-4}, and approaches zero in continuous permafrost areas (Lapointe, 1977; van Everdingen, 1987).

Groundwater flow regimes during past climatic conditions, from the period of the continental Laurentide ice-sheet cover of the Wisconsinian glaciation (120 ka) to present, have been investigated by numerical modelling. This modelling is supported by isotopic and hydrogeochemical data, for the northern part of North America, including

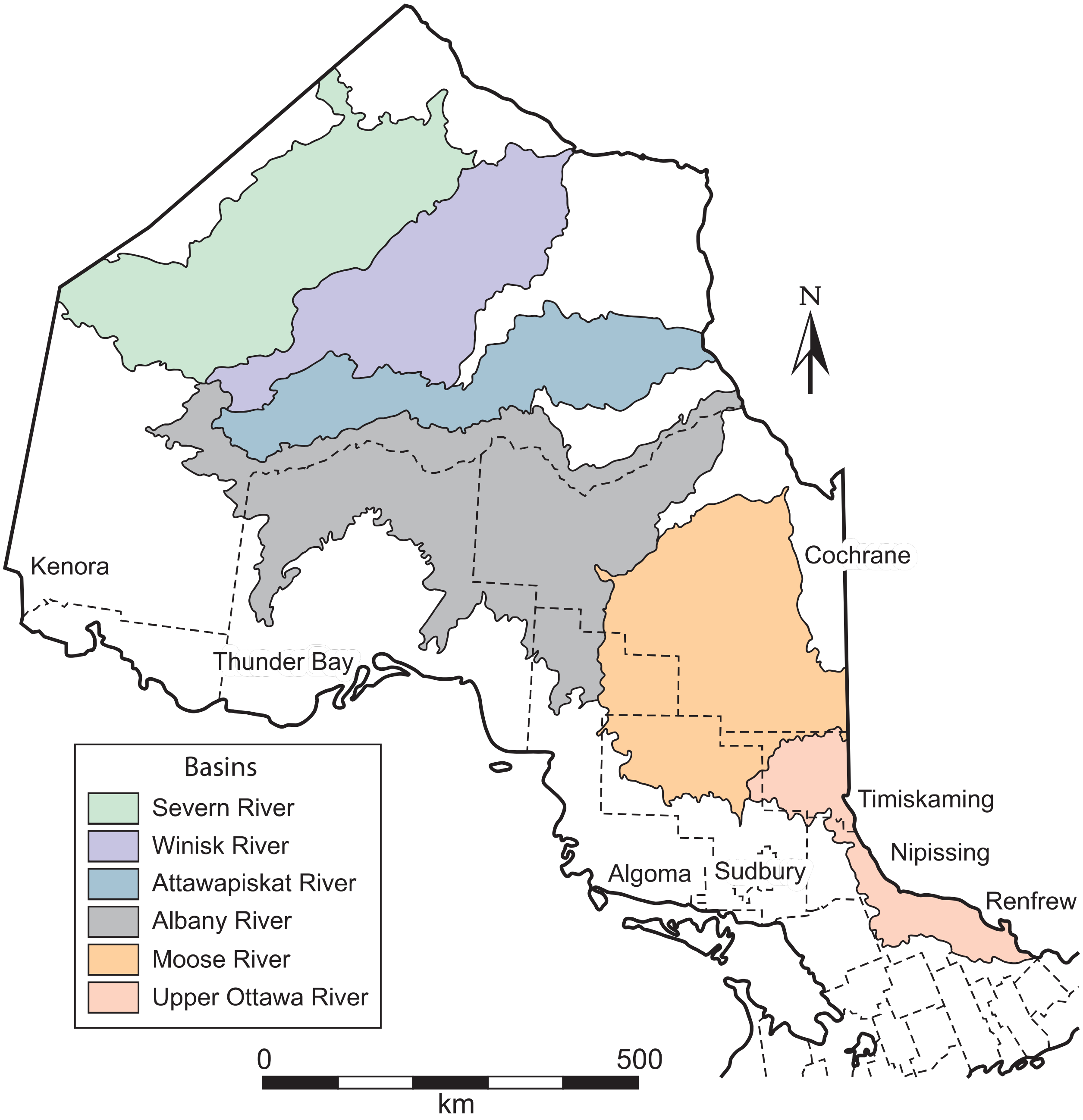


Figure 11.5 Map of northern Ontario watersheds draining into Hudson Bay, James Bay and Upper Ottawa River (From Singer and Cheng, 2002).

the entire Precambrian Shield region. The results suggest that most infiltration of subglacial meltwater occurs during ice sheet progression. Furthermore, during ice sheet regression, groundwater mainly exfiltrates on the surface, in both the subglacial and periglacial environments (Person et al., 2007; Lemieux et al, 2008).

11.4.2 Groundwater geochemistry

11.4.2.1 Overburden groundwater geochemistry

Overburden groundwaters on the Shield are generally dilute (TDS< 300 mg/L), Ca-HCO_3-type waters because overburden materials are generally comprised of low-solubility silicate minerals (quartz and feldspars) with trace to minor amounts of carbonates. Exceptions occur such as at Whiteshell where brackish overburden Ca-Mg-HCO_3-SO_4-type groundwaters have TDS concentrations up to 9,000 mg/L due to dissolution of more soluble minerals such as gypsum present in the clay-rich overburden (Gascoyne, 2004). Overburden groundwaters in the Hudson Bay drainage system of northern Ontario are also typically of the Ca-HCO_3 type with TDS concentrations generally less than 400 mg/L (Singer and Cheng, 2002).

11.4.2.2 Bedrock groundwater geochemistry

Testing at the AECL research sites provided the opportunity to analyze groundwater chemistry from near surface to as deep as about 1,000 metres. Groundwater samples from Shield mines have been collected from depths up to about 2,000 m. In recharge areas, groundwaters in the upper 200–300 m of the bedrock are typically fresh with TDS values of up to about 500 mg/L. TDS values reflect dissolution of silicate minerals and reactions with carbonate minerals present in the overburden or on fracture surfaces in the bedrock. There is also a gradual downward trend from Ca-HCO_3- toward Na-HCO_3-type water in the upper bedrock due to the exchange of Ca for Na sorbed onto clay minerals in the fractures. At depths of about 200–300 m, mixing between recent meteoric recharge and an older glacial meltwater component that infiltrated up to 20 kyr ago may be evident from the stable isotopic composition of the water (Bottomley et al., 1984, 1990; Clark et al., 2000). However, because both sources are relatively fresh, mixing of these two components does not typically result in a major increase in TDS. In contrast to recharge areas, regional groundwater discharge zones may be brackish Na-Cl-type water due to the upward flow of more saline groundwaters from depth along major fracture or fault zones (Gascoyne, 2004). High-Cl and high-TDS groundwater have also been observed in shallow wells drilled into the Precambrian bedrock in Quebec (Simard and Des Rosiers, 1979), particularly around Lake Saint-Jean (Walter et al., 2006).

Hypersaline brines are ubiquitous at depths greater than about 1,000 m in the Canadian Shield. These brines are of the (Ca-Na)-Cl type with TDS values up to 300 g/L (Frape et al., 1984b; Bottomley et al., 1994) and are clearly unfit for human consumption, livestock watering or irrigation. In Ontario, Quebec and the Northwest Territories these ancient brines appear to have penetrated the Shield by downward infiltration of early Paleozoic seawater that had been concentrated beyond halite saturation by evaporation (Bottomley et al., 1999, 2002). Exceptions to this mechanism may be seen at certain sites on the Shield near the contact with basinal sediments, such as the Whiteshell area, where formation waters may have been driven laterally into the Precambrian basement rocks in the past (Gascoyne, 2004). However, these saline waters have TDS values of less than about 100 g/L and are predominantly of the (Na-Ca)-Cl type. Because of their high density and the generally low regional hydraulic gradient in the Shield, hypersaline brines have not been observed as naturally discharging to the surface at present. They do, however, discharge into deep mines via fractures, faults and flowing boreholes, requiring pumping to surface for disposal (e.g., Benlahcen, 1996). Less dense brackish to saline bedrock groundwaters may discharge to surface under favourable hydrogeological conditions such as at the Whiteshell area (Gascoyne, 2004) and the enigmatic saline “moose licks” near Thunder Bay, Ontario (Frape et al., 1984a).

The transition zone between the hypersaline Shield brine at depth and the upper zone of fresh groundwater will vary to some degree between sites on the Shield depending on local hydrogeological conditions. In mining areas, where hydraulic depressurization promotes the downward flow of fresh water and its mixing with brine, the boundary between the two is likely to be rather gradational. The boundary may be sharper in undisturbed areas due to the significant density contrast between the two water masses, although some mixing will always be present due to diffusion. However, because the frequency of open fractures decreases with depth, the zone of active groundwater circulation in the Shield is typically limited to depths of less than about 400 m: below this, the probability that a borehole will encounter a fracture zone capable of yielding a sufficient water supply of potable quality rapidly diminishes.

Table 11.2 lists selected representative chemical analyses for groundwaters from several of the AECL research areas and selected Shield mines along with the predominant rock type at each site (Bottomley et al., 1984, 1990, 1999; Cramer and Smellie, 1994; Benlahcen, 1996; Boutin, 2001; Benlahcen, 2003; Gascoyne, 2004; Also shown are "reference" Shield groundwater chemical compositions based on average concentrations from hydrogeochemical datasets for AECL research areas and mine waters at Sudbury, Thompson, and Yellowknife (McMurry, 2004). Reference groundwater CS-50 in Table 11.2 is the average of chemical analyses for groundwater samples collected at these sites from the depth range of 0 to 100 m (average 50 m), while reference groundwater CS-750 is the average of chemical analyses for groundwater samples collected from the depth range of 500 to 1,000 m (average 750 m). It should be noted, however, that the range in concentration for certain parameters in both reference groundwaters may be very large. For example, the range in sulphate concentrations in samples used for CS-50 is about two and a half orders of magnitude (McMurry, 2004). Nevertheless, it can be concluded from Table 11.2 that the probability of encountering potable groundwater in the upper 100 m of the bedrock is very good but below a depth of 500 m the water is unlikely to be suitable for human consumption. The Cigar Lake groundwater analysis (Table 11.2) reveals that very good water quality can still be present at depth in the Shield under certain favourable hydrogeochemical conditions. At Cigar Lake, bedrock is comprised of the Proterozoic Athabasca Basin sandstone which consists largely of chemically resistant quartz, resulting in very low concentrations of total dissolved solids even at depths of 400 m. Notwithstanding these uncertainties, Figure 11.6 shows schematically how the major ion chemistry of groundwater typically changes in the Shield with increasing depth. It is important to note, however, that the chemical compositions shown, and the actual depths of the boundaries between the different compositional types, are controlled largely by site-specific dynamics of mixing between fresh meteoric recharge, glacial meltwater and deep Shield brine components.

11.4.3 Isotopes in groundwater

The recharge origin and age of groundwaters found within the Canadian Shield range from very local freshwater sources and seasonal recharge to high-salinity brines recharged up to hundreds of millions of years ago. The former are mostly associated with the clastic surficial aquifers of glacial outwash sands and gravels found throughout the Shield. They are also found in the

TABLE 11.2 REPRESENTATIVE CHEMICAL ANALYSES OF SHIELD BEDROCK GROUNDWATERS FROM AECL RESEARCH AREAS AND SELECTED MINE SITES. REFERENCE “AVERAGE” COMPOSITIONS FOR SHALLOW AND DEEP SHIELD GROUNDWATERS ARE ALSO SHOWN

LOCATION AND DEPTH	CA	MG	NA	K	HCO^3	SO^4	CL	PH
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	
Mine Niobec, Saguenay, Que.[1] (Carbonatite intrusion, Grenville)								
NiAB10, 210m	1000	370	3900	70	37	754.8	9700	6.7
NiAB30, 300m	1900	410	8500	360	46.4	120.4	19800	6.6
Mine Joe Mann, Chibougamau, Que.[2] (Archean greenstone belt)								
JM417, 128m	142	52	8	5.6	207	345	6.8	7.5
JM18100, 546m	82	20	82	2	122	117	410	7.5
Mine Bouchard-Hébert (Mobrun), Abitibi, Que.[3] (Archean greenstone belt)								
BH-2, 300m	111	20	125	3.3	92[a]	394	56	7.6
BH-7, 550m	590	31	150	1.4	38 [a]	1614	39.6	7.3
Chalk River, Ont.[4] (Grenville gneiss)								
CR13, 86m	17.0	2.8	36	0.4	158	8.0	1.0	8.5
CR13, 341m	35.1	2.4	209	1.1	50.1	53.8	325	7.9
Perth, Ont.[5] (Grenville gneiss)								
TW3, 32m	64	19	12	5.4	270	39	5.0	8.1
East Bull Lake, Ont.[6] (Archean gabbro-anorthosite)								
P1, 32–53m	1.9	0.1	53	0.4	139	6.7	0.6	9.1
EBL2, 111–126m	3.0	1.0	66	2.4	172	3.4	6.8	10.1
Whiteshell, Man.[7] (Archean granite)								
WD2-72-5, 65m	28.0	5.5	59.0	2.6	255	11.7	1.6	7.3
WB2-20-12, 725m	10540	34.2	4360	14.3	20	835	27900	8.6
Thompson T3 mine, Man.[8] (Proterozoic gneiss)								
B93035, 1067m	13195	408	7932	349	17	307	36849	6.4
Cigar Lake mine, Sask.[9] (Proterozoic Athabasca sandstone)								
B139, 439–443m	3.7	2.1	2.7	1.1	34.1	3.3	0.2	6.5
Yellowknife Con mine, N.W.T.[10] (Archean metagabbro)								
B8906, 1067m	194	75	995	7.8	256	113	388	6.9
B7126, 1616m	73789	198	30670	278	28	247	174582	6.9
“Reference” groundwater[11]								
CS-50 (0–100m)	40	11	75	3	235	50	40	7.9
CS-750 (500–1000m)	4110	60	3080	22	30	560	11925	8.0

[a] Total alkalinity (mg/L of $CaCO_3$)

[1] Benlahcen, 1996; [2] Boutin, 2001; [3] Benlahcen, 2003; [4] Bottomley et al., 1984; [5] Bottomley (unpublished data); [6] Bottomley et al., 1990; [7] Gascoyne, 2004; [8] Bottomley et al., 2003; [9] Cramer and Smellie, 1994; [10] Bottomley et al., 1999; [11] McMurry, 2004.

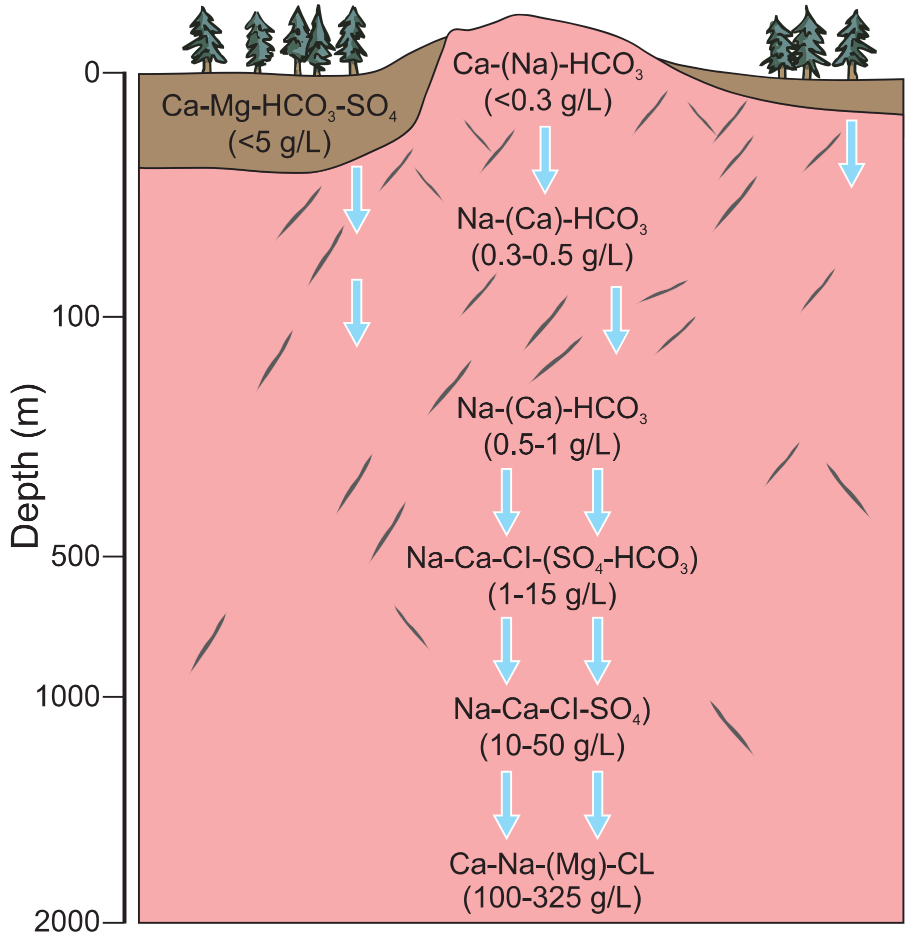


Figure 11.6 Schematic diagram showing typical hydrogeochemical variations with depth in the Shield (modified after Gascoyne, 2004).

shallow fractured bedrock. The brines, by contrast, are of scientific interest with little bearing on water resources; they do represent an end-member in a continuum of ages and origins. Research on the origin of groundwaters in the Canadian Shield is largely based on the use of naturally occurring stable isotope tracers. The $\delta^{18}O$ and δD signature of most groundwaters is established during precipitation and recharge. Here, the temperature-driven process of rain-out acts to enrich the rainfall in warmer climates with the heavy isotopes, ^{18}O and D. Lower-temperature precipitation in higher latitude, higher altitude and more continental regions then become more depleted in these isotopes. The correlation between temperature and the mean annual $\delta^{18}O$ in precipitation for central Canada can be approximated by $\delta^{18}O = 0.5\ T_{annual} - 15‰$ (based on Fritz et al., 1987).

Figure 11.7 provides the distribution of $\delta^{18}O$ in Canadian Shield groundwaters, showing gradients toward the higher latitudes and toward the continental interior. Groundwater data used in the construction of this diagram contains measurable tritium, signifying that groundwater is part of the active meteorological system. Tritium, ^3H or T, is a short-lived radioisotope of hydrogen, H. It is produced in the stratosphere by cosmic ray impacts on N and is transferred to the troposphere where it enters the hydrological cycle. Natural concentrations in precipitation over the Canadian Shield range from about 15 to 25 TU (1 TU or tritium unit represents a concentration of T per 10^{18} H in water). T was also produced during the era of atmospheric testing of hydrogen bombs, from 1952 culminating in the 1963 "bomb peak" in precipitation where this anthropogenic source reached over 4,000 TU in the northern hemisphere. While of little radiological hazard, the tritium peak in groundwater provides a time horizon for dating.

The recharge origin and age of groundwaters in the surficial aquifers have been mostly studied at sites near the southern margin of the Canadian

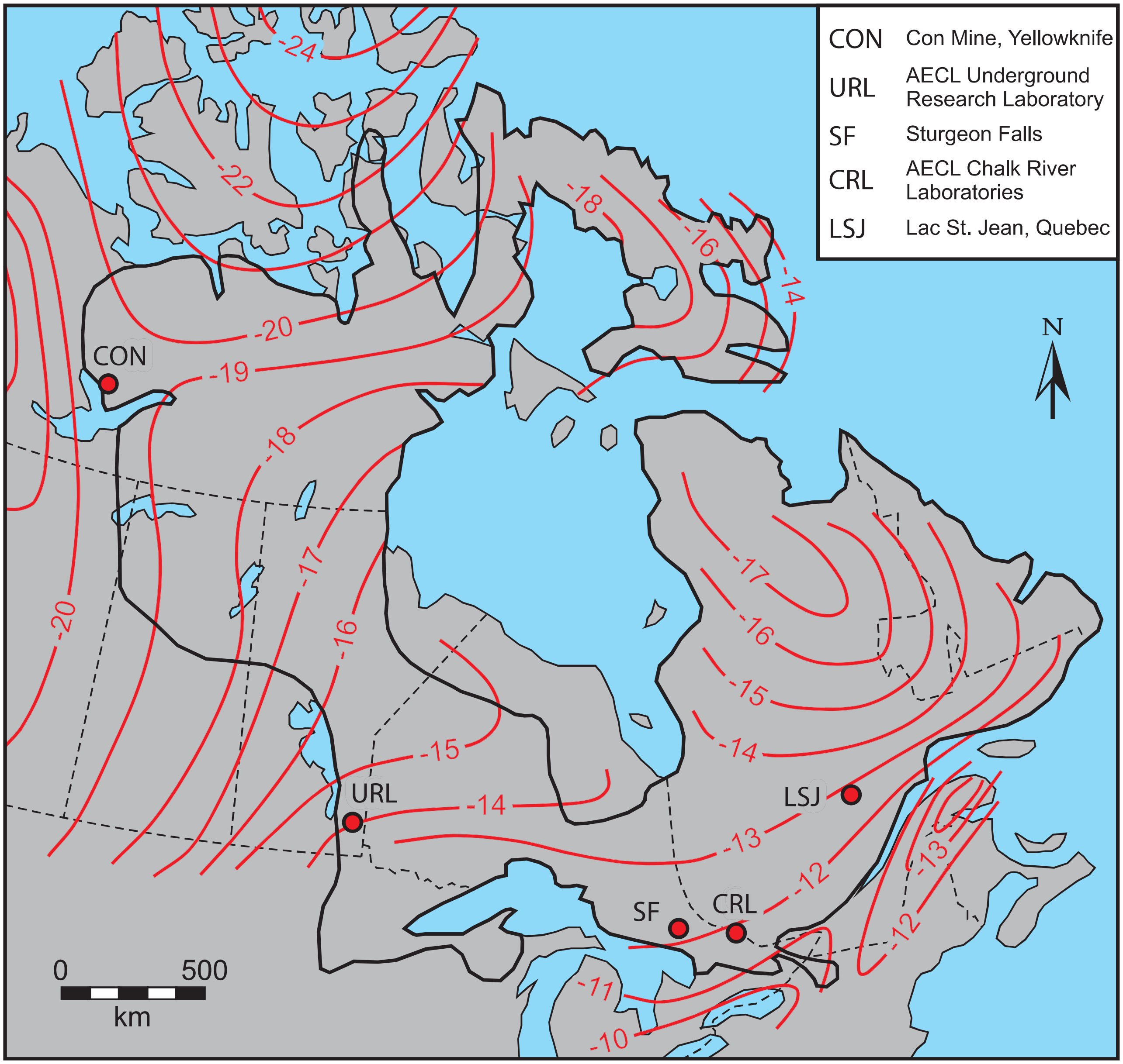


Figure 11.7 Stable isotope content ($\delta^{18}O$) of groundwater in the Canadian Shield. Isopleths (‰) based on data for tritium-bearing groundwaters that are considered to represent modern recharge (modified from a countrywide diagram in Clark and Fritz, 1997).

Shield. The shallow nature of these aquifers and tendency toward higher permeability due to the crystalline bedrock origin of the glacial material favours active recharge of precipitation although older groundwaters can be preserved. Most such groundwaters have isotope signatures that demonstrate local recharge, and most are tritium-bearing. Tritium-free groundwaters may be preserved under conditions of low natural gradients in deeper parts of surficial aquifers.

11.4.3.1 Isotopes in groundwater from surficial aquifers

The Sturgeon Falls aquifer near North Bay Ontario, studied by Robertson and Cherry (1989) and Renaud et al. (2005), comprises some

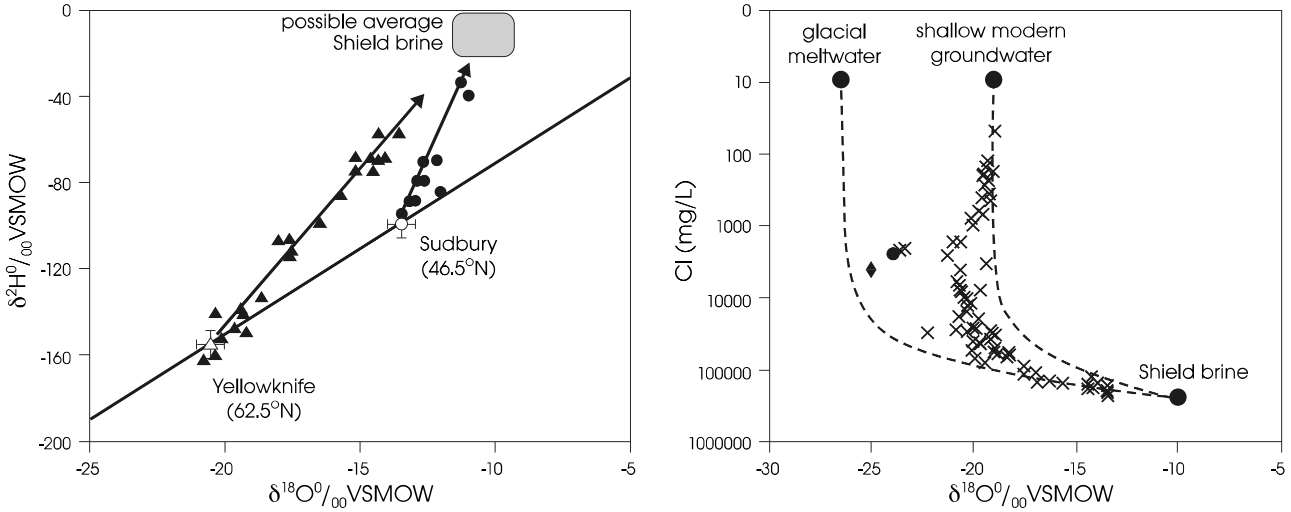


Figure 11.8 Isotope signature for Shield groundwaters. Left: δ^{18}O - δD diagram for Canadian Shield brines (closed symbols) with Ca-Cl salinities reaching 300 g/L. Sudbury (south) data from Frape and Fritz (1982), Yellowknife data from Frape et al. (1984b) and Clark et al. (2000). The characteristic strong deuterium enrichment over local meteoric waters (open symbols) is due to exchange reactions during hydration of primary silicate minerals. Right: glacial meltwaters in the Canadian Shield at Yellowknife (Clark et al., 2000), mixing with meteoric groundwaters in the shallow subsurface and with Shield brines up to 1600 m depth

23m of glaciolacustrine silty sand with hydraulic conductivity, $K = 2 \times 10^{-4}$ cm/s to 3×10^{-5} cm/s, underlain by 6 m of clayey silt and a basal sand aquifer with $K = 6 \times 10^{-3}$ cm/s. Water table contours demonstrate recharge by direct infiltration and downward movement. The thermonuclear tritium peak is preserved in these shallow groundwaters and constrains their age to the past 50 years. By contrast, the groundwaters in the underlying higher-permeability aquifer are tritium-free and so recharged prior to 1957. They also have a δ^{18}O signature of –11.5‰, which is about 1‰ depleted from the shallow, tritiated groundwaters, signifying a more regional recharge origin at a higher elevation. This example demonstrates that even within a local clastic sediment package on the Shield, groundwaters of differing age exist with local to regional recharge origin.

During deglaciation, some 8,000 to 12,000 years ago, peripheral regions of the ice-covered Shield were bounded by large glacial lakes and inland seas. As isostatic rebound reclaimed these areas of the Shield, fields of sand dunes developed by aeolian transport of the emerging landscape, and are particularly well developed along the eastern Lake Winnipeg region, the Ottawa River valley and in the Lake Saint-Jean region of Quebec. Eventually stabilized by vegetation, these fossil sand dunes now host actively circulating groundwater resources. Groundwater recharge and circulation in one such aquifer near the AECL Chalk River Laboratories (CRL) has been studied by Alverado et al. (2002). Infiltration is rapid into these fine sands and interstratified sand and silt sediments, with little to no surface runoff. The high permeability of this well-sorted material cannot sustain a high water table, and so the unsaturated zone can exceed 10 m in thickness. Groundwater flow rates on the order of 0.3 to 0.5 m/day have been measured by tritium-^{3}He dating (Noack, 1995). Discharge into a wetland along the aquifer boundary is typical of the Canadian Shield, where the considerably lower hydraulic conductivity of bedrock precludes regional drainage from surficial aquifers.

11.4.3.2 Isotopes in groundwater from crystalline aquifers

A few studies of groundwaters in the crystalline bedrock of the Canadian Shield have used environmental isotopes to identify recharge origin as well as mean circulation times. Commercial mines have provided valuable insights into the occurrence and movement of groundwater within the Canadian Shield. The access provided by drifts and exploration boreholes allows not only high-quality samples for isotope and geochemical investigations, but a visual presentation of fracture and fault architecture. Research over the past decades has revealed that below a lens of recently recharged fresh water lie high TDS brines with Ca-Cl salinities approaching 300 g/L (Frape et al., 1984b). Extensive interaction with silicates has altered the isotope signature of these brines, giving them a characteristic enrichment in D (Figure 11.8; left diagram).

The Con Mine in Yellowknife is an example of where over 25 years of studies have deconvolved a complex system of mixing between three different groundwaters (Clark et al., 2000), which seems typical of Shield groundwaters elsewhere. The deep subsurface (500 m to 1600 m) hosts an ancient brine (δ^{18}O value of approximately –10‰) that infiltrated millions of years ago (based on ^{129}I measurements; Bottomley et al., 2002) from an overlying marine evaporite basin (Bottomley et al., 1994). Open faults and fractures connected to the surface have allowed modern low-salinity groundwaters (δ^{18}O value of –19‰) to circulate within the upper 100 to 200 m of bedrock, although depressurization from mining now allows penetration of tritium-bearing meteoric waters down to a depth of some 1,600 m. Interestingly, the intermediate depths between the brines and fresh meteoric waters host a glacial meltwater component identified by a trend toward a glacial δ^{18}O value of about –28‰ (Figure 11.8; right diagram). Modelling shows that the high hydraulic gradient below the margin of the retreating Laurentide ice sheet circulates water to a much greater depth (hundreds of metres through fracture rock with ~1% porosity) than the 100 to 200 m depth of Holocene precipitation. The low-salinity groundwaters at the Con Mine plot very close to the local meteoric water line constructed from monthly precipitation data collected over a multiyear period. This suggests that recharge through the fractured surface of the crystalline bedrock is direct and unaffected by partial evaporation.

The Sudbury Basin provides an additional perspective on the recharge of groundwater in the Canadian Shield. Frape and Fritz (1982) found that the ubiquitous Shield brines have a common isotopic signature, generated by equilibration with the crystalline host rock at moderate to low temperature (Frape et al., 1984b). Groundwater from a range of depths shows dilution along mixing lines defined by the isotopic composition of local meteoric waters and the common brine, with clear regional distinctions. For example, even within the Sudbury Basin, the trend for groundwater from the northern mining camps is more depleted than that for the southern rim mines. This demonstrates the occurrence of local groundwater penetrating to depths of several hundred metres under the influence of the steep vertical gradients generated by mining activities.

AECL constructed the 450 m deep Underground Research Laboratory (URL) near Pinawa, on the southern Manitoba-Ontario border to investigate groundwater dynamics within the Canadian Shield. Research was undertaken on groundwater sampled from both surface-spudded and subsurface boreholes down to 1000 m (Gascoyne, 2004).

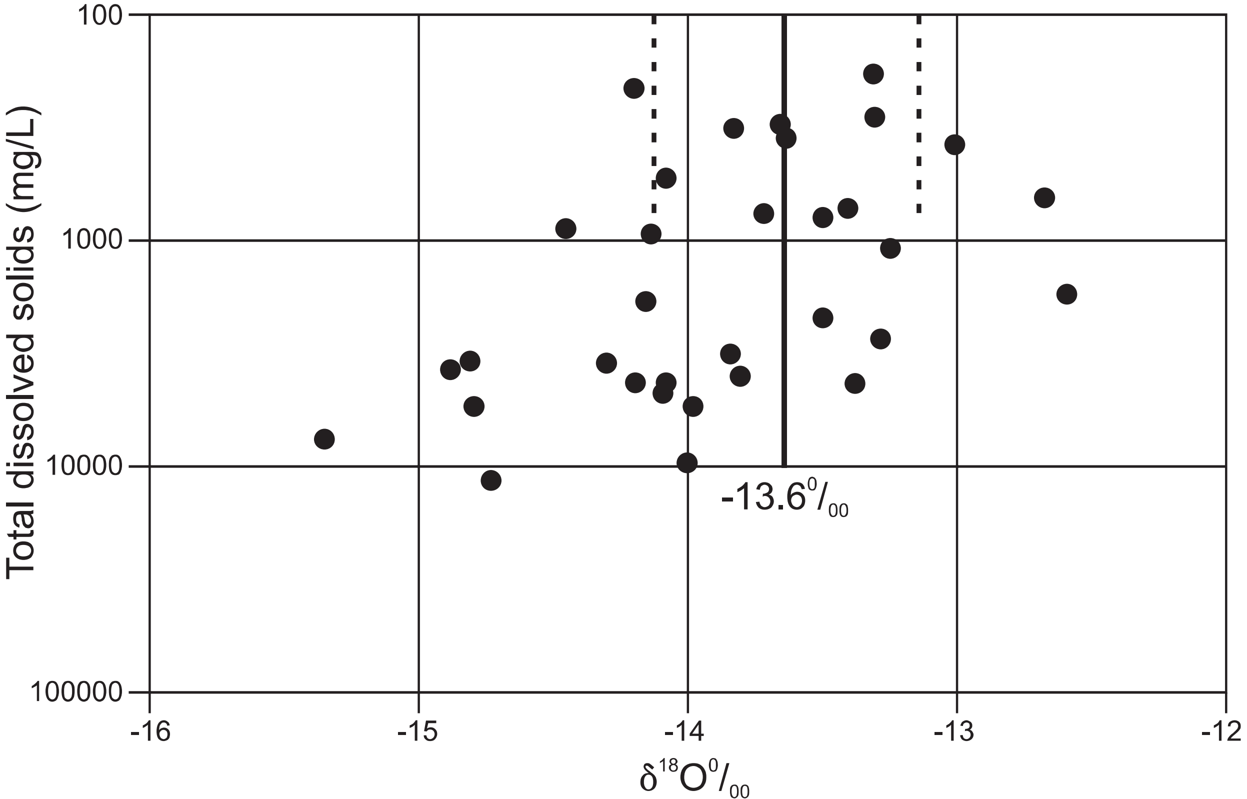


Figure 11.9 $\delta^{18}O$ composition of shallow Canadian Shield groundwaters around Saguenay-Lac St. Jean, Quebec, and trends with increasing solute concentration (modified from Walter et al., 2006). Low-salinity groundwaters are used to provide an estimate for the mean annual $\delta^{18}O$ of local meteoric waters (–13.6 ±0.49‰). Higher-salinity groundwaters show a depletion trend attributed to a glacial meltwater signal resident in the subsurface since the late Pleistocene.

They found that shallow groundwater in the upper 200 m fracture network is dilute (300 mg/L) Ca-Na-HCO_3 waters. Their $\delta^{18}O$ value of –13.5‰ is consistent with modern waters for that geographic region (Figure 11.7) and the groundwater contained modern tritium levels. Like the Con Mine setting, Gascoyne (2004) found that groundwater between 200 and 400 m in the Pinawa URL contained a glacial meltwater component with lighter $\delta^{18}O$ values. Groundwaters at greater than 500 m depth have a Ca-Cl geochemical facies and carry the signature deuterium enrichment found in Shield brines.

Not all Shield groundwater data comes from mines: other studies have used domestic wells. In the region of Lake Saint-Jean in Quebec, Walter et al. (2006) characterized the isotope geochemistry of groundwater in the upper 100 m of the crystalline Grenville province with geochemical facies varying between Na-(Ca)-HCO_3 and Na-Ca-Cl. The Cl– facies is attributed to leaching from marine clay pore waters preserved following deposition from the early Holocene Laflamme Sea. The mean isotope value for the low-salinity groundwaters (TDS < 1000 mg/L) is –13.8 ±0.49‰ (Figure 11.9). This value is close to that anticipated for this geographic region from Figure 11.7, with minor depletion perhaps reflecting recharge in the elevated topography surrounding the Lake Saint-Jean Basin. Higher-salinity groundwaters in these crystalline rocks, by contrast, show a depletion trend to values below –15‰. This depletion trend is attributed to a glacial meltwater component incorporated during deglaciation at about 12 ka before present. Walter et al. (2006) found that most groundwaters recharge with little to no evaporation.

11.4.3.3 Summary on isotopes studies

The growing number of isotope studies of groundwater in the Canadian Shield is developing an improving picture of their recharge origin and mechanisms. Surficial aquifers are composed of glacially derived sands and gravels in eskers, outwash fans and dunes. Most are phreatic, and stable isotopes show that they host groundwater recharged by local, direct infiltration with little to no evaporative loss. Tritium levels indicate active circulation with residence times on the order of decades. Such aquifers can be sensitive to inter-annual variability in precipitation and, of course, to land-use impacts on both recharge and water quality.

The crystalline basement outcrops over much of the Canadian Shield, present a fractured and faulted carapace that offers locally good aquifer potential. Discontinuities extending to hundreds of metres in depth allow active circulation of low-salinity meteoric waters. Stable isotopes show such groundwater originates through direct recharge at higher elevations within the local catchments. However, active circulation is restricted typically to 100 to 200 metres depth due to the subdued topography available as the hydraulic drive. No thermal springs (which would indicate circulation to depths of a kilometre or more as observed in the Cordillera) have been identified in the Shield.

Shield groundwater below about 100 m is found to include a remnant glacial meltwater component recharged beneath the retreating margin of the Laurentide ice sheet at the end of the Pleistocene period, and evident from a characteristic depletion in both ^{18}O and D. This ubiquitous meltwater lens has been preserved during the Holocene by the diminished hydraulic gradients present beneath the Shield's subdued topography.

The deepest permeable discontinuities within the Canadian Shield host Ca-Cl brines with salinities up to 300 g/L. Stable isotopes and geochemical constraints suggest an origin in some regions by infiltration of highly evaporated Paleozoic marine brine. Other brines may have evolved through leaching of salinity intrinsic to the rocks themselves. In all cases, extensive rock-water interaction and the ingrowth of radiogenic isotopes indicate that the Shield brines are of geological age.

11.4.4 Groundwater and mining

Mining constitutes the most important human activity in many areas of the Precambrian Shield. Groundwater plays an important role in many aspects of that industry, from the mineral exploration stage to mine closure.

11.4.4.1 Groundwater as a mineral exploration tool

Groundwater geochemistry surveys conducted for mineral exploration (Lalonde and Chouinard, 1983) have identified zones of potential sources of metal such as Cu, Pb, Zn, Ni, Co, Mn, Ag, in a number of regions in the Canadian Shield in Quebec (Lalonde et al., 1980; Lalonde and Pelletier, 1983; Pelletier, 1986; Kirouac, 1987). Hydrogeochemistry has also been proposed as an exploration tool for gold (Fréchette, 1986) and uranium mineralization (Otis, 1988). Considering the flow regime (e.g., recharge or discharge) at the sampling points, however, would improve considerably the usefulness of such studies.

11.4.4.2 Groundwater withdrawal for mining

The quantity of groundwater extracted for mine dewatering is relatively little (Charron, 1967) considering the large quantity of drifts and other excavations, all of which constitute groundwater drains often installed down to a depth of a few thousands metres. Fault zones, on the other hand, often yield large quantities of water into mines. This localized high water flow is favoured by those mine sites in the Shield which are often located under lakes and near major structural discontinuities. The hydrogeological functions of structural discontinuities become more important where these structures are in contact with a surface water body or a permeable surficial deposit. Gneissic rocks and greenstone belts are often cut by shear zones parallel to the foliation (Benson et al., 1974), which could make them very permeable down to a depth of about 600 m (Raven and Gale, 1986).

Local hydrogeological data, particularly from mine sites, is available only in the most populated areas of the Precambrian Shield: these are located in the Grenville Province and in the southern part of the Superior geological Provinces. Even in these populated areas, however, little use is made of groundwater, partly due to surface water abundance. Most of the water wells in the bedrock are used for individual household or for small communities.

Rouleau et al. (1999) compiled groundwater withdrawal data for the year 1993 in the Quebec part of the Abitibi geological Subprovince (Table 11.3). This area is part of the Abitibi Plains ecoregion, a subdivision of the Boreal Shield Ecozone (Environment Canada, 2005) that presents the highest number of mining sites of all Canada's ecoregions.(NRCan, 2003). In this territory, which covers about 90,000 km^2 of the Shield in Quebec, total groundwater withdrawn from the bedrock at the 35 mines amounts to about 57,000 m^3/day. This is roughly equivalent to the groundwater withdrawn by the 150,000 inhabitants of this mining region for all other usages, including drinking water, pisciculture and other industries. Moreover, the groundwater withdrawal not related to mining is mostly from granular Quaternary deposits overlying the bedrock, whereas mine dewatering takes place mostly within the bedrock.

11.4.4.3 Coupling of hydrogeological and geomechanical processes

Excavation in a rock mass disturbs the geomechanical stress field, which in turn affects the hydrogeological properties (Rouleau et al., 1999a). However, field data on rock mass permeability around excavations suggest that other processes, such as groundwater degassing and dissolution-precipitation along fracture planes, may also affect the hydrogeological properties of a rock mass around drained excavations (Benlahcen et al., 2001; Benlahcen, 2003).

Groundwater drainage in mines often produces an important drawdown cone. The presence of air in this enlarged unsaturated volume of rock enhances a number of geochemical reactions affecting the groundwater. In a rock mass with a high content in sulphide minerals, such reactions often result in an increase in the acidity and in sulphate concentration in the infiltrating groundwater (Benlahcen, 1996; Rouleau et al., 1995; Benlahcen et al., 1999).

11.4.4.4 Contamination from mine tailings

Tailings and waste rock associated with mining are likely the largest potential sources of contamination

TABLE 11.3 GROUNDWATER WITHDRAWAL IN THE QUEBEC ABITIBI REGION IN 1993 (FROM ROULEAU ET AL., 1999)

PURPOSE	WITHDRAWAL (M^3/YEAR)
Mine dewatering (ca. 35 mine sites)	57,000
Drinking water distribution system	28,000
Pisciculture	16,000
Others: bottled water, private wells, other industries, etc.	6,000
TOTAL	**107,000**

for Shield groundwater. In particular, base metal and gold mines across the Shield, and uranium mines in the Elliot Lake area of Ontario and northern Saskatchewan, have subaerially disposed massive volumes of these materials. Where they contain significant amounts of residual sulphides and arsenides, oxidation of these minerals frequently results in acid mine generation and the leaching of toxic metals, such as arsenic, nickel, uranium and radium-226, into surface waters and groundwaters (Morin et al., 1982). Bussière (2007) describes a number of innovative methods being developed and field-tested to reduce environmental risks associated with tailings storage: these include densified tailings, environmental desulphurization, various cover materials (Germain et al., 2004), and co-disposal of tailings and waste rock. Even if many aspects need to be optimized, these approaches can be considered today as interesting alternatives to conventional tailings management. Toxic materials have been disposed of in underground mine workings, posing a significant risk to the environment because of their high solubility and mobility in groundwater flow systems. For example, about 237,000 tonnes of arsenic trioxide dust was disposed in the now abandoned Giant Mine in Yellowknife, Northwest Territories, and is now leaching into infiltrating groundwater resulting in arsenic concentrations as high as 4 g/L (Clark and Raven, 2004).

11.4.5 Sparse data on well yield, hydraulic properties

Although intact crystalline rock has a very low hydraulic conductivity (typically less than 10^{-9} m/s), fractured bedrock may be up to 5 orders of magnitude more conductive (Raven et al., 1987; Gascoyne, 2004). Fortunately, the Canadian Shield is typically fractured to depths of 300 to 400 m so the probability of a borehole encountering a sufficient groundwater supply for domestic water well is often very good.

In his regional study of groundwater resources within a strip of territory about 25 to 50 km wide on the northern side of the St. Lawrence River, between Montreal and Quebec City, McCormack (1983) identified about 180 water wells supplying a distribution system (or an industry). Twenty of these wells were drilled in the Precambrian bedrock (Grenville Province); the other wells were pumping water either from overlying sedimentary units of the St. Lawrence Lowlands, or from granular surficial deposits. McCormack found that water wells in the Precambrian bedrock generally yield less than 3 m^3/hr and are used for small communities with less than 500 people. Water wells with the highest yields in the bedrock are generally located in areas overlain by a significant layer of permeable sand or gravel, insuring a good groundwater recharge.

Singer and Cheng (2002) compiled a number of water well parameters for Northern Ontario using data obtained from Ontario's Water Well Information System (WWIS, Mantha, 1988). They distinguished data for wells in the Precambrian Shield (10,022 wells), in the Paleozoic sedimentary

TABLE 11.4 COMPILATION OF ROCK MAS HYDRAULIC CONDUCTIVITY VALUES REPORTED IN THE LITERATURE FOR THE CANADIAN SHIELD (FROM LEMIEUX ET AL., 2008B)

DEPTH	MEDIUM	HYDRAULIC CONDUCTIVITY K (M/YEAR)	POROSITY	REFERENCES[a]
Shallow (<500 m)	Matrix	$10^{-5} - 10^{0}$		3, 4
	Fracture	$10^{-3} - 10^{3}$	0.001 - 0.042	2, 3, 4
	Bulk	$10^{-1} - 10^{2}$	0.027	1, 5, 6, 7, 8
Deep (>500 m)	Matrix	$10^{-6} - 10^{-4}$		4
	Fracture	$10^{0} - 10^{4}$		4
	Bulk	10^{-2}		1

[a] The references are as follows: 1 is Raven et al. (1987), 2 is Raven (1986), 3 is Farvolden et al. (1988), 4 is Stevenson et al. (1996), 5 is Frost and Everitt (1997), 6 is Kuchling et al. (2000), 7 is Raven and Gale (1986), and 8 is Frost (1997).

rock cover (1,944 wells), and in the overburden (2,737 wells). A cumulative plot of the specific capacity of these wells on a logarithmic probability paper (Figure 11.10) shows approximately a straight line for each of these hydrogeological units, suggesting a log-normal distribution of the data. In this case, the 50% probability level corresponds to the geometric mean and to the most probable specific capacity value for a given hydrogeological unit. The geometric mean of specific capacity is 5.0 L/min/m (0.3 m^3/h/m) for the overburden wells, 2.5 L/min/m (0.15 m^3/h/m) for the wells completed in the Paleozoic rocks, and 1.9 L/min/m (0.114 m^3/h/m) for the wells completed in the Precambrian rocks. This geometric mean value of specific capacity for the wells completed in the Precambrian rocks is lower than all of the mean values given in Table 11.1 for Quebec; this is likely due in part to the fact that the geometric mean is generally lower than the arithmetic mean.

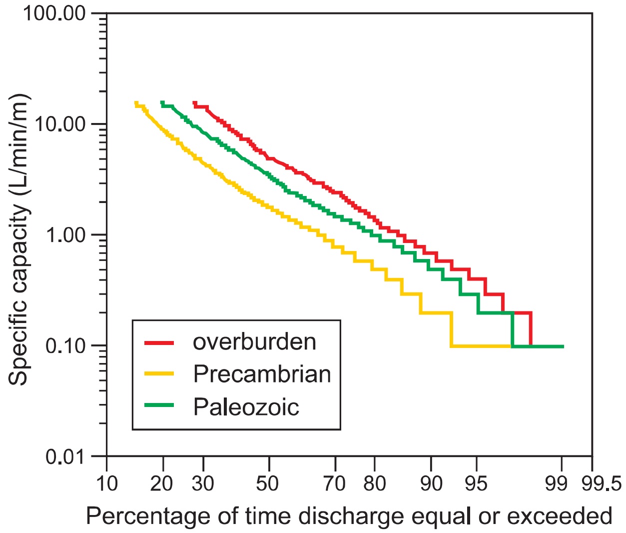


Figure 11.10 Specific capacity of wells completed in Precambrian, Paleozoic, and Quaternary formations in Northern Ontario (from Singer and Cheng, 2002).

Most of the detailed studies on the hydrogeology and the hydraulic properties of the bedrock in the Canadian Shield are related to the geological storage of radioactive nuclear wastes deep within crystalline rocks. These studies were mainly conducted in the Chalk River and Atikokan areas in Ontario, and at the Underground Research Laboratory (URL) near Pinawa, Manitoba. Lemieux et al. (2008b) presented results of a compilation of the hydraulic property values measured in the Canadian Shield and reported in the literature. Most of the values reported were derived from studies related to nuclear waste disposal. The objective of these studies was to examine the suitability of rocks of low permeability to isolate radionuclides for a sufficiently long time so as not to pose a threat to human health should a release occur from an engineered repository located at depth. Therefore, plutons and batholiths (intrusive bodies) which are less fractured than the other rocks of the Shield were primarily investigated. The values presented in Table 11.4 are thus biased by low hydraulic conductivity values.

11.5 CASE STUDIES AND SPECIFIC ISSUES

11.5.1 Groundwater vulnerability

Overburden aquifers on the Shield are often covered by relatively thin, fine-grained, low-permeability materials and so are, therefore, susceptible to contamination from the same point and non-point sources of potential contamination that threaten the quality of overburden groundwater in other hydrogeological regions in Canada. Bedrock groundwater on the Shield is also highly susceptible to contamination because protective overburden deposits are frequently thin or absent. Fracturing in the rock is capable of rapidly transporting near-surface contaminants to depths typically penetrated by water wells.

11.5.2 Contamination from natural sources

In certain settings granitic Shield rocks may also be a significant natural source of uranium and radium contamination for bedrock wells (Gascoyne, 1989). Betcher et al. (1988) reported that about 60% of the bedrock wells that they sampled in southeastern Manitoba had U concentrations in excess of the Canadian Drinking Water Guideline concentration of 20 µg/L, with maximum concentrations of about 2000 µg/L. They attributed this to the oxidation of reduced uranium that is often present in fracture minerals in this area. A number of Ontario and Quebec communities located on the Precambrian Shield have also shown elevated uranium concentrations in drinking water obtained from groundwater sources (Health Canada, 2006). Examples are water wells near the cities of Tweed and Dryden in Ontario, as well as a few wells in the Quebec regions of Laurentides, Outaouais, and Abitibi-Temiscamingue. Other radioactive elements, such as radium-226 and radium-228 have also shown concentrations exceeding 1.0 Bq/L, in some of these wells, particularly in the community of Kitigan Zibi in the Outaouais region. There appeared to be little correlation between the uranium and radium exceedance.

In the Abitibi region of Quebec, a few water wells in the bedrock show arsenic levels slightly exceeding the recommended limit of 0.025 mg/L (Poissant, 1997). In the Lake Saint-Jean area, fluoride has been observed exceeding the recommended limit of 1.5 mg/L in a number of wells (Simard and Des Rosiers, 1979; Walter et al., 2006, 2011). Less commonly, mafic Shield rocks may be a source of metal contamination for wells. About 50% of the wells sampled in the East Bull Lake gabbro-anorthosite pluton contained chromium concentrations above the guideline value of 50 µg/L. This is likely due to the weathering of Cr-bearing minerals such as pyroxenes, olivine and chromite present in the host gabbro (Raven et al., 1987).

11.5.3 Man-made contamination

As mentioned above, groundwater contamination from mine tailings is an important issue in mining camps located in the Canadian Shield. Other frequent sources of contamination include individual septic systems, municipal waste disposal sites, industrial waste sites related to metallurgical and forest industries, leakage of petroleum products from reservoirs, and infiltration of deicing agents used at airports.

11.5.4 Comparisons with other Shield areas in the world

Precambrian Shield is found in all of the continents of the World (Derry, 1980; Eriksson et al., 2004), under a wide variety of climatic and socio-economic conditions. The importance of groundwater in the Shield areas, as well as the type of interference with human activities varies accordingly: in some areas this groundwater constitutes the sole source of drinking water (Larsson, 1984), in other places, groundwater problems are related to tunnelling or mine excavations, to radioactive waste disposal, or to the extraction of geothermal energy (Gustafson et Krásný, 1994). In other parts of the World, exploration efforts are often required for source water supply in the Precambrian Shield and other bedrock basement regions, making use of a variety of approaches including lineament analysis (Magowe and Carr, 1999; Moore et al., 2002), structural geology and geophysical prospecting (Banks and Robins, 2002; Lipponen, 2006). Similar efforts should provide valuable information on the available groundwater resources in the Canadian Shield.

11.6. CONCLUSIONS

The Canadian Shield covers roughly half of Canada surface area and is constituted of fractured crystalline bedrock, Precambrian in age. The lithologies comprise belts of stratified or banded rocks, that have been metamorphosed and deformed to various degrees, as well as bodies of intrusive and highly metamorphosed rocks. These highly deformed units are overlain locally and unconformably by remnants of stratigraphic units deposited during a number of distinct episodes of sea invasion in the Proterozoic and Paleozoic eras.

These rock types are typically of low porosity, but the presence of discontinuities and fractures, such as joints, dykes, shear and fracture zones, allows for groundwater flow to take place locally, at different scales and down to a depth of a few kilometres. Groundwater is also present in granular aquifers, Quaternary in age, constituted of glaciofluvial deposits, put in place at the end of the last glaciations, and post-glacial deposits (large outwash plains and deltaic systems, particularly along Shield margins).

Hydrogeological data is available at few sites over the Shield region. These include a number of mine locations, as well as research sites for nuclear waste disposal. A general decrease in rock mass permeability with depth has been observed at many sites, as well as an increase in TDS within the groundwater. Mining constitutes the most important human activity in many areas of the Canadian Shield. Groundwater plays an important role in many aspects of that industry, from the mineral exploration stage to mine closure. Groundwater quality is also affected at several sites by tailings and waste rock associated with mining.

In recharge areas on the Shield, groundwater in the upper hundreds of metres in the bedrock is typically fresh with TDS values of up to about 500 mg/L. A gradual downward trend is observed from Ca-HCO_3 toward Na-HCO_3. Hypersaline brines are ubiquitous at depths greater than about 1000 m in the Canadian Shield. These brines are of the (Ca-Na)-Cl type with TDS values up to 300 g/L and are clearly unfit for most uses, particularly human consumption.

Discontinuities that extend to hundreds of metres in depth in the crystalline basement allow active circulation of low-salinity meteoric waters. Stable isotopes show that at higher elevations within the local catchments, groundwater originates through direct recharge. Shield groundwater below about 100 m is found to include a remnant glacial meltwater component recharged beneath the retreating margin of the Laurentide ice sheet at the end of the Pleistocene period, and evident from a characteristic depletion in both ^{18}O and D. Stable isotopes and geochemical constraints suggest that brines present at greater depths originate in some regions by infiltration of highly evaporated Paleozoic marine brine. Others may have evolved through leaching of salinity intrinsic to the rocks themselves. In all cases, extensive rock-water interaction and the ingrowth of radiogenic isotopes indicate that the Shield brines are of geological age.

CANADA'S GROUNDWATER RESOURCES

Compiled and Edited by Alfonso Rivera

Chief Hydrogeologist, Geological Survey of Canada

Fitzhenry & Whiteside

Published in Canada by Fitzhenry & Whiteside, 195 Allstate Parkway, Markham, ON L3R 4T8
Published in the United States by Fitzhenry & Whiteside, 311 Washington Street,
Brighton, Massachusetts 02135

Fitzhenry & Whiteside Limited, 195 Allstate Parkway, Markham, Ontario, L3R 4T8.
www.fitzhenry.ca godwit@fitzhenry.ca
10 9 8 7 6 5 4 3 2 1

Fitzhenry & Whiteside acknowledges with thanks the Canada Council for the Arts,
and the Ontario Arts Council for their support of our publishing program. We acknowledge the financial support
of the Government of Canada through the Canada Book Fund (CBF) for our publishing activities.

Canada Council for the Arts Conseil des Arts du Canada
ONTARIO ARTS COUNCIL
CONSEIL DES ARTS DE L'ONTARIO
50 YEARS OF ONTARIO GOVERNMENT SUPPORT OF THE ARTS
50 ANS DE SOUTIEN DU GOUVERNEMENT DE L'ONTARIO AUX ARTS

The Publisher acknowledges with thanks the work of Cordelia Tang, Kerry Plumley, and Uma Subramanian,
for without their efforts and passion, this book would not be the accessible resource it is.

Library and Archives Canada Cataloguing in Publication
Canada's Groundwater Resources
ISBN 978-1-55455-292-4 (HC)
Data available on file

Publisher Cataloging-in-Publication Data (U.S.)
Canada's Groundwater Resources
ISBN 978-1-55455-292-4 (HC)
Data available on file

Text and cover design by Kerry Designs

Printed and bound in Canada by Friesens Corporation

FSC
www.fsc.org
MIX
Paper from
responsible sources
FSC® C016245

ACKNOWLEDGEMENTS

The conception, preparation and production of a book of this size require time, patience and a lot of work. Approximately 50 people were involved in preparing the 16 chapters. This was a true teamwork of multidisciplinary experts in groundwater sciences who worked hard to integrate the subject matter of their chapters. This book is the result of a combination of expertise and knowledge of 50 Earth scientists from across Canada, seven years of ad hoc research for the purposes of this book (2005–2012), extensive literature research, integration and analysis of widely distributed data (archives from federal, provincial, universities, consultants), and results from the Groundwater Program of the Geological Survey of Canada.

I am grateful to many government, university, and private organizations that allowed these authors to take on this commitment. I thank managers from provincial governments for allowing some of their staff to become coauthors or write full chapters in this book. I thank universities for allowing their professors to spend their time to participate as authors of this book.

I thank the following GSC managers for allowing out time to complete this synthesis of knowledge: Jan Boon, David Boerner and Diane Campbell.

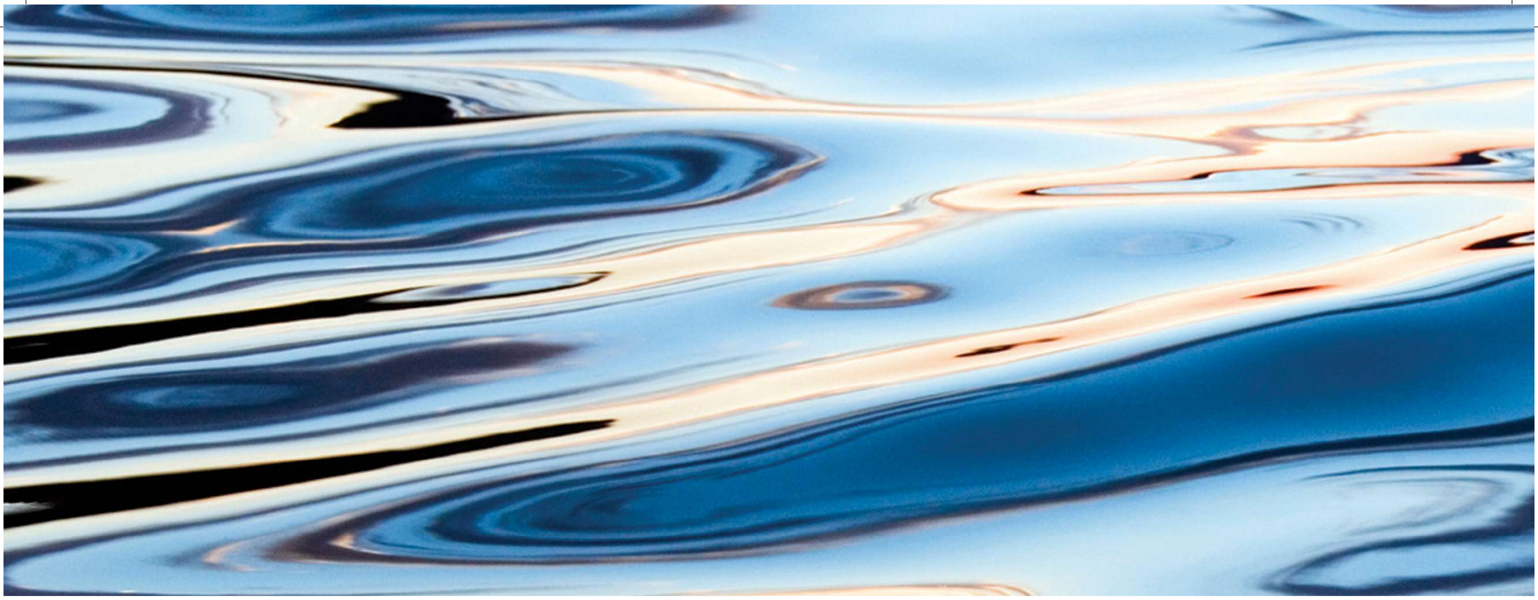
I gratefully acknowledge the following individuals for their excellent peer review. They took the time of their otherwise very busy schedules to review each one of the chapters presented in this book.

Alan Freeze
Marios Sophocleous
Bob Leech
Dick Jackson
R. Allan Dakin
John Gartner
Bob Betcher
John Miller
Denis W. Roy
Rob Matthews
Rick Healy
John Molson
Mazaki Hayashi
Pat Lapcevic
Grant Ferguson
René Therrien
Christie Vodden
Alice Cohen

This book benefited from the artistic talents of Richard Franklin who illustrated most of the figures. I am much indebted to the support of Fitzhenry and Whiteside Limited, in particular to the sterling work of Cordelia Tang, and to Kerry Plumley, who provided the last visual touches and beautiful design to the book.

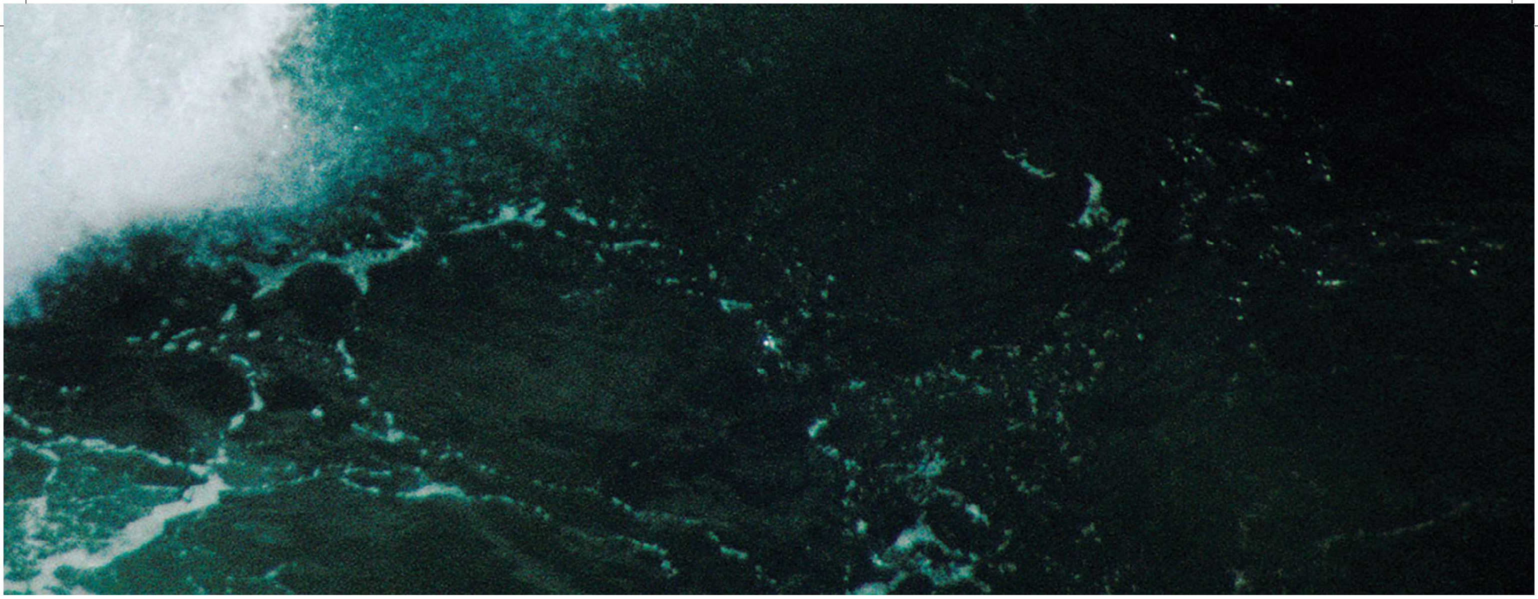
Finally, I wish to thank Heidi Rivera-Schnider for her patience. It was a long process and sometimes I stole private time from us. She never complained and supported me all the way.

Alfonso Rivera
November, 2013



CHAPTER 3 AN APPROACH TO REGIONAL ASSESSMENTS OF GROUNDWATER

CONTENTS



CHAPTER 14 APPALACHIANS 541