Feasibility of Using Geoscientific Criteria for Early Screening of Large Geographic Areas that would be Unsuitable for Safely Hosting a Deep Geological Repository

NWMO TR-2009-13

May 2009

R.E.J. Leech, T.L. Wlodarczyk, S. Davies, M. Lee

AECOM Canada Ltd.

NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Nuclear Waste Management Organization
22 St. Clair Avenue East, 6th Floor
Toronto, Ontario
M4T 2S3
Canada

Tel: 416-934-9814
Web: www.nwmo.ca

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ABSTRACT

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Author(s): R.E.J. Leech, T.L. Wlodarczyk, S. Davies, M. Lee
Company: AECOM Canada Ltd.

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Abstract

The Nuclear Waste Management Organization (NWMO) is responsible for implementing Adaptive Phased Management (APM), Canada's plan for the long-term care of the used nuclear fuel produced by Canada's nuclear reactors. The end point of APM is long-term containment and isolation of used nuclear fuel in a deep geological repository constructed in a suitable rock formation at a depth of approximately 500 m.

One of the major tasks with regard to implementing APM is to collaboratively develop the process that will be used for seeking an informed and willing community to host the deep geological repository. For fairness, the siting process will be focused in the four provinces directly involved in the nuclear fuel cycle: Saskatchewan, Ontario, Québec and New Brunswick. In order to inform the siting process, the NWMO identified the need to review the available geoscientific information in the four nuclear provinces as well as the scope and application of geoscientific factors at early stages in a siting process for a geological repository, based on international guidance, Canadian regulatory requirements and the experience of other countries.

In this context, NWMO retained AECOM Canada Limited (AECOM) to undertake the following: i) review geoscientific factors that need to be considered to ensure the safety of a geological repository; and ii) assess the feasibility and practicality of using proposed geoscientific exclusion criteria for early identification of large geographic areas within the four nuclear provinces that would be unsuitable for safely hosting a deep geological repository without the need for further field investigation.

This report reviewed the geoscientific characteristics of the four nuclear provinces as well as the geoscientific factors would be considered to ensure the safety of a deep geological repository. The safety functions considered include the ability of the repository to safely contain and isolate used nuclear fuel, the long-term stability of the site, the ability to easily characterize the site, the safe construction, operation and closure of the repository and the potential for human intrusion in the long term. The geoscientific characteristics and factors reviewed were grouped under geology, geomechanics, seismicity, hydrogeology, hydrogeochemistry and the potential for economically exploitable natural resources.

The assessment of whether the geoscientific factors considered could be used to exclude large areas of the four nuclear provinces early in the siting process highlighted two main challenges. First, most of the geoscientific factors that need to be considered require site specific information at depth which is typically lacking at early stages in the siting process. The other challenge is associated with the large geographic extent of the four nuclear provinces (3,300,000 km^2) compared to the typical repository scale at which site specific geoscientific information is needed (~6 km^2). After reviewing the international literature and the available geoscientific information from the four provinces, it is concluded that:

It is not practical to exclude large areas of the four nuclear provinces early in the siting process (pre-screening) based on the geoscientific factors identified herein. However, some of the geoscientific factors may be used as exclusion factors at later stages of the site evaluation process as more local scale and site specific information becomes available such as during screening studies, feasibility studies and detailed field investigations.

The findings of this report are consistent with international experience and the outcome of general siting studies conducted in other countries.

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1. INTRODUCTION

1.1 BACKGROUND

The Nuclear Waste Management Organization (NWMO) is responsible for implementing Canada's plan for the long-term care of the used nuclear fuel produced by Canada's nuclear reactors. The plan, approved by the Government of Canada in 2007, is called Adaptive Phased Management (APM). It ensures that the generations that benefit from nuclear energy will have a plan in place for the responsible care of the used fuel arising from electricity production, ensuring long-term safety and security (NWMO, 2005).

APM is both a technical method and a management system and is the approach that emerged following NWMO's three-year national dialogue with citizens, specialists and Aboriginal people. It has as its end-point the long-term containment and isolation of used nuclear fuel in a deep geological repository constructed in a suitable rock formation. The repository to be located at approximately 500 m underground will rely on a multi-barrier system that includes engineered barriers such as copper and steel used fuel containers surrounded by swelling bentonite clay, as well as natural barriers provided by the surrounding host rock to contain and isolate the fuel over the timeframes it remains a hazard. At the surface, the site may occupy a space of about 2 km by 3 km. Underground, the repository will be about 1.8 km^2 in area, depending on the volume and type of used fuel in the repository. It will consist of a series of access and service shafts and a network of horizontal tunnels leading to placement rooms where used nuclear fuel will be safely sealed in stable rock. Once there, the used fuel will be monitored to confirm the safety and performance of the repository until a decision is made to close the facility. Used fuel will remain retrievable until such time as a future society decides on final closure and on the appropriate form and duration of post closure monitoring.

One of the major tasks with regard to implementing APM is to collaboratively develop the process that will be used for seeking an informed and willing host community. For fairness, the siting process will be focussed in the four provinces directly involved in the nuclear fuel cycle: Saskatchewan, Ontario, Québec and New Brunswick.

One consideration in any siting exercise is to assess whether it is possible and practical to exclude large geographic areas prior to or at early stages of siting using exclusion criteria and readily available geoscientific information. To this end, the NWMO identified the need to review the available geoscientific information in the four nuclear provinces as well as the scope and application of proposed geoscientific factors at early stages in a siting process for a geological repository, based on international guidance, Canadian regulatory requirements and the siting experience of other countries.

1.2 OBJECTIVES OF THIS REPORT

Within this context, the NWMO retained AECOM Canada Limited (AECOM) to undertake this review, with the following specific objectives:

- Review geoscientific factors that need to be considered to ensure the safety of a geological repository.

- Assess the feasibility and practicality of using geoscientific exclusion criteria for early identification of large geographic areas within the four nuclear provinces that are unsuitable for safely hosting a deep geological repository without the need for field investigation.

1.3 KEY DEFINITIONS AND ASSUMPTIONS

The following definitions and assumptions have been adopted for the purposes of this report.

- “Geoscientific factors” are those considerations on which a decision or judgement of the geological, hydrogeological, hydrogeochemical, geomechanical and seismic suitability of a site(s) are to be determined.
- “Exclusion criteria” are those specific geoscientific conditions that when applied early in a siting process for a geological repository would result in the elimination of large geographic areas from further consideration.

It has also been assumed that

- “large areas” are those that can be identified and delineated on existing geospatial mapping available from each of the four nuclear provinces and applicable to the geoscientific factor or criterion under consideration. Another consideration is that there should be certainty that excluded areas would not contain potentially suitable local areas.
- “Existing geoscientific information” represents the data and state of knowledge relevant to each of the four nuclear provinces that is currently available from secondary sources (i.e., no new repository related field investigations are needed).

For the purposes of this study, it has been assumed that the safety of a site would be evaluated according to a number of steps[1].

In the first step (screening), a willing community would need to meet a minimum set of initial screening criteria to enter the site evaluation process. Sites within these communities that meet these initial criteria would be identified for further consideration and desktop studies (feasibility studies) are conducted to assess whether the sites are potentially suitable for hosting a deep geological repository. Next, one or more potentially suitable sites would be the subject of a progressively more detailed evaluation involving field studies and safety analyses.

1. NWMO is preparing a proposed site selection process for discussion with Canadians. Geoscientific suitability would contribute to the overall evaluation of a potential site for long term used fuel management.

2. IDENTIFICATION OF GEOSCIENTIFIC FACTORS

2.1 INTERNATIONAL GUIDANCE

The International Atomic Energy Agency (IAEA) has developed a guidance document on the siting of geological repositories for radioactive waste management (IAEA, 1994). This guidance document recommends that important siting factors be identified, potential host rocks and possible siting area be identified in the early planning stages of the process, followed by progressively more detailed investigations and site characterization activities aimed at identifying a preferred site for confirmation. At each stage of the siting process, societal, ecological, and legislative issues would be evaluated and addressed. This type of process relies on the application of "siting criteria" at various levels of detail as the process moves forward, including "geoscientific" criteria.

The geoscientific factors recommended by the IAEA guidance from Safety Series No. 111-G-4.1 include the following:

- ***Geological Setting:*** The geological setting of a repository should be amenable to overall characterization and have geometrical, physical and chemical characteristics that combine to inhibit the movement of radionuclides from the repository to the environment during the time periods of concern.
- ***Future Natural Changes***: The host rock should not be liable to be affected by future geodynamic phenomena (climatic changes, neotectonics, seismicity, volcanism, diapirism {i.e., intrusion of rock caused by buoyancy}) to such an extent that these could unacceptably impair the isolation capability of the overall repository system.
- ***Hydrogeology:*** The hydrogeological characteristics and setting of the geological environment should tend to restrict groundwater flow within the repository and should support safe waste isolation for the required times.
- ***Geochemistry:*** The physicochemical and geochemical characteristics of the geological and hydrogeological environment should tend to limit the release of radionuclides from the repository facility to the accessible environment.
- ***Human Activities:*** The siting of a repository facility should be made with consideration of actual and potential human activities at or near the site. The likelihood that such activities could affect the isolation capability of the repository system and cause unacceptable consequences should be minimized.
- ***Construction:*** The surface and underground characteristics of the site should permit application of an optimized plan of surface facilities and underground workings and the construction of all excavations in compliance with appropriate mining rules.

2.2 Canadian Regulatory Requirements

In Canada, regulatory guidance on the geological considerations that need to be considered for siting a deep geological repository is contained in regulatory guide R-72 issued by the Atomic Energy Control Board ((now Canadian Nuclear Safety Commission) Geological Considerations in Siting a Repository for Under-Ground Disposal of High-Level Waste, 1987). This regulatory guide identifies the following five geoscientific considerations:

1. The host rock and geological system should have properties such that their combined effect significantly retards the movement or release of radioactive material.
2. There should be little likelihood that the host rock will be exploited as a natural resource.
3. The repository site should be located in a region that is geologically stable and likely to remain stable.
4. Both the host rock and the geological system should be capable of withstanding stresses without significant structural deformation, fracturing or breach of the natural barriers.
5. The dimensions of the host rock should be such that the repository can be deep underground and well removed from geological discontinuities.

2.3 INTERNATIONAL EXPERIENCE

Several countries have radioactive waste management programs at various stages of implementation. Some have developed and implemented their siting criteria or are in the process of developing siting criteria for their long-term management facilities. For the purposes of this study, the geoscientific factors being considered by a representative number of countries with deep geological repository programs were reviewed, including Finland, Sweden, Switzerland, Germany, Japan and United Kingdom. The geoscientific factors identified by these countries and their use in the context of siting a geological repository is discussed below.

In general, most of the geoscientific factors that have been considered by the various countries with geological repository programs have many similarities and are consistent with those recommended by the IAEA and considered in Canadian regulatory guidance documents, where relevant. However, there are also significant differences in the level of details, the definitions of each factor as well as in the way they are applied to identify and/or evaluate potential sites.

With respect to level of detail, Switzerland has identified very broad sets of factors (e.g., Geochemistry, Fracture Zones, Geologic Stability) while other countries such as Sweden and Germany identify very specific and in some cases, quantitative criteria. With respect to their application, the siting criteria in Finland are associated with “favourable” or “unfavourable” factors, general features which may indicate a potentially good site or general features which may indicate a potentially unsuitable site. The siting criteria in Sweden contain few “requirements”, a larger number of “preferences” and a set of “abandonment” criteria. In contrast to the siting programs in most countries and international guidance, the siting criteria in Germany contain explicit exclusionary criteria and minimum geoscientific requirements with numerical constraints. Japan also has a number of legal siting “requirements” but also a number of “factors” to assess site suitability.

2.3.1 Finland

The Finnish site selection process began around 1983 with regional studies of the country and by 1987 five candidate sites were identified for future study and analysis. Preliminary site characterization was conducted from 1987 to 1992 and detailed site characterization was conducted from 1993 to 1999. The final site selection for Olkiluoto was based on the Environmental Impact Assessment that was completed in 1999. In 2001, the Finnish Parliament ratified the decision-in-principle for the selection of Olkiluoto as the site for a deep geological repository for used nuclear fuel in Finland.

The general requirement for a site was stated by the Finnish Government (STUK, 1999):

> "*The bedrock properties of the final disposal site taken as a whole have to be favourable for isolating the disposed substances from the natural environment. The site for final disposal should not possess anything viewed as disadvantageous with regard to long-term safety*".

The geoscientific factors used for the siting of a deep geological repository in Finland included those that were considered favourable for the siting of a repository and those that were considered unfavourable (Posiva, 2000; McEwen and Äikäs, 2000). These are listed below:

Table 1: Geoscientific Factors Considered in Finland

Favourable Geoscientific Factors	Unfavourable Geoscientific Factors
• Seismicity / Stability	• Natural Resources
• Repository Depth	• High Rock Stress
• Rock Volume	• Anomalous Seismic Activity
• Homogeneity	• Adverse Groundwater
• Rock Type	• Rock Complexity
• Geochemistry	
• Rock Strength	
• Fracture Zones	
• Groundwater Resources	

2.3.2 Sweden

In Sweden, feasibility studies were conducted in eight municipalities in the 1990s for a host community for a deep geological repository for used nuclear fuel. In 2002, two candidate sites for a repository were identified in Forsmark and Oskarshamn. In 2007, SKB, the Swedish authority charged with this project, indicated that provided both sites are found to be available and suitable for the final repository then a comparative evaluation would be made from a holistic perspective (SKB, 2007). Detailed site investigations at these candidate sites were completed in 2008 and SKB plan to select a preferred site for a deep geological repository for used nuclear fuel in 2009. The principle geoscientific factors developed by SKB for a deep geological repository in Sweden (SKB, 2000; SKB, 2001) were categorized as requirements (i.e., conditions of direct importance to site suitability), preferred conditions (i.e., conditions that are desirable); and abandonment conditions (i.e., conditions if encountered that would trigger the discontinuation of site investigations). These are listed below:

Table 2: Geoscientific Factors Considered in Sweden

Requirements	Preferences	Abandonment
• Resources • Fracture Zones • Rock Strength • Geochemistry • Salinity	• Resource Potential • Fracture Density • Rock Stress • Rock Strength • Coefficient of Expansion • Thermal Conductivity • Temperature • Hydraulic Conductivity • Fracture Zones • Hydraulic Gradient • Geochemistry • Groundwater Velocity • Geosphere Retardation • Matrix Diffusion • Rock Cover • Rock Homogeneity	• Resources • Distance from Fractures • Rock Stability • Dissolved Oxygen

2.3.3 Switzerland

In 1993, the Swiss Federal Nuclear Safety Inspectorate (HSK) issued a general preference for siting deep geological repositories (HSK, 1993) for the long term management of radioactive wastes. In January 2007, the Swiss Federal Office of Energy issued a draft Sectoral Plan for Geological Repositories for broad review prior to issuing a final Plan (Aebersold, 2007). The draft Plan covers general siting criteria, including the following geoscientific factors (Table 3).

Table 3: Geoscientific Factors Considered in Switzerland

General Geoscientific Factors	
• Host Rock Dimensions	• Site Characterization
• Fracture Zones	• Geochemistry
• Resource Potential	• Gas Generation
• Hydraulic Barrier	• Site Geomechanics
• Geologic Stability	

2.3.4 Germany

Operation of the Morsleben repository in salt for low and intermediate level waste in the former German Democratic Republic was stopped in 1998. In 1999, the German Federal Minister for the Environment set up the Committee on a Selection Procedure for Repository Sites (AkEnd, 2002). In 2000, exploration of the Gorleben salt dome as a potential repository site for used fuel and exploration of the Konrad repository for low and intermediate level waste in an abandoned iron ore mine was stopped in 2002. To this end, the Federal Government has instructed a Siting Committee that at least two sites must be selected by 2010 for underground exploration and one site shall suffice for a single repository for all types and amounts of radioactive waste. The planned site selection procedure in Germany envisages the identification of areas that do not meet specific geoscientific minimum requirements and would be excluded, followed by a comparative weighted evaluation of sites based on favourable conditions.

Table 4: Geoscientific Factors Considered in Germany

Exclusion Criteria	Requirements	Favourable Requirements
• Erosion • Fault Zones • Seismicity • Groundwater Age	• Hydraulic Conductivity • Depth of Rock Zone • Thickness of Rock Zone • Repository Depth • Area of Rock Zone • Rock Burst • Future Conditions	**Weighting Group 1** • Groundwater Transport • Rock Zone • Site Characterization • Predictability **Weighting Group 2** • Rock Damage • Groundwater Flow **Weighting Group 3** • Gas Generation • Temperature • Retardation • Chemistry

2.3.5 Japan

In Japan, the Nuclear Waste Management Organization of Japan (NUMO) began the siting process for a deep geological repository in December 2002. NUMO sent out information packages in Japan to solicit volunteer communities to explore the feasibility of constructing a final repository for high-level radioactive waste (NUMO, 2004). This would be followed by a selection of Detailed Investigation Areas (DIAs) and eventually selection of a repository site. NUMO is continuing to call for municipalities in Japan to apply as a volunteer area to explore the feasibility of constructing a repository for high-level radioactive waste. The geoscientific factors considered for a deep geological repository in Japan are grouped according to those that are required to assess a site for compliance with legal requirements (i.e., evaluation factors for qualification); national wide evaluation factors, site specific evaluation factors, and favourable siting factors (NUMO, 2004).

Table 5: Geoscientific Factors Considered in Japan

Evaluation Factors for Qualification (EFQ)	Nationwide Evaluation Factors (NEF)	Site-specific Evaluation Factors (SSEF)	Favourable Factors
• Geological History • Geological Future • Rock Features • Mineral Resources	• Volcanic Activity • Active Faults	• Volcanic Activity • Seismicity • Seismic Shaking • Seismic Perturbation of Groundwater Flow • Uplift and Erosion • Unconsolidated Deposits • Mineral Resources	• Properties & Condition of Geological Formations at a Site • Hydrogeological Properties of Rock Formations • Investigation & Assessment of the Geological Environment • Potential for Natural Disasters during Repository Construction & Operation

2.3.6 United Kingdom

In 2007, the United Kingdom (UK) Government issued a framework for implementing geological disposal of radioactive waste (Defra, 2007). The 2007 framework outlines the Government's preferred approach for siting a geological repository facility based on the principles of "voluntarism" and "partnership". The proposed geoscientific factors being considered in the UK for a deep geological repository have been categorized as either exclusion criteria or selection criteria (i.e., General Criteria to be used in the Site Selection Process)**.** The exclusion criteria include the presence of natural resources such as coal, oil and gas, oil shales, selected metal ores, waste repository and gas storage areas; and the presence of aquifers, shallow permeable formations and specific complex hydrogeological environments. Geoscientific selection criteria include earthquakes, faults, uplift, erosion, rock stress and geotechnical engineering issues and will be assessed when detailed site data are available.

2.4 GEOSCIENTIFIC FACTORS NEEDED TO ENSURE THE SAFETY OF A GEOLOGICAL REPOSITORY IN CANADA

Regardless, of the level of detail, the definition of geoscientific factors or the manner in which they are applied within a siting process, the guidance documents and the international experience discussed above, points to five key geoscientific safety related factors that could be considered in the siting of a geological repository in Canada .

The proposed geoscientific factors are:

- ***Containment and isolation of the host rock:*** This factor considers the characteristics of the host rock that:
  - promote the long-term isolation of nuclear used fuel from humans, the environment and surface disturbances caused by humans and natural events;
  - promote the containment of the nuclear materials within the repository;
  - restrict groundwater movement; and
  - retard the movement of any released radioactive materials.
- ***Long-term Stability of the site***: This factor considers the containment and isolation functions of the repository site with respect to future geological process and climate change.
- ***Repository Construction, Operation and Closure:*** This factor considers the surface and underground characteristics of the repository site that promote the safe construction, operation, closure and long-term performance of the repository.
- ***Human Intrusion:*** This factor considers the containment and isolation functions of the repository site with respect to existing and future human activities
- ***Site Characterization:*** This factor considers the characteristics of the repository site that make it amenable to site characterization and site data interpretation activities in order to demonstrate long term safety.

In the context of safety, it is also noteworthy that the international approach to deep geological repositories is based on the multi-barrier concept in which the safety of a repository system does not rely on one single component or barrier but on the combined performance of multiple barriers. The geosphere, that is the rock surrounding a repository extending up to the biosphere, provides one such barrier. The following sections discuss the types of geoscientific factors that would be considered to ensure the safety of a geological repository in Canada, including those that could be considered by the NWMO as criteria for the exclusion of large areas of the four nuclear provinces early in a siting process.

2.4.1 Geological Factors

Clearly, any geological repository must be sited in a suitable host rock formation (i.e., ***rock type***). The host rock formations surrounding a repository represent the primary natural barriers within a multi-barrier repository system that ensures safety. International experience indicates that no one rock type is favoured and that sedimentary rocks (e.g., claystones, shales, salt formations, limestones, dolostones) and crystalline rocks (e.g., granites, gabbros, volcanics) are all expected to offer adequate containment capabilities. For example, crystalline rock has intrinsic properties that make it an excellent host rock for a repository. These properties relate to the low ingress of groundwater into the repository and well defined geotechnical characteristics that would facilitate repository construction. Sedimentary rocks, such as massive dolostones, limestones and shales also possess the characteristics of very low permeability and suitable geotechnical strength and could also be considered as a host rock environment. Salt strata (e.g., anhydrite, halite) is also considered to be a suitable host rock, due to its extremely low permeability and its propensity to deform plastically (i.e., self-sealing). The IAEA general guidance is simply that a repository should be located in a geological medium with a lithology and depth appropriate for the categories and quantities of waste to be managed.

Regardless of the rock type, the host rock should be sufficiently homogeneous with small variation of rock properties in the vicinity of the repository site. Uniform rock formations in comparatively simple geological settings are preferred because they are likely to be more easily characterised and their properties more predictable. Similarly, a host rock's geometric, structural and physical properties that are simple are also preferred. As such, host rocks and geological formations having high ***homogeneity and continuity*** and more generally showing uniform properties are favoured.

Although perhaps self-evident, the depth and dimensions (i.e., ***rock volume***) of the host rock should be sufficient for hosting the repository. The host rock formation should be situated deep enough and be large enough to effectively isolate the repository from the biosphere and surface perturbations. The depth and dimensions of the host rock need to be a sufficient distance from large discontinuities and heterogeneities (e.g., deformation zones or fault zones) to provide an adequate subsurface buffer from existing features that could be potentially reactivatived in the future and thus compromise repository safety.

The depth of the repository should also be sufficient to take into account future erosion of the ground surface, as there should be no possibility that radioactive materials could be exposed to the biosphere until the radionuclides have decayed to safe levels. Typically, there is no specific definition of the term 'deep', but there are practical limitations to depth. For example, there may be geotechnical or geochemical problems of going too deep, as a result of increasing temperatures and confining rock stresses.

Finally, the surface characteristics of the site (i.e., topography, soil cover, soil types, etc.) should be favourable to the safe construction, operation, closure and long-term performance of the repository. For example, ***soil cover*** depth over the bedrock should not hinder site characterization, while topography and the type of soil present at the surface should not hinder safe repository and surface facilities construction activities.

2.4.2 Geomechanical and Seismic Factors

The principal guidance documents and international experience summarized above indicate that the geomechanical properties of the host rock should be favourable for the safe construction, operation and closure of the facility and for ensuring the long term stability of the geological barrier. As such, a repository should be located away from existing ***deformation and fault zones***. This is because these features may serve as direct pathways or short circuits to the biosphere, and in addition, may cause repository instability.

The in situ ***rock stress field*** should also be amenable to repository construction and repository system long-term integrity. Ongoing ***uplift and erosion*** processes should not alter the repository containment and isolation functions. It may also be necessary for the rock to have appropriate ***thermal properties*** to ensure that any heat released by the waste is appropriately dispersed without impairing the confinement properties of the formation or induce undue heating of the overlying sediments and groundwater. In addition the mechanical behaviour of the rock should ensure that an appropriate sealing of the various repository areas and shafts can be achieved.

It is common to all the guidance documents and siting processes, that a repository should be sited in a host rock formation and at a site that is not susceptible to seismic activity to such an extent that it could impair the isolation capability of the overall repository system. This includes the consideration of fault zones that could be potentially reactivated during post-glacial events. The repository system, that is, the engineered barrier system and the geosphere itself, need to withstand long-term seismic events in a manner that would not compromise safety. To this end any repository site needs to demonstrate a high degree of ***seismic stability***, that is, the site should be deemed to be stable as long as necessary according to a safety assessment.

2.4.3 Hydrogeochemical Factors

The principle guidance documents and international experience summarized above indicate that the ***hydrogeochemical characteristics*** of the host rock and surrounding geological environment in general should tend to limit the transport of radionuclides by favouring their retention. These characteristics are many, but typically include: acidity (pH), salinity, redox, Eh, conductivity, major and trace element concentrations and dissolved gases. There are a number of reasons why such parameters need to be considered, but one of the most important reasons is to provide confidence in the development of conceptual models of the site that will be used to measure the long-term performance of the repository. For example, groundwater and rock porewater compositions that are reducing prevent used fuel containers from corrosion and limit used fuel dissolution, thereby promoting long-term safety. In formations where groundwater movement through fissures and pores occurs, retardation of radionuclide transport by matrix diffusion in the host rock and on the fracture walls is important to ensure satisfactory long-term performance of the repository system.

2.4.4 Hydrogeological Factors

The requirement for favourable hydrogeology exists in all guidance documents and is considered by each country with a geological repository program. This is because groundwater is the most effective natural carrier of radioactivity away from a deep geological repository. Overall, there is agreement that the hydrogeological characteristics of the host rock should tend to restrict groundwater flow within the repository and, on a wider scale, that the hydrogeological characteristics of the surrounding geological environment should favour long-term waste isolation. To this end, host rocks with ***low groundwater velocities*** along the flow path from the repository to the biosphere are considered desirable. Nevertheless, the presence of low groundwater flow and/or attenuation capabilities, need to be considered together with the geochemical characteristics of the groundwater and the geomechanical characteristics of the host rock (i.e., unfractured with low frequency of open, interconnected fractures) to ensure safety.

2.4.5 Natural Resource Related Factors

Overall, there is a need to minimise the risk of inadvertent human intrusion into a repository particularly during the long post closure period. The siting of a facility should be made with consideration of actual and potential human activities at or near the site. The most likely activities giving rise to such intrusion is considered to be the pursuit of economically ***exploitable natural resources.*** As such, preference tends to be given to geological formations that have a low potential for economically exploitable resources. Clearly with increasing depth, the risk of human intervention decreases, but as shown in Section 3 below, some minerals, coal and evaporates in Canada are frequently mined at depths well in excess of

1,000 m. In the same vein, areas containing extensive ***groundwater resources*** (i.e., aquifers) should also tend to be avoided, specifically at the repository depth.

2.4.6 Summary

Table 6 provides a summary of the proposed geoscientific factors that would need to be considered to ensure the safety of a geological repository in Canada, including those that could be considered by the NWMO as criteria for the exclusion of large areas of the four nuclear provinces early in a siting process. The factors listed in Table 6 below include the exclusionary criteria that are being considered by other countries with geological repository programs along with other factors that are being considered early in these siting programs.

Table 6: Summary of Potential Geoscientific Factors that Need to be Considered to Ensure Safety and could be Considered as Exclusionary Criteria

Geological Factors	Geomechanical and Seismic Factors	Hydro-geochemical Factors	Hydro-geological Factors	Natural Resource Factors
• Rock type • Homogeneity and continuity • Rock volume • Soil cover	• Deformation and Fault zones • Rock stress field • Uplift • Erosion • Climate change (Glaciation) • Thermal properties • Seismic stability	• Rock mineralogy • Rock porewater composition • Groundwater composition	• Low groundwater velocities	• Exploitable natural resources • Ground-water resources (i.e., aquifers)

3. GEOSCIENTIFIC DESCRIPTION OF THE NUCLEAR PROVINCES

The objective of this section is to provide a general geoscientific description of the four nuclear provinces in Canada, namely, Saskatchewan, Ontario, Québec and New Brunswick, with reference to the relevant geoscientific factors discussed above. To provide context, a brief overview of the geology of Canada is also presented. The following geoscientific descriptions are based on existing sources of information, including: government reports, maps, journal publications existing private and public geoscientific databases.

3.1 GEOLOGY OF CANADA

On a broad scale, the major geological structures of Canada consist of the Canadian Shield flanked by two large mountain chains, the younger Cordilleras in the west and the Appalachians to the east. In the arctic, the Canadian Shield is flanked and overlain by Arctic Platform sedimentary rocks and mountainous areas of Ellesmere and Axel Heiberg islands. The Canadian Shield represents the largest piece of ancient continental crust (or craton) in the world. It is primarily comprised of very old Precambrian (>1 billion years) crystalline rock and covers an area of more than 5.5 million km^2. Younger deformed sedimentary, igneous and metamorphic rocks have been added, or accreted, to the Canadian Shield margins through collisions of ancient continental or ocean floor landmasses throughout various mountain building events, termed orogenies. The Cordillera in western Canada, was formed when various geologically distinct zones, called terranes, were accreted together as the North American continent moved westward, driven by the gradual opening of the Atlantic Ocean. The resulting rocks form the well known Canadian Rocky Mountains and Coast Mountains. In Eastern Canada, the Appalachian Mountains formed in response to several very old continental collisions, and have since been eroded down to much lower elevations than the Cordillera Mountains.

Sedimentary rocks overly portions of the Canadian Shield in central Canada, as well as the accreted terranes in eastern and western Canada and the arctic. These sedimentary rocks were deposited within ancient seas during Paleozoic and Mesozoic times and formed large sedimentary rock basins. The location of sedimentary cover/basins within Canada is shown in **Figure 1**. Over geologic time, a gradual uplift of the continent has resulted in the subsequent erosion of a large amount of the overlying younger sedimentary rocks, exposing the Canadian Shield over much of central Canada. In western Canada, there are the various Pacific and intermontane basins of British Columbia, and the economically important Western Canada Basin, itself comprised of the Alberta and Williston basins. In the Hudson Bay area of central Canada are the Hudson Bay and Moose River sedimentary basins. The northern Arctic Island basins include the Sverdrup Basin and the multiple basins of the Arctic Platform. Extending from southern Ontario through Québec are the Michigan and Appalachian basins and the Saint-Lawrence Platform.

Much of eastern Canada is covered by a series of sedimentary basins, the largest being the Maritimes Basin (both on and off shore) and the extensive Scotian Basin off the coast of Eastern Canada. In general, sedimentary basins across Canada contain substantial thicknesses (up to kilometres) of sedimentary rock.

Figure 1: General Geology of Canada Showing Onshore Basins

Canada is located on the western half of the North American crustal tectonic plate, which includes the western portion of the Atlantic Ocean and the all but the western edge of North America. Due to its location on the plate, Canada contains both seismic and non-seismic (aseismic) regions that may be subject to earthquakes or have a higher probability of earth shaking hazards.

East of the Cordillera, through much of the interior of the country, Canada is nearly aseismic or low seismicity due to the geological stability of the underlying Canadian Shield. Increased seismic activity or hazard have been identified by the Geological Survey of Canada along the country's the west, east, and north coasts **(Figure 2)**.

Figure 2: Historical Earthquakes in Canada (1627 – 2007)

3.2 SASKATCHEWAN

3.2.1 Geology

The bedrock geology of Saskatchewan is divided into two main geologic regions: the Canadian Shield, which is exposed in the northern one-third of the province and consists of Precambrian-aged crystalline basement rocks and a smaller area of Precambrian-aged sedimentary rocks in the Athabasca Basin; and the younger Paleozoic and Mesozoic aged (approximately 542 through 65 million years ago) sedimentary rocks of the Western Canada Basin (WCB) and Williston Basin that overlie the Canadian Shield in the southern two-thirds of the province. The general geology of Saskatchewan is illustrated on **Figure 3.**

The Precambrian-aged rocks of the Canadian Shield underlie all of Saskatchewan but are only exposed in the northern one-third of the province, in an area covering approximately 210,000 km^2. Studies of the exposed portion of the shield in Saskatchewan have determined it to be an amalgamation of ancient continents and ancient ocean floors that collided during large mountain-building events, or orogenic events, to form part of a large geological region known as the North American craton. The major mountain building event that formed the North American craton occurred approximately 1.9 billion years ago. The area affected by this event is approximately 500 km wide and extends from Hudson Bay, through Saskatchewan to South Dakota.

The exposed Precambrian geology of Saskatchewan comprises a mixture of sedimentary rocks, granites, volcanic rocks and other intrusive igneous rocks, some of which underwent different degrees of metamorphism and as a result, host most of the base and precious metal occurrences in the province.

The Athabasca Basin of the Canadian Shield covers an area of approximately 100,000 km^2 in the northwestern part of the province. The relatively undeformed and flat-lying sedimentary Athabasca Group overlies Precambrian-age crystalline basement rocks. The sediments within the basin reach a maximum thickness of about 1,400 m in the central part of the basin. This basin hosts Canada's major uranium deposits.

In the Phanerozoic Era, through the Paleozoic and Mesozoic shallow seas inundated the continent, depositing nearly flat-lying sedimentary rocks on the western side of the North American craton into a vast sedimentary basin, termed the Western Interior Basin. This basin covers much of the Canadian and USA prairies east of the Rockies, from the Gulf of Mexico to the Arctic Sea. In Canada, this is termed the Western Canada Basin (WCB) and it extends from the eastern edge of the Canadian Rocky Mountains to the southwestern margin of the Canadian Shield (Figure 1). The basin reaches a maximum thickness in Canada in Alberta along the edge of the Rocky Mountain foothills, where it is up to 5,500 m thick. Within Saskatchewan, the maximum thickness of preserved Phanerozoic sedimentary rocks is about 3,200 m within the Williston Basin. The Williston Basin is a sub-basin within the WCB that covers an area of approximately 250,000 km^2 in North Dakota, Manitoba, Saskatchewan, Montana and South Dakota. The centre of this basin occurs near Williston, North Dakota.

During the Quaternary period (from approximately 2 million years ago to present), episodic continental-scale glaciers scoured and eroded the Canadian Shield and WCB resulting in the deposition of unconsolidated Quaternary sediments forming the surficial geology of the

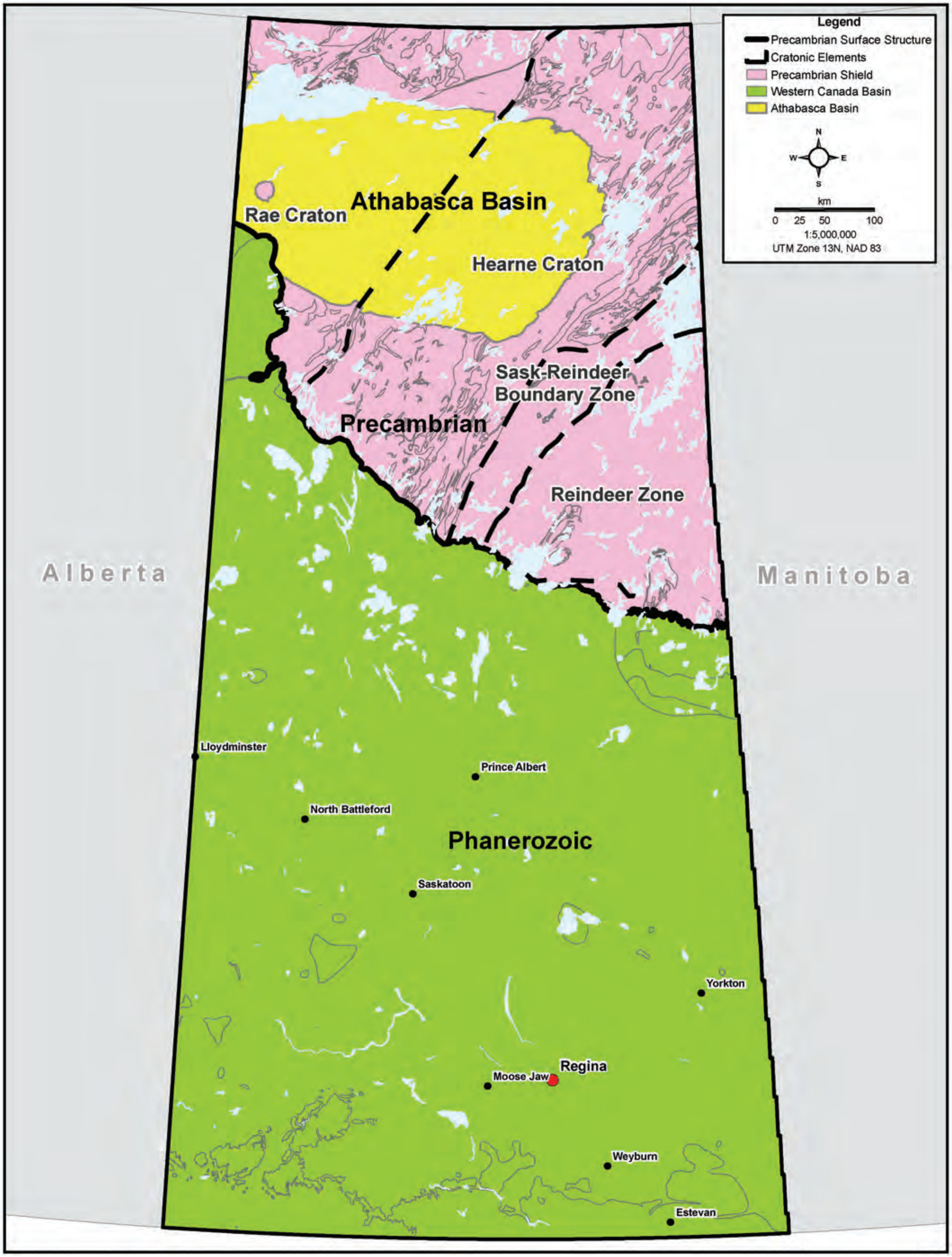


Figure 3: General Geology of Saskatchewan

province. Glacial deposits and glacial erosional features are widespread over much of Saskatchewan. The Canadian Shield is typically covered by only a thin layer of Quaternary sediments or is completely exposed due to the hard, resistant nature of bedrock in that area. Within the WCB, thick layers of glacial drift (50 to 300 m) are common because the sedimentary rocks in this area are softer and more easily eroded. Numerous layers of glacial deposits occur in southern Saskatchewan as a result of the repeated major and minor glacial advances and retreats. Till plains and hummocky moraines, often with an abundance of glacial kettles, are dominant features of the area. An important regional feature is the Missouri Coteau, a major northeast-facing bedrock escarpment. Numerous large ice-pushed ridge complexes exist along this escarpment, such as the Dirt Hills, south and southwest of Regina. The Cypress Hills and Wood Mountain areas of southern Saskatchewan are notable areas where glacial deposits are absent.

3.2.2 Structural Geology and Seismicity

Much of the province's tectonic history occurred in the Precambrian during ancient mountain building events. A number of well documented shear zones (e.g., Snowbird Tectonic Zone) occur in northern Saskatchewan as a result. Few tectonic events affected Saskatchewan in the Paleozoic (approximately 540 million years ago). Since that time, the province has been largely protected and isolated from tectonic stresses and as a result, the rock units of the WCB within Saskatchewan are relatively undeformed.

Salt dissolution of evapourite formations has caused subsidence and associated faulting; however, detailed mapping of these features is only available on a local scale. Present-day uplift in the prairies relating to rebound since the last glaciation ranges from about 5 mm/a to 0 mm/a. Recent data demonstrates that the southwestern portion of Saskatchewan is no longer experiencing isostatic rebound.

Along with Manitoba, Saskatchewan is one of the most seismically stable regions in North American, with very few earthquakes recorded. Only nine earthquakes were recorded between 1909 and 1978, the largest earthquake being the 1909 event with a magnitude of 5 (M5) likely centred near the US border deep underground in the Canadian Shield Precambrian rocks. Earthquakes are generally restricted to the extreme southern portion of the province. There is some evidence of seismicity in the province caused by mining activities mainly in northern Saskatchewan that have been recorded up to M3.7.

3.2.3 Hydrogeochemistry

Groundwater composition in Saskatchewan is variable depending on the depth and geological unit. Most bedrock aquifer systems are generally highly saline and of poor drinking water quality. Overall, there is a paucity of available geochemistry information available for the deep formations in Saskatchewan in both the Canadian Shield and the WCB. Groundwater quality in the shield rocks at shallow depths (less than approximately 150 m) is typically relatively fresh and of potable quality. With increasing depth, salinity of the groundwater also increases becoming brackish and eventually brine at depths of approximately 500 m. The geochemistry of the sedimentary basin aquifers has been established on a regional scale and is found to be quite variable with both depth and geographical location. Brines are common in the Phanerozoic basin strata of Saskatchewan and, as a result saline seeps are a common problem in terms of loss of arable land. Groundwater composition in Quaternary aged aquifers varies according to location across Saskatchewan and is heavily influenced by the characteristics of the glacial deposits. Aquifers present below till sheets often have poor groundwater quality with elevated concentrations of sulphate salts, and total dissolved solids. The groundwater chemistry of deep intertill, buried valley aquifers are not well described.

3.2.4 Hydrogeology

Groundwater in Saskatchewan occurs in three different aquifer types: 1) fractured bedrock in the Canadian Shield; 2) sedimentary bedrock deposits of the WCB; and 3) within unconsolidated Quaternary deposits.

In the Canadian Shield, groundwater commonly occurs as small localized aquifers within fractured metamorphosed rocks as well as through pores and fractures of unmetamorphosed sedimentary deposits associated with the Athabasca Basin. In the WCB, aquifers are mainly associated with the more permeable sandstone and carbonate rock units. Basin brine discharges from the salt rich units are common as both discrete springs and diffuse discharge in east-central Saskatchewan. Quaternary-aged relatively shallow overburden aquifers are widespread, and are generally interbedded with glacial till sequences that form aquitards. Although local scale information exists within the province, the information is more variable when considering hydrogeological properties on a regional scale.

The base of groundwater exploration typically extends no more than 200 m below ground surface down to the Upper or Lower Cretaceous aged sedimentary bedrock aquifers. The agricultural industry is the biggest user of water resources, mainly through irrigation.

3.2.5 Natural Resources

There are abundant natural resources in Saskatchewan including oil and gas, potash, uranium, precious metals, and groundwater. The locations of the major natural resource areas in Saskatchewan are depicted on **Figure 4.** Metallic mineral resource areas are concentrated in the Canadian Shield. Saskatchewan currently produces 100% of Canada's uranium and about 34% of the world's output. Saskatchewan ranks second in Canada for oil reserves, and third for both natural gas and coal. Approximately 95% of Canada's potash and 33% of the world's potash is produced from Saskatchewan.

The majority of petroleum production in the Saskatchewan portion of the WCB has been from Devonian formations with the remainder from Ordovician and Mississipian aged formations. Oil fields are concentrated in two main groups: in a region around Estevan and an elongate region stretching from Swift Current northwards to Lloydminster. Crude oil is produced from underground reservoirs ranging in depth from 360 to 3,130 m. Oil sands in Saskatchewan have been observed in the Clearwater River Valley in northwestern Saskatchewan but, to date, there has been limited oil sands exploration in Saskatchewan.

Potash is the primary economic mineral resource in the province, with deposits located within the Phanerozoic bedrock evapourite units of the WCB between 400 and 2,740 m below surface in south central Saskatchewan. There are currently ten producing potash mines in Saskatchewan. Uranium is currently the second most valuable mineral resource in Saskatchewan and it is mined exclusively from the Athabasca Basin. The uranium deposits are found predominantly at or near the contact between the Athabasca Basin sediments and underlying, older Precambrian basement rocks. Other metallic mineral resources, comprising gold, copper, zinc, silver and cadmium, are mined within the Canadian Shield area of the province.

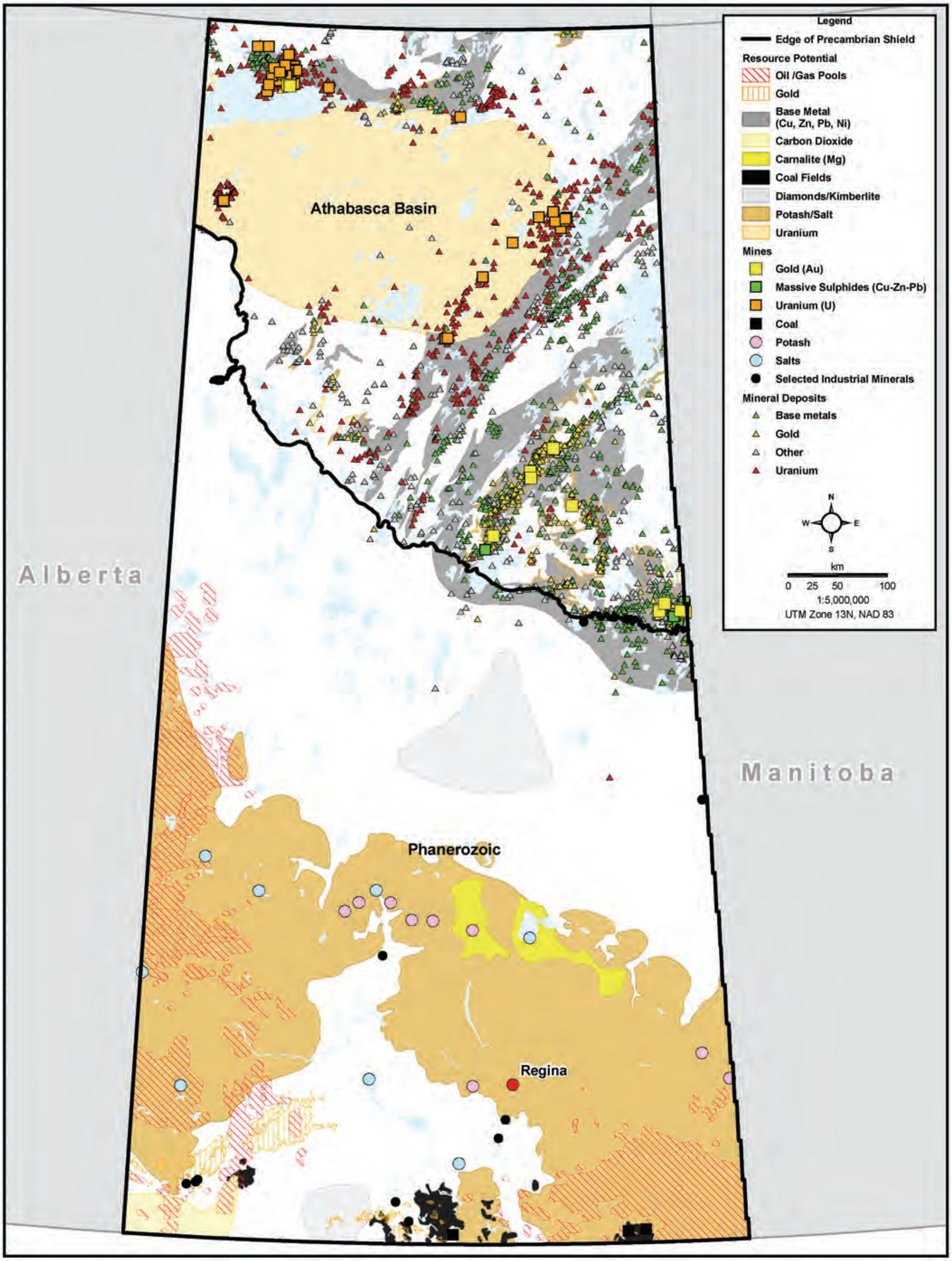


Figure 4: Natural Resources of Saskatchewan

3.3 ONTARIO

3.3.1 Geology

The general geology of Ontario is depicted on **Figure 5.** There are two main geological regions in Ontario: the crystalline Precambrian rocks of the Canadian Shield that are predominant in the northern portion of the province; and the younger sedimentary Phanerozoic rocks that border the Canadian Shield in southern Ontario, and in the James Bay area.

In Ontario, the Canadian Shield is differentiated on the basis of age and tectonic history into three main geological provinces: the Superior Province, the Southern Province, and the Grenville Province. These provinces are an amalgamation of ancient continents and ancient ocean floors that collided during large mountain-building events and which formed part of a large geological region known as the North American craton. The Phanerozoic sedimentary rocks in Ontario occur in four distinct sedimentary basins: the Appalachian Basin; the Michigan Basin; the Hudson Bay Basin; and the Moose River Basin (Figure 1). The Appalachian and Michigan Basins are also collectively known as the St. Lawrence Lowlands, and, the Hudson Bay and Moose River Basins are collectively known as the Hudson Bay Lowland. These sedimentary basins were formed as a result of shallow seas that inundated the continent in the early Paleozoic and continued into the Mesozoic. Following the Mesozoic, the sedimentary basins were above sea level and there was a long period of erosion that has resulted in the current distribution of Paleozoic sedimentary rocks.

The Hudson Bay Basin centre is located beneath Hudson Bay. Associated sedimentary deposits have a maximum thickness of approximately 2,000 m. The Moose River Basin is a sub-basin of the Hudson Bay Basin and its centre occurs southwest of James Bay. Sedimentary rocks within this basin reach a maximum thickness of 500 m to the southeast of James Bay. The Michigan Basin is an extensive basin with its centre located in the Lower Peninsula of Michigan where the basin has a maximum depth of approximately 4,800 m. In Ontario, the Michigan Basin sediments extend to a maximum depth of approximately 1,000 m near Sarnia. The basin grades eastward into the Appalachian Basin and pinches out against the Canadian Shield rocks along the southern shore of Georgian Bay. The Appalachian Basin covers eastern Ontario and the east half of southern Ontario. In Ontario, the Appalachian Basin pinches out on the Canadian Shield between Orillia and Kingston. The basin's greatest depth is over 7,600 m in the USA, whereas, in Ontario, the maximum depth is approximately 1,000 m along the shore of Lake Erie. In Ontario, the Appalachian and Michigan basins are separated by a ridge of Precambrian basement rocks known as the Algonquin Arch. To the northwest of the arch, the sedimentary deposits dip westward into the Michigan Basin, whereas, to the south and southeast the deposits dip south into the Appalachian Basin.

During the Quaternary period, continental-scale glaciers scoured and eroded the Canadian Shield and Phanerozoic basins resulting in the deposition of overburden sediments and forming the surficial geology of the province. Final retreat of the glaciers began approximately 10,000 years ago. In Ontario, glacial deposits associated with the last 130,000 years are commonly preserved. These deposits are complex and variable deposits of till, sand and gravel, silts and clay, reflecting a wide range of depositional environments associated with changing glacier positions, post-glacial lakes, and changing climatic conditions. The Canadian Shield is an area

Figure 5: General Geology of Ontario

of predominantly glacial erosion with little glacial deposition. The more erosion-resistant crystalline Canadian Shield areas of the province are generally covered with only a thin layer of overburden while southern Ontario is covered by thick glacial deposits derived from more easily eroded Phanerozoic bedrock and previous glacial sediments . It was during this time that the Great Lakes were formed. Notable glacial features in southern Ontario include the Oak Ridges Moraine, the Oro Moraine, and the Waterloo Moraine.

3.3.2 Structural Geology and Seismicity

Large scale geological structures found within the Precambrian basement and associated faults that extend through the sedimentary rock units have been generally well characterized and are correlated to the tectonic history of the region. Ontario is located on the northeast part of the North American continent and is part the North American plate. Throughout the Precambrian, rock stresses related to tectonic activities created rifting under Lake Superior, and formation of major basement structural features such as the Grenville Front Tectonic Zone (GFTZ) and the Central Metasedimentary Belt Boundary Zone (CMBBZ). The Canadian Shield and its overlying sedimentary basins have been relatively tectonically stable since the Late Paleozoic time period (the last 250 million years). The opening of the Atlantic Ocean beginning in the Mesozoic resulted in extension of the North American tectonic plate and the creation of a series of faults and depressions known as the St. Lawrence rift system, which extends in Ontario north to the Ottawa area (known as Ottawa-Bonnechere Graben). This seismically active region is known as the Western Québec Seismic Zone. Low seismicity areas; however, can be found within this larger region

Ancient dissolution of salt beds within the Michigan Basin occurred at various times throughout the Paleozoic, this may have resulted in the creation of collapse features and faulting within the overlying strata. Conversely, although salt dissolution likely occurred over millions of years, it has been suggested that periods of rapid dissolution were coincident with fracture reactivation from larger tectonic events during the Paleozoic possibly creating preferential pathways of salt dissolution. This has affected the distribution and thickness of all salt units beneath southern Ontario and, in addition, affected the geometry and stratigraphy of the overlying (younger) units.

It is estimated that glaciers depressed the land surface by more than 500 m during the last glaciation from approximately 115,000 to 10,000 years ago. Following retreat of the glaciers, the land surface has been steadily rebounding. Post-glacial isostatic rebound is still occurring in most of Ontario and varies from approximately 12 mm/a to a few millimetres per year. The rate of greatest rebound is in the Hudson Bay area where the glacial ice was the thickest.

Most of Ontario lies within the tectonically stable interior of the North American continent and, as a result, the seismic hazard in much of Ontario is low. Zones of increased tectonic activity; however, have been delineated and include the northeastern Ontario Seismic Zone (Timmins to Hearst area), the Southern Great Lakes Seismic Zone (the area surrounding Lake Erie and Lake Ontario) and the Western Québec Seismic Zone (an area encompassing the Ottawa Valley from Montreal to Temiskaming, as well as the Laurentians and the Eastern Ontario). The remainder of the province is generally not seismically active and is referred to as the Stable Craton Interior. In northern Ontario, only two magnitude 5 (M5) earthquakes were reported (1905, northern Michigan, and 1928, northwest of Kapuskasing). In the Southern Great Lakes Seismic zone, three M5 events were recorded in the past 250 years, all in the American portion of that area. The seismicity for the last 30 years averages two to three M2.5 or greater earthquakes per year, primarily in northern Ontario and the Southern Great Lakes Seismic Zone. Earthquake focal depths are thought to vary systematically across the province and three general earthquake regions have been delineated: the Precambrian central craton, with most events generally at depths of several kilometres; the late Proterozoic rifted margin with depths between 5 and 15 km but some events as deep as 30 km; and the Appalachian Orogen (of which the Southern Great Lakes Seismic Zone is at the margin), with depths between 5 and 10 km.

3.3.3 Hydrogeochemistry

The geochemical composition of groundwater in the province can generally be delineated based on the three main aquifer types; Precambrian rocks, Paleozoic rocks and the Quaternary glacial sediments. The water within the Precambrian rocks is subdivided into two general hydrogeochemical regimes: a shallow, generally fresh water regime and an intermediate brackish to deep, saline groundwater regime which is not potable. Within the Paleozoic basin sedimentary bedrock units of Ontario, two geochemical systems are typically recognized at the regional-scale. The upper shallow system comprises groundwater at less than approximately 150 m depth that typically contains fresh water to slightly brackish water. The intermediate to deep system occurs at depths greater than approximately 150 m and contains predominantly brines. Groundwater within Quaternary overburden deposits is typically fresh, hard water.

3.3.4 Hydrogeology

The groundwater regime in Ontario varies significantly depending on the location, the host rock or overburden sediments and the depth. Groundwater flow in the shallow system is controlled by topography, whereas diffusion controlled flow is more common in the deep system (>300 m). Groundwater flow systems in Ontario typically occurs in one of two broad systems based on depth: a shallow system (< 150 m); and intermediate system to deep system (> 150 m).

A number of significant individual bedrock aquifers or aquifer systems occur in Ontario. In the Canadian Shield, fractured bedrock that outcrops at or near surface is one of the primary aquifers for these regions. Groundwater in the shield and the associated groundwater flow is controlled by fracture patterns within the crystalline bedrock. This aquifer is important for small local or individual supplies. Significant aquifers are found in the permeable carbonate strata from the sedimentary basins. In these settings, the sandstones, limestones and dolostones are generally good aquifers. The most abundant groundwater aquifers within the sedimentary bedrock units are found in the Silurian limestones and dolostones west of the Niagara Escarpment. These aquifers are capable of supplying much of the potable water for large urban centres such as Guelph, Cambridge and Kitchener-Waterloo. Within the Quaternary deposits, buried valley, inter-till and surficial aquifers are also an important source of groundwater. Groundwater represents approximately 29% of Ontario’s water supply.

Regional scale and local scale assessments of hydraulic conductivities and gradients have been completed in areas where significant quantities of groundwater is used for drinking water purposes, such as in much of southern Ontario. However, this information is unavailable across most of the province.

3.3.5 Natural Resources

Ontario has abundant natural resources including groundwater, base metals, diamonds, gypsum and oil and gas. The locations of major natural resource areas in Ontario are depicted on **Figure 6.**

More than 30 metals and non-metal minerals are produced in Ontario. The top five metallic minerals produced are nickel, copper, gold, platinum group metals and zinc. These metal deposits are located in the Canadian Shield in several mineral producing regions including the Abitibi Greenstone Belt gold camp in the Timmins area and the Sudbury Nickel Basin. Recently, diamond exploration has also increased in the Northern Ontario and the first diamond mine is currently being licensed in the Attawapiskat area in the James Bay region. Southern Ontario mining production includes non-metallic minerals such as salt, gypsum, calcium carbonate, phosphate, talc and structural materials (such as sand, gravel and building stone). These resources are associated with Paleozoic sedimentary bedrock and Quaternary overburden (e.g., sand and gravel) deposits. Salt deposits in Ontario occur within the Paleozoic basin sedimentary strata near the eastern edge of the Michigan Basin. The sedimentary rocks of southern Ontario are also exploited for oil and natural gas resources. Hydrocarbons have been found in more than a dozen stratigraphic units throughout the Paleozoic sedimentary cover. The majority of petroleum exploration has been in southwestern Ontario in the London, Sarnia and Chatham-Kent area. The main gas producing regions are along the north shore of Lake Erie within the Appalachian Basin.

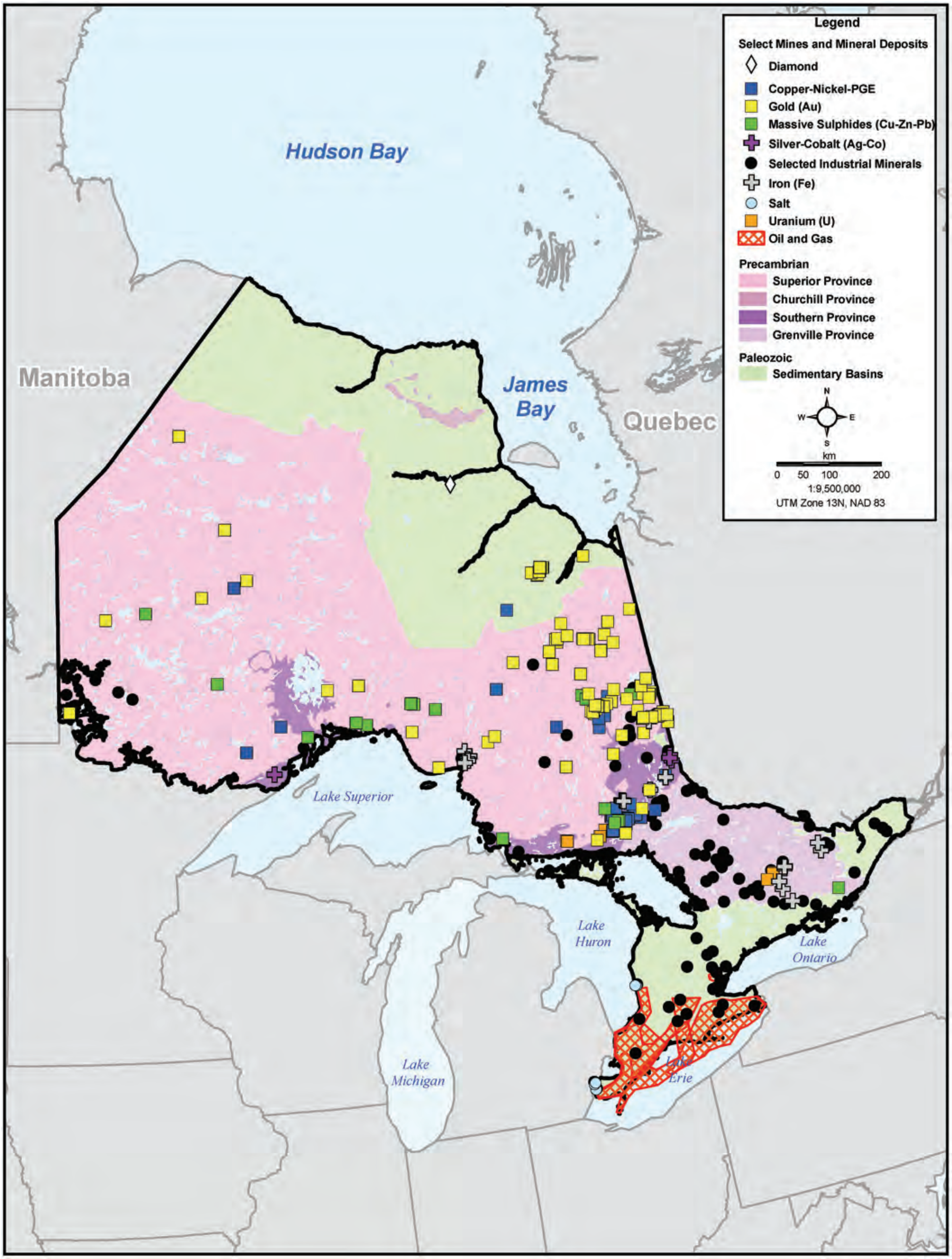


Figure 6: Natural Resources of Ontario

3.4 QUÉBEC

3.4.1 Geology

The bedrock geology of Québec is divided into three main geologic regions: the crystalline Precambrian Canadian Shield; the sedimentary Saint-Lawrence Platform at the south margin of the Canadian Shield; and the Appalachians of southern Québec. The general geology of Québec is depicted on **Figure 7.**

The Precambrian Canadian Shield covers over 90% of Québec. It is made up of three geological provinces: the Superior, the Churchill and the Grenville provinces. The Superior Province covers approximately one-third of the surface area of Québec (600,000 km^2) and forms the core of the Canadian Shield. It comprises a diverse assemblage of structurally deformed, metamorphic sedimentary, volcanic, and crystalline plutonic (e.g., granite) rocks with ages up to 4 billion years. The Churchill Province covers an area of about 150,000 km^2 northeast of the Superior Province. It is mainly composed of rocks deformed by three ancient mountain-building events: Ungava; New-Québec; and Torngat. The youngest Canadian Shield province in Québec is the Grenville Province (approximately 1.2 billion years), a metamorphic belt that covers 600,000 km^2 on the southeastern margin of the Superior Province. The strongly metamorphosed Grenville Province is the primary exposure of a major ancient mountain-building event known as the Grenville Orogen.

The Saint-Lawrence Platform is composed Precambrian to Paleozoic aged, flat-lying, sedimentary rocks deposited in a depression formed by faulting that occurred during extensional events relating to the breakup of Gondwana (an ancient continent). The Iapetus Ocean (equivalent to the modern Atlantic Ocean) also began to open approximately 110 million years ago during this period. The Saint-Lawrence Platform only covers an area of about 17,250 km^2 but is host to most of the population of Québec. The Saint-Lawrence Platform is divided into two sub-platforms/basins: the Saint-Lawrence Lowlands and the Anticosti Platform that structurally overlie rocks of the Grenville Province. The Saint-Lawrence Lowlands comprise clastic and carbonate sedimentary rocks that range from 1,500 to 3,000 m in thickness, whereas, the carbonate sedimentary Anticosti Platform sequence has been found up to 5 km thick.

The Appalachian Mountains, found within the Appalachian region of Québec along the southeast border with New Brunswick, were formed during a composite 500 to 250 million year old mountain-building event known as the Appalachian Orogeny. Rocks of the Appalachian Mountains are primarily folded and faulted metamorphic rocks that have since been eroded through time to their current elevation.

The bedrock of Québec was scoured and eroded by episodic, continental-scale glaciers, during the Quaternary Period. The final retreat of the glaciers that began approximately 10,000 years ago resulted in the deposition of a blanket of Quaternary-aged sediments over much of the province. Similar to Ontario, the Canadian Shield in Québec is an area of predominantly glacial erosion with little glacial deposition. As a result, the northern part of Québec is characterized by a thin cover of till as well as sparse marine clays associated with ancient seas that were located in this area following glacial retreat. The southern part of Québec, particularly in the St. Lawrence Platform is also covered by till; however, clay deposits of marine origin, known as the Champlain Clays predominate. Much of the Appalachian area, such as the Gaspé, has very little glacially derived overburden.

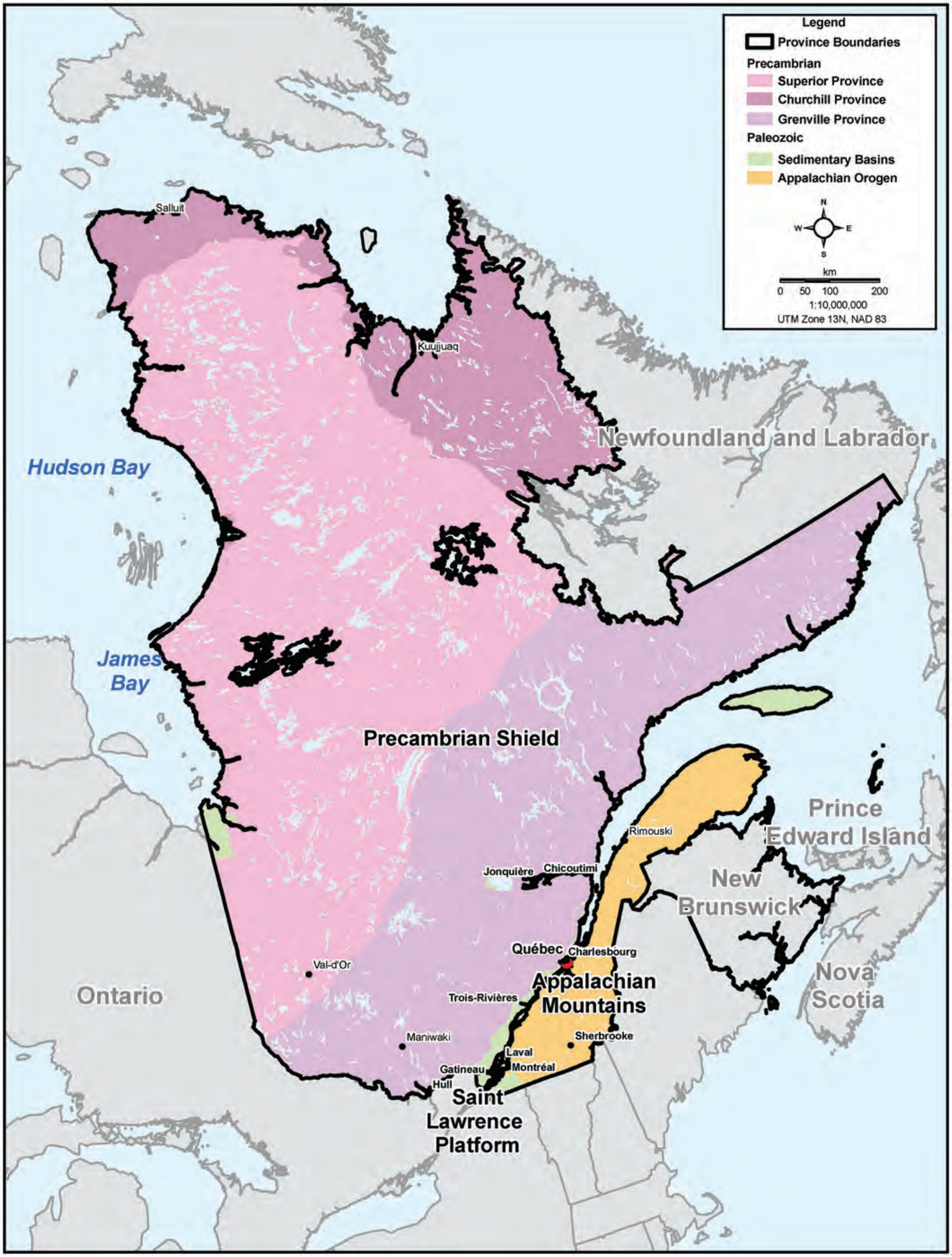


Figure 7: General Geology of Québec

3.4.2 Structural Geology and Seismicity

Much of the province's tectonic history occurred in the Precambrian, culminating with the Grenville Orogeny. Subsequent tectonism during the Paleozoic formed the Saint-Lawrence Platform (700 to 350 million years ago), the Appalachian Mountains (500 to 350 million years ago), and opened the Iapetus and Atlantic Ocean (~110 million years ago to present). Québec is currently being compressed in the northwest-southeast direction by the spreading of the Atlantic Ocean. The most tectonically active zone of Québec is related to faulting in the Saint-Lawrence rift system in the south of the province (**Figure 7**).

In Eastern Canada, the spatial distribution of postglacial aged (recent) faulting occurs in identified seismically active areas and have involved reactivation of existing faults and fractures. Within Québec examples of postglacial faulting have been observed in the Saint-Lawrence Valley region, the Ottawa-Bonnechère Graben and the Bell Arch of the Ungava Peninsula. Postglacial isostatic rebound is most pronounced in James Bay, where the ice sheet was the thickest. At present, isostatic rebound in the southern part of Québec is negligible at about 2 mm/a. Subsidence may actually be occurring south of the Saint Lawrence region. It has been estimated that earthquakes in Eastern Canada could potentially be triggered by stresses created from isostatic rebound but restricted to reactivation of pre-existing faults in tectonically pre-weakened zones.

Québec is part of the stable interior of the North American Plate. Québec contains three regions of historical seismicity, or seismic zones, as identified by Natural Resources Canada: West Québec Zone, Charlevoix-Kamouraska Zone, and the Lower Saint-Lawrence Zone. The Western Québec Zone encloses the Ottawa Valley from Montreal to Temiskaming, Ontario and has been the site of at least three significant earthquakes in the past with magnitudes of M5.6 to M6.2. In this area, the earthquakes have been concentrated in a zone of significant seismicity that trends northwest from the Ottawa-Montreal region through the Maniwaki area related to the Ottawa-Bonnechère Graben. The Charlevoix Seismic Zone, which is located 100 km east of Québec City, is the most seismically active region of eastern Canada. Historically, the zone has been subject to five significant earthquakes of M6 or larger. The Lower Saint-Lawrence (Bas Saint-Laurent) Seismic Zone is located 400 km downstream from Québec City in the estuary of the Saint-Lawrence River. Two earthquakes of M5.1 have been reported in addition to numerous lower magnitude events. The Saint Lawrence and Charlevoix areas are located within an intraplate setting, where seismicity is focussed. A 350 million year old meteorite impact in the Charlevoix seismic region added to the complexity of the local structural regime by creating a ~60 km diameter system of concentric faults and fractures.

3.4.3 Hydrogeochemistry

There are three main geochemical zones as dictated by the bedrock aquifers: i) fractured crystalline bedrock in the Canadian Shield; ii) carbonate rock associated with the Saint-Lawrence Platform; and iii) metamorphosed sedimentary strata associated with the Appalachian Mountains. The water quality in the Canadian Shield environment of Québec is similar to that found in Ontario and Saskatchewan in that two hydrogeochemical regimes exist: a shallow, generally fresh water regime and an intermediate brackish to deep saline groundwater regime that is not potable. Within the Saint-Lawrence Platform setting, groundwater quality can be highly mineralized and/or saline. Shallow groundwater is poor in the Appalachian setting in that it is hard and mineralized. These three broad sources of groundwater yield water with relatively poor drinking water quality.

Aquifers hosted in Quaternary deposits usually yield groundwater that is acceptable for general use. Typically glacially-derived sedimentary aquifers produce hard, mineralized (calcium-bicarbonate) potable water.

3.4.4 Hydrogeology

Approximately 20% of the population of Québec uses groundwater for consumption. The majority of groundwater used by municipalities and industries is drawn from permeable glacial and glacial lake and riverine (i.e., glaciofluvial and glaciolacustrine) deposits. By contrast, the main groundwater withdrawal from bedrock within the province is mine drainage (dewatering).

The regional bedrock groundwater systems of the Canadian Shield or Appalachian Mountains involve either igneous or metamorphic-rock hosted systems. The porosity of these aquifers is controlled by fracture and fault systems and rock fabric orientation (i.e., the predominant orientation of structural features of the rock). Permeability in Canadian Shield bedrock typically decreases with depth as the primary fracture network becomes tighter with increasing rock stress. Based on experience from mines and deep excavations within the Canadian Shield, major structural features such as faults generally constitute the groundwater flow pathways below depths of approximately 300 m. Within the Saint-Lawrence Lowlands of southwestern Québec, bedrock aquifer systems are hosted in the permeable sedimentary units such as the clastic Covey Hill, Cairnside, and Lower Chazy formations; the dolomitic Beauharnois, Theresa, and Carillon formations; and the limestone formations of the Upper Chazy, Black River, and Trenton. The permeable unconsolidated Quaternary aquifer deposits of Québec are typically characterized by aquifers with have moderate to high permeabilities.

3.4.5 Natural Resources

Québec produces of gold, copper, nickel, zinc and industrial minerals. In addition, there is considerable future potential for exploration of iron ore, precious metals and diamonds. The locations of the major areas of natural resources in Québec are depicted on **Figure 8**.

The main mining region of Québec is the Abitibi-Témiscamingue region in the northwest of the province. This region hosts most of the province’s economic metal deposits in deposits formed by ancient volcanic activities and lode gold deposits associated with veins that cut through the Canadian Shield. The Churchill Province contains nickel-copper and platinum-group deposits and is well known for its iron and manganese deposits (e.g., Labrador Trough). The Grenville Province is recognized for its iron and titanium mines. Numerous diamond exploration programs have occurred in regions associated with kimberlite intrusions in portions of Québec underlain by the Canadian Shield (e.g., Torngat and Renard regions); however, no economically feasible diamonds have been produced in Québec to date.

Industrial minerals and rocks of Québec from the Canadian Shield include: chrysotyle, ilmenite, titanium scorias, graphite, mica, rock salt and silica, brines and marble. Industrial minerals also from the sedimentary deposits of Québec include clay minerals, silica, and limestone/dolomite. Oil and gas exploration has substantially increased since the mid 1990s within the southern sedimentary basins; however, no economically exploitable resources have yet been found, with the exception of two small natural gas deposits in sedimentary deposits of the Appalachian region in Gaspésie, and one small natural gas deposit within sedimentary deposits in the St. Lawrence Lowlands basin in the Pointe-du-Lac area.

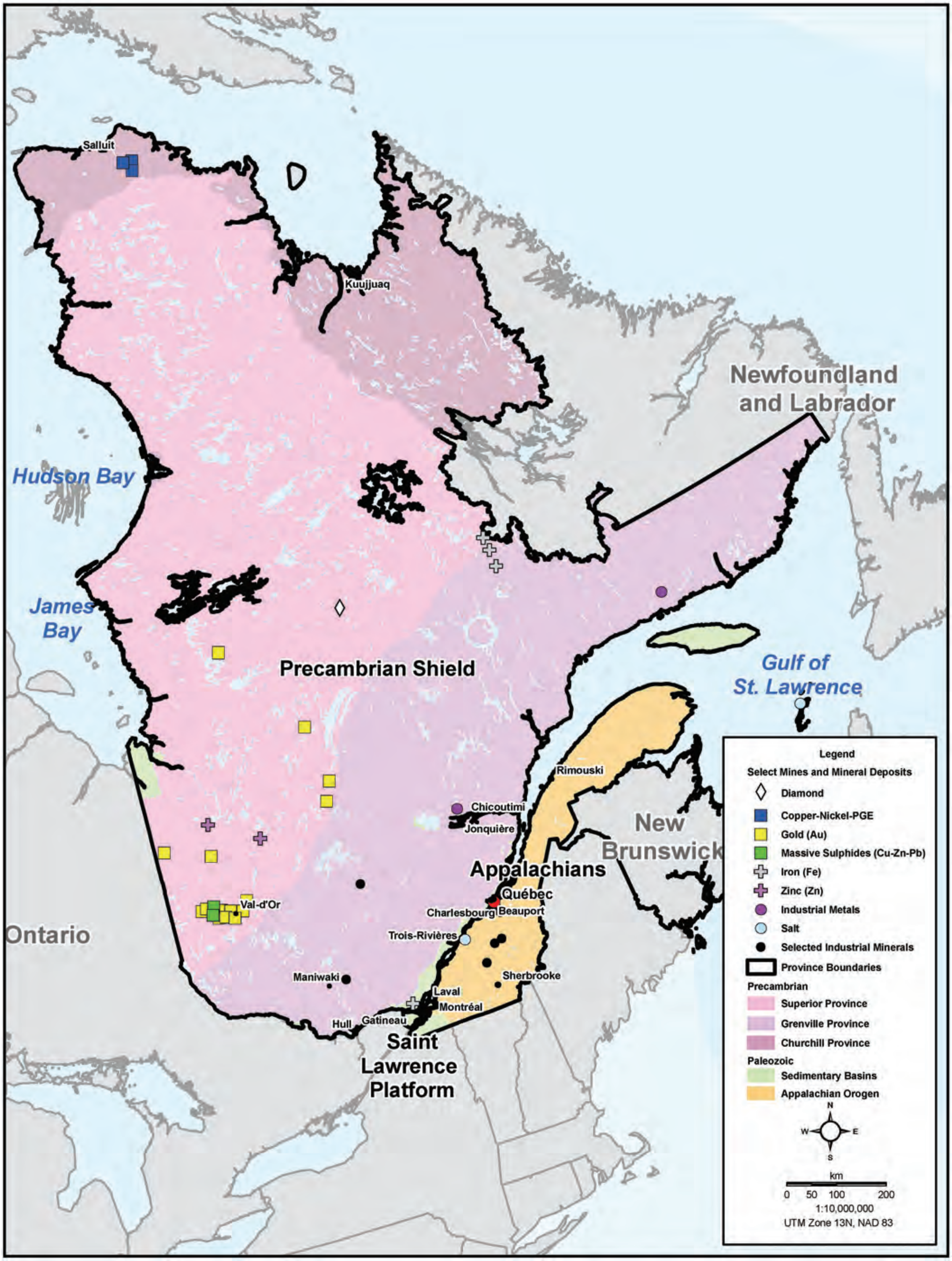


Figure 8: Natural Resources of Québec

3.5 NEW BRUNSWICK

3.5.1 Geology

The geology of New Brunswick is complex due to a number of major tectonic events occurring over the past 650 million years. The general geology of New Brunswick is depicted on **Figure 9.** New Brunswick is located on the eastern margin of the North American craton where a number of mountain building events (e.g., the Appalachian Mountains) have occurred. These major geological events have left a diverse assemblage of structurally deformed, sedimentary, volcanic, and crystalline plutonic rocks throughout the province.

The three main geological regions that underlie the majority of the province, from northwest to southeast, are the Dunnage, Gander and Avalon Zones. These were formed during the Appalachian Mountain building events. These zones consist of folded and faulted, metamorphosed, sedimentary and volcanic rocks that were originally formed in an ancient ocean.

Younger sedimentary belts (Gaspé Belt, Fredericton Trough, and Mascarene Belt) were deposited during the Paleozoic and cover the northern and western portions of the province. Crystalline granitic intrusions (dating 350 to 420 million year old), cover large portions of the southwest of the province. These intrusions can have individual surface areas up to 300 km^2. Overlying portions of the Dunnage, Gander and Avalon Zones is a fourth major region referred to as the Maritimes Basin, which was formed as a result of subsidence during the later stages of the Appalachian mountain building events. It is composed of Carboniferous (350 to 300 million years old) flat-lying, laterally extensive sedimentary rock sequences that are up to 12,000 m thick in the centre of the basin located in the Gulf of St. Lawrence. In New Brunswick, the Maritimes Basin covers approximately one-third of the province (45,000 km^2), dominating the entire eastern coastline, and narrows to a point towards the west of the province near Oromocto Lake. The thickness of Carboniferous-aged sedimentary rock in the on-shore Moncton Basin, a sub-basin of the Maritimes Basin, has been shown to exceed 4 km. For resource exploration reasons, the most detailed stratigraphic work has focused on the deepest and most central portions of the Maritimes Basin. This is an area with significant potash, salt, oil, natural gas, and oil shale resources, as well as potential for unconformity-related uranium deposits.

Episodic, continental-scale glaciers covered New Brunswick, during the Quaternary Period. These events resulted in the deposition of glacially derived sediments that form the majority of the surficial deposits in the province. New Brunswick’s glacial deposits are between 100,000 and 10,000 years old and cover much of the province to a thickness of up to 20 m except for bedrock ridges in the Caledonian and Miramichi highland regions that remained unglaciated.

3.5.2 Structural Geology and Seismicity

Much of the province’s tectonism occurred during the Paleozoic and Mesozoic between 500 and 250 million years ago with the creation of the Appalachian Mountains; consisting of a minimum of five distinct mountain-building events. A prominent northeast-southwest trending orientation or fabric was imparted upon the province early during these tectonic events that is still readily evident in the geological features of the province. Regional-scale faults, shear zones and zones of past deformation in the province are oriented roughly parallel to this pervasive structural feature.

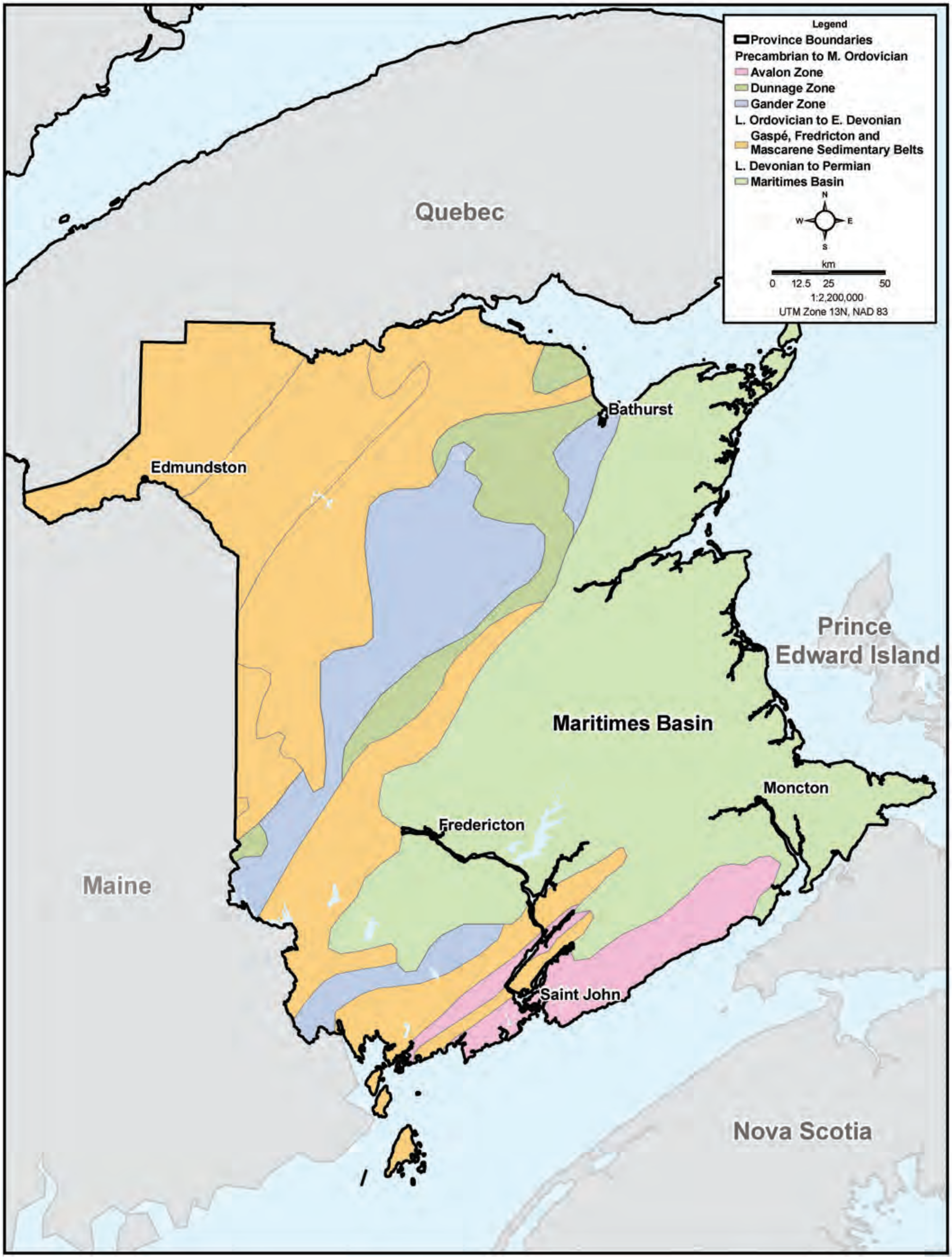


Figure 9: General Geology of New Brunswick

Like most of Canada east of the Rocky Mountains, New Brunswick is currently being compressed in the northeast-southwest direction due to the active spreading of the Atlantic Ocean. The most recent folding and faulting events in the Mesozoic is likely the result of the horizontal, or compressional, stresses associated with this seafloor spreading.

Similar to the other provinces, isostatic rebound is occurring in New Brunswick following the final retreat of the last glaciers; however New Brunswick is central to a region of post-glacial emergence in Atlantic Canada. Current rates of rebound in New Brunswick are on the order of between 0 to 1 mm/a. This uplift is thought to primarily result from isostatic rebound but neotectonic forces from the opening of the Atlantic may be at least partially responsible.

The majority of New Brunswick occurs within an area defined by Earthquakes Canada as the Northern Appalachian Seismic Zone although portions of the province also reside within the "felt" region of more distal areas such as the Charlevoix-Kamouraska and Lower St. Lawrence Valley Seismic Zones of Québec, and the offshore Laurentian Slope Seismic Zone. Most Regions of New Brunswick have experienced some level of seismic activity, although the seismic hazard levels associated with these is typically quite minor. The Passamaquoddy Bay zone near St. John is the most active area in the province. Between 1800 and 1999, 26 small magnitude events, up to M3.8 were recorded in the Moncton area of this Zone. These seismic events are thought to be related to re-activation along faults within the on-shore Moncton Sub-basin of the Maritimes Basin. With respect to the historical earthquake activity for the province, earthquakes have been historically noted in the Passamaquoddy Bay area, the Central Highlands, and the Moncton regions; however, the magnitudes of these events were relatively low. Earthquakes up to M5.7 and M5.2 have been reported in the Central Highlands and Moncton regions, respectively. Earthquake activity in the Passamaquoddy Bay area is associated with post-glacial vertical movement either from: movement along existing faults, or due to general subsidence of the area.

3.5.3 Hydrogeochemistry

Groundwater produced in New Brunswick for domestic consumption from surficial and bedrock aquifers is generally of good quality with the only regionally consistent groundwater quality problems being hardness, iron and manganese; each of which is a aesthetic concern. Locally, groundwater quality degradation is the result of naturally high levels of arsenic and uranium (e.g., Harvey and Lake George areas near Fredericton). In addition, salt water intrusion has been noted in aquifers of some coastal regions. Salt seeps resulting from evaporation of brines from local salt springs have also been noted throughout the Maritimes Basin.

Groundwater within the major bedrock aquifers of the Maritimes Basin is mineralized, moderately hard, and slightly alkaline. On a regional basis, drill records suggest that within the Maritimes Basin, groundwater is commonly stratified with an upper layer of fresh water overlying a deeper layer of saline water. Saline, or brackish, water has been found in wells as shallow as 60 m.

3.5.4 Hydrogeology

Most municipal water and private residential groundwater comes from relatively shallow unconsolidated Quaternary deposits. These surficial deposits consisting of coarse-grained sediments (e.g., sands and gravels) typically found within relatively thick bodies of glaciofluvial deposits, marine deltas and beaches and alluvial plains. High yield aquifers are typically restricted to narrow zones near major streams and rivers (e.g., Miramichi River valley), where infiltration through existing permeable glaciofluvial sediments in the river valleys occurs.

The regional bedrock groundwater systems in New Brunswick are either igneous and metamorphic-rock hosted systems, controlled by fracture and fault systems and rock fabric orientation, or shallow sedimentary rock hosted systems of the Maritimes Basin. Typically the basement rocks in New Brunswick, composed of folded and consolidated rocks in the north and a region of intrusive igneous and metamorphic rocks in the south, are generally considered to have poor aquifer potential. Within the Maritimes Basin hydrogeological system, groundwater predominantly flows through fractures and to a lesser extent through the porous matrix of the rock formations. These aquifers extend laterally up to a few kilometres depending on local stratigraphic variation. Three Carboniferous age bedrock aquifers have been identified as important hydrostratigraphic units based on their productivity and proximity to New Brunswick's urban centres. These include, from youngest to oldest, the Pictou Group, the Boss Point Formation of the Cumberland Group, and the Hillsborough Formation of the Windsor Group.

3.5.5 Natural Resources

Current and past geological resource exploration and extraction in New Brunswick has ranged from precious and base metals to evapourites and to coal and hydrocarbon resources. The locations of major natural resource areas in New Brunswick are depicted on **Figure 10**. The highest petroleum resources potential in New Brunswick is currently in the Maritimes Basin where natural gas, oil, oil shale, bitumen and coal have been identified. Crude oil and natural gas have been produced in New Brunswick since the early 1900s and, although, there has been a decline in activity, sweet natural gas is still being produced from the McCully Gas Field near Sussex and oil is again being pumped from the Stoney Creek field near Hillsborough. In northern New Brunswick, Middle Ordovician sediments, along the southern margin of the Gaspé Belt, also exhibit hydrocarbon potential. There are also bituminous shale licences south of Moncton along the Petitcodiac River; however, there is currently no commercial production. Significant coal resources occur within the Maritimes Basin at Minto that have been mined for more than 300 years from a single seam of coal 30-90 cm thick, 33 km long and 13 km wide.

In addition to hydrocarbon and coal resources, the base metal deposits (e.g., copper, lead, zinc, and silver) occur in the Bathurst region, epigenetic gold deposits are found throughout the province and there is a burgeoning potential for economically feasible uranium deposits in the Maritimes Basin.

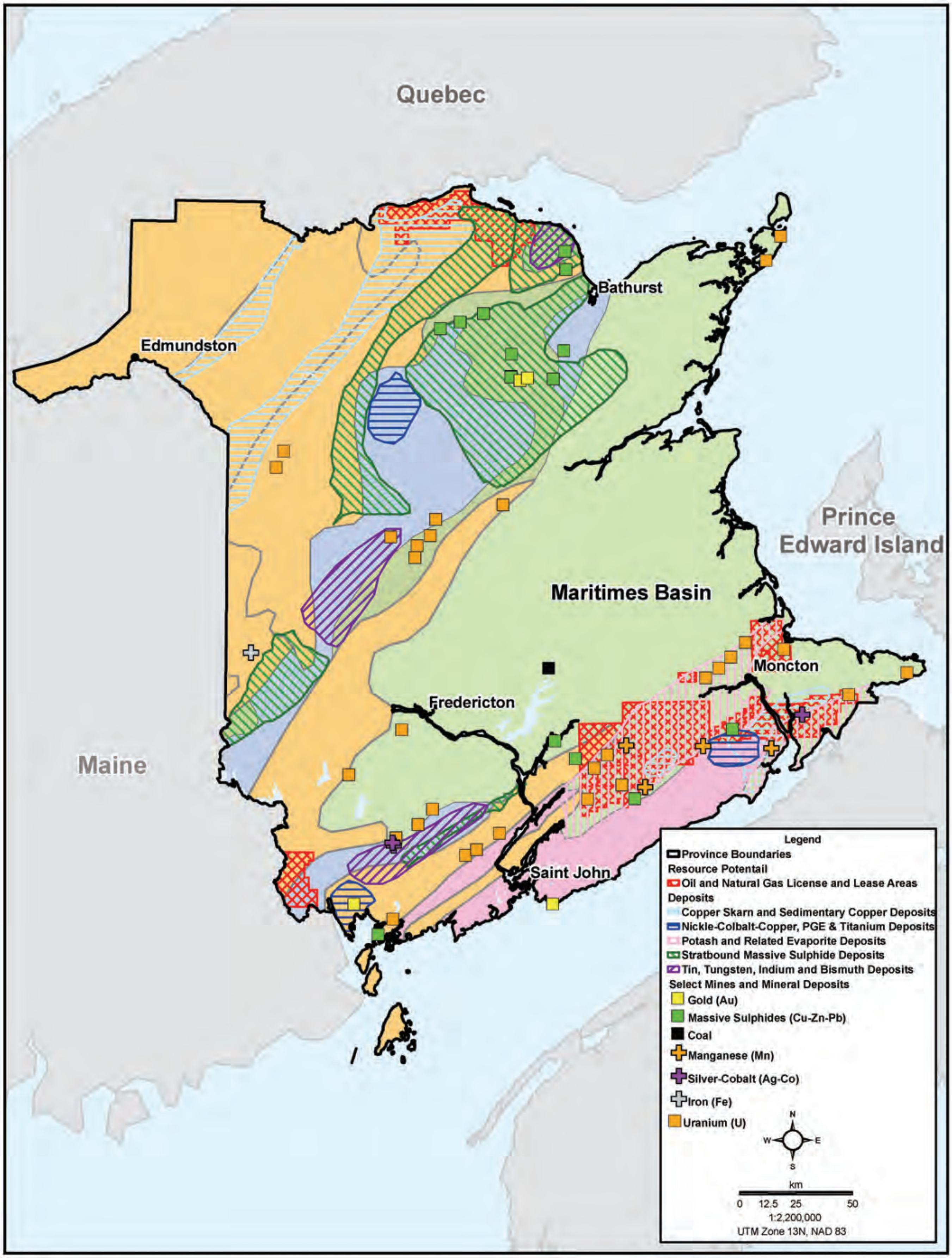
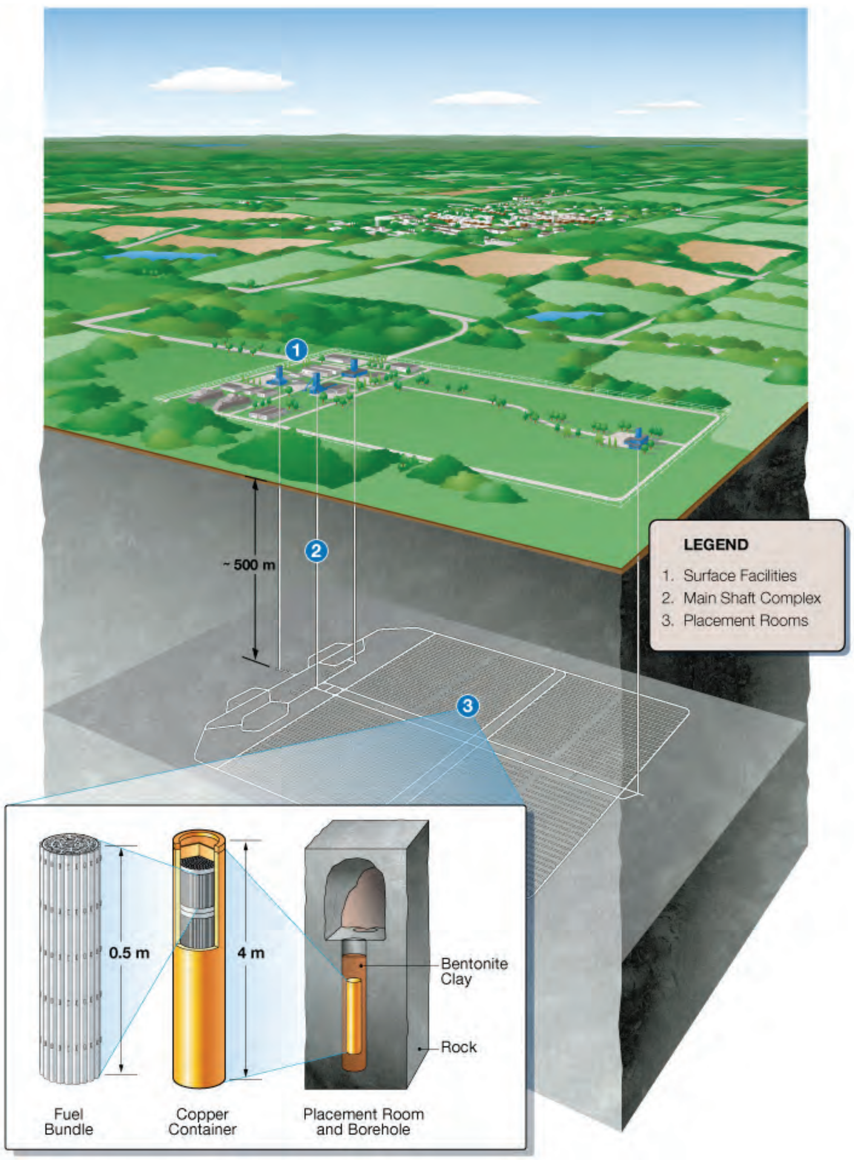


Figure 10: Natural Resources of New Brunswick

4. FEASIBILITY OF USING GEOSCIENTIFIC FACTORS FOR EARLY IDENTIFICATION OF LARGE UNSUITABLE GEOGRAPHIC AREAS FOR SITING A DEEP RESPOSITORY

4.1 ASSESSMENT APPROACH FOR THE FOUR NUCLEAR PROVINCES

The ability of a deep geological repository to safely contain and isolate used nuclear fuel relies on a multi-barrier system comprised of the form and properties of the waste, the engineered barriers around the waste and the natural barrier provided by the host rock formation in which the repository will be located (**Figure 11**).



Reference: NWMO, 2009

Figure 11: Conceptual Layout of a Repository Showing Multi-barrier Isolation of the Used Nuclear Fuel

The geoscientific factors that are needed to ensure safety in the Canadian context were discussed in Section 2.4 and summarized in Table 6. The following sections assess whether these factors could be practically used by the NWMO to exclude large geographic areas of the four nuclear provinces prior to or early in the siting process, as described in the objective for this study.

The assessment of whether a given geoscientific factor could be used as an early exclusion criterion was conducted considering the following questions:

1. Are existing data available for a geoscientific factor at a geographic scale that is comparable to the size of a geological repository (i.e., about 6 km^2 at the surface and about 1.8 km^2 in area underground)?
2. Are existing data available for a geoscientific factor at the depth proposed for the geological repository (i.e., approximately 500 m underground)?
3. Are the geoscientific data to be applied for the exclusion of a large area available at a consistent scale and level of detail across all four nuclear provinces?
4. Are the geoscientific data readily available from existing sources or is it necessary to undertake field investigations (e.g., geophysical surveys, intrusive investigations, etc.)?
5. In the context of a multi-barrier approach to safety, can a geoscientific constraint be addressed through engineering design of the repository, waste containers or other features of the repository system?
6. How much certainty is there that existing information relevant to a geoscientific factor will be valid in the future or representative of prevailing conditions at a repository site in the future?
7. How much certainty is there that existing geoscientific data regarding past natural events (e.g., earthquakes) are representative of future conditions?

4.1.1 Geological Factors

The geologic setting is clearly important to safety assessment of a potential repository as the host rock formations surrounding a repository represent the primary natural barriers within a multi-barrier repository system that ensures safety. As noted in Table 6, key geological factors considered as potential exclusion criteria are rock type, homogeneity and continuity of the rock type, the potential host rock volume, and soil cover. For each of these factors, there are favourable and unfavourable natural characteristics with respect to siting a potential geological repository.

International experience indicates that no one rock type is favoured and that sedimentary rocks (e.g., claystones, shales, salt formations, limestones, dolostones) and crystalline rocks (e.g., granites, gabbros, volcanics) all have the potential to offer adequate containment and isolation capabilities. Therefore, there is no reason to exclude general areas associated with a specific rock type.

A major challenge when trying to use geological factors in screening studies is associated with the consistency and scale at which these characteristics are mapped. The foot print of a geological repository (~6 km^2) constitutes a very small surface area compared to the geographic extent of the four nuclear provinces. The question is whether the scale of available geological mapping is refined enough to identify large areas that are not suitable and at the same time being certain that these large areas do not include local areas that would be potentially suitable for safely hosting a geological repository.

As shown in Table 7, geological characteristics have been mapped at various scales in the four nuclear provinces. Province-wide mapping ranges from approximately 1:50,000 (representing an area of 625 km^2 to 1: 1,000,000 (representing an area of 15,625 km^2). As such, small scale mapping of the geological characteristics within one map sheet would likely be too diverse to exclude the whole map sheet. It is important to recognize that, at these scales, all geoscientific details are not consistently represented from province to province. Although there may be regions that appear unfavourable at these scales, there may be sub-regions within those regions that could be favourable. Similarly, regions that appear favourable may contain localised areas that are not suitable. This point is conceptually illustrated in Figure 12.

Table 7: Scales of Geological Mapping available in the four nuclear provinces

Map Type	Saskatchewan	Ontario	Québec	New Brunswick
Surficial Geology	**All Province:** 1: 250,0000	**South Ontario:** 1:50,000 **All Province:** 1:1,000,000	Currently N/A	**All Province:** 1:500,000 30% of province available at 1:50,000.
Bedrock Geology	**All Province:** 1: 250,000 Selected geological maps at 1: 20,000	**South Ontario:** 1:50,000 **All Province:** 1: 250,000	**All Québec:** 1:250,000 Majority of Province at 1: 50,000	**All Province:** 1:50,000 Province is planning on producing 1:20,000 for the entire province.

In northern Ontario, the best data set for bedrock geology mapping is compiled at 1:250,000 scale. One 250,000 scale map sheet, for example, covers the whole Central Abitibi Greenstone belt that includes the communalities of Timmins, Kirkland Lake, Englehart and Iroquois Falls. At this scale, considerable variation in geology occurs and, more importantly, considerable generalization of the data is necessary. For example, in the Central Abitibi Greenstone belt, rock types range from granite to metavolcanic to relatively undisturbed clastic sedimentary rocks. This may, on a small scale, seem to be an inappropriate area for a repository due to the complexity of the geology, the fault features that exist, and the number of existing or abandoned mines. However, within that map sheet there are granitic/grandiorite plutons covering an area of over 200 km^2 in area. These rocks could be suitable for hosting a geological repository but site-specific study would be necessary to confirm this.

Other large scale specialty maps exist in specific areas of Ontario, which generally range from approximately 1:5,000 to 1:50,000. Areas of greater economic interest typically have finer scale mapping completed. For example, within the Central Abitibi Greenstone belt map sheet, there are a number of 1:20,000 scale map sheets but even these represents areas of approximately 100 km^2, which is an area large enough to potentially have considerable variation in the geological characteristics.

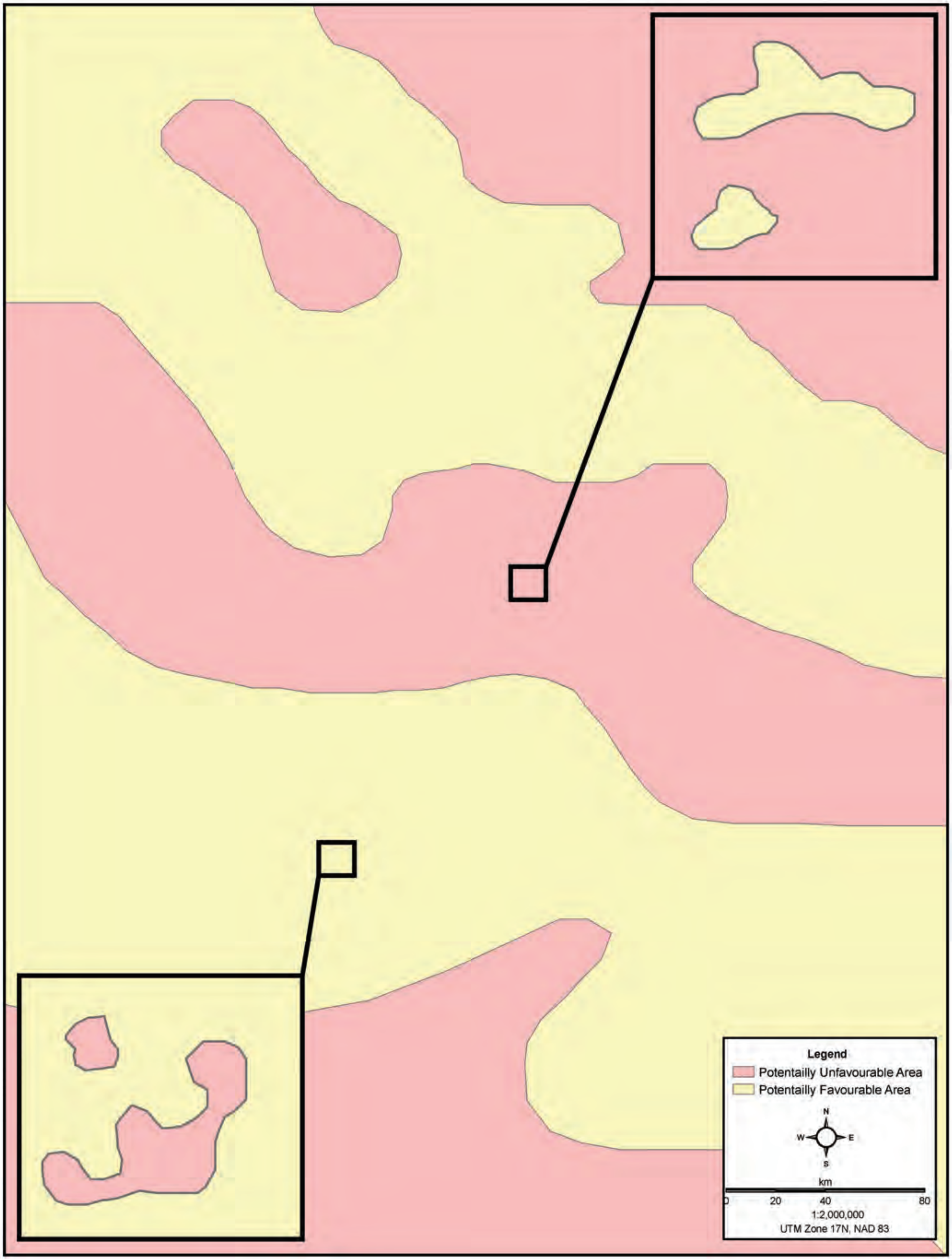


Figure 12: Examples Illustrating that Identification of Favourable & Favourable Areas Depend on Study Scale

Similarly, in New Brunswick, bedrock geological mapping at 1:50,000 scale is available for the entire province. The province is known to have some areas of very complex geology and one significant example of this is the area surrounding the Bathurst Mining Camp in the Bathurst region of northeast New Brunswick.

In this area, mapping at 1:20,000 exists and the bedrock geology at this scale is illustrated on Figure 13. The figure shows that the area is comprised of the very complexly folded and faulted Lower Paleozic rocks with younger (Late Devonian) crystalline felsic plutonic intrusions. These fairly massive, homogenous and unfaulted crystalline rock environments could be considered as potentially suitable rock formations for hosting a repository both in terms of geological characteristics and rock volume. Figure 13 shows that the surface area of a repository, as shown in the legend, is small compared to the surface area covered by these massive plutonic intrusions. This example illustrates that, even at the fairly large scale of 1:20,000, areas of mapped complex geology cannot not be excluded as they may contain potentially suitable host rocks.

The factor that the host rock should be sufficiently homogeneous with small variation of rock properties in the vicinity of the repository site cannot be assessed on a regional scale. The homogeneity of the rock type can really only be assessed by local studies (e.g., drilling and surface based research) to gain an understanding in three dimensions. Using the volume of host rock as an exclusionary criterion, it would be impossible to exclude a site based on information available from regional mapping. These studies do not accurately reflect changes in the rock property with depth and this can only be done at an appropriate level of precision and resolution, with certainty, by local site specific studies.

Finally, it is not possible to adequately assess surface characteristics of the site (i.e., topography, soil cover, soil types, etc.) to exclude large areas. Within a large area, there will typically be considerable variations in these features such that it is impossible to uniformly characterize the area for soil cover without detailed site specific investigations. As an example, the Region of York in southern Ontario extends from the south shore of Lake Simcoe south to the City of Toronto and contains a portion of the Oak Ridges Moraine (ORM), a regionally significant physiographic feature. The overburden thickness of the ORM is more than 200 m in places, which would hinder the characterization of a deep potential host rock as well as construction activities. The ORM is known to contain some of the thickest overburden deposits in southern Ontario. However, within the Region, the overburden thickness thins dramatically towards Lake Simcoe where, in places, it can be less than 5 m. Therefore, the Region would not necessarily be excluded from further consideration on the basis of overburden thickness alone due to its considerable variation within this large area.

Given the different scales and detail on existing geological maps and the uncertainty of regional information on geological conditions at repository scale and depth, there is no reason to exclude large areas based on geological factors.

4.1.2 Geomechanical and Seismic Factors

4.1.2.1 Geomechanical Factors

Geomechanical properties of the host rock should be favourable for the safe construction, operation and closure of the repository and for ensuring the long term stability of the various

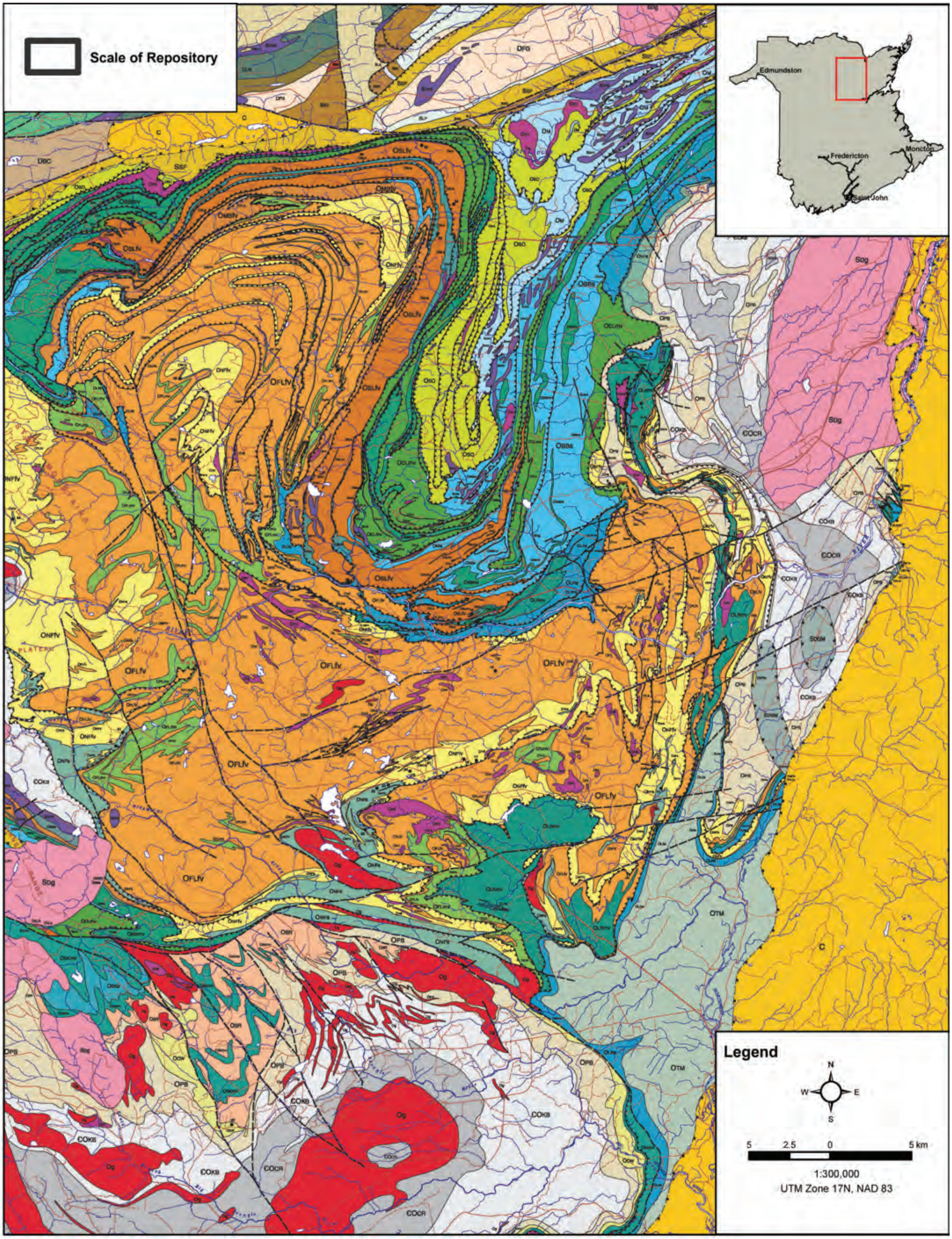


Figure 13: Geological Complexity in the Bathurst Region Versus Repository Scale, New Brunswick

components of the repository systems, including the geological barrier. Existing ***deformation and fault zones*** may cause damage to the repository components (container and seals) and serve as direct pathways or short circuits to the biosphere. Similarly, ***in–situ stress*** conditions and the rate of erosion and uplift may also compromise the integrity and the long-term performance of the repository.

Deformation and fault zones can vary from discrete well defined major zones to complex networks of minor deformation and fault zones. Major deformation zones are well known and mapped at a regional scale as they are typically associated with tectonic features. However, fracture density and deformation areas identified in lineament maps are not detailed enough to rule out with certainty the existence of stable and less structurally complex areas within or in the vicinity of existing deformation and fault zones. Figure 14 provides a detailed example of a major deformation zone in northeastern Ontario, the Porcupine – Destor Deformation Zone, and associated major and minor fault structures. While areas associated with this complex deformation zone should clearly not be favoured for siting a geological repository, the full area cannot be ruled out based on available mapping as sufficiently large areas of more structurally sound rocks are available at a repository scale.

Similarly, regional rock stress maps display great detail about the regional stress direction and magnitude. It is, however, insufficient to exclude large areas based on these data, as stress data commonly shows variation over short distances. Assessment of the suitability of a site in terms of in-situ stress conditions needs to be done using site specific information and analysis at the repository scale.

Based on available information on geomechanical rock properties across the four nuclear provinces and the variability of regional information, there is insufficient information to exclude large areas at a pre-screening stage using geomechanical factors.

4.1.2.2 Seismic Factors

It is common to all the guidance documents and siting processes, that current and future seismicity at the selected site should not compromise the containment and isolation capability of the overall repository system. This includes the consideration of fault zones that could be potentially reactivated during post-glacial events.

An example of a potentially large area that could, at first glance, be ruled out based on seismicity is the Charlevoix Seismic Zone (CSZ), located near Québec City (Figure 15). This is the most seismically active zone in eastern Canada and has been subject to five significant earthquakes of M6 or larger. Work completed by the Geological Survey of Canada; however, in the 1970s, delineated the CSZ to be an active zone about 30 by 85 km, elongated along the St. Lawrence River. The subsurface in this area is known to be faulted and, based on experience in other seismically active and faulted terrains (e.g., Japan), there is a high probability that some faults may move again, perhaps repeatedly, during the next million years due to earthquakes.

However, as Figure 16 illustrates, it may be possible to locate a repository away from the fault, once they have been mapped in detail. This is justifiable because a repository could be located relatively close to an active fault without sustaining any damage from shearing by future fault displacements. Large displacement along an active fault, possibly triggered by an earthquake, might only cause small (millimetre to centimetre) shear displacements along existing fractures as little as a few hundreds of metres away from the active fault zone, (NUMO, 2004).

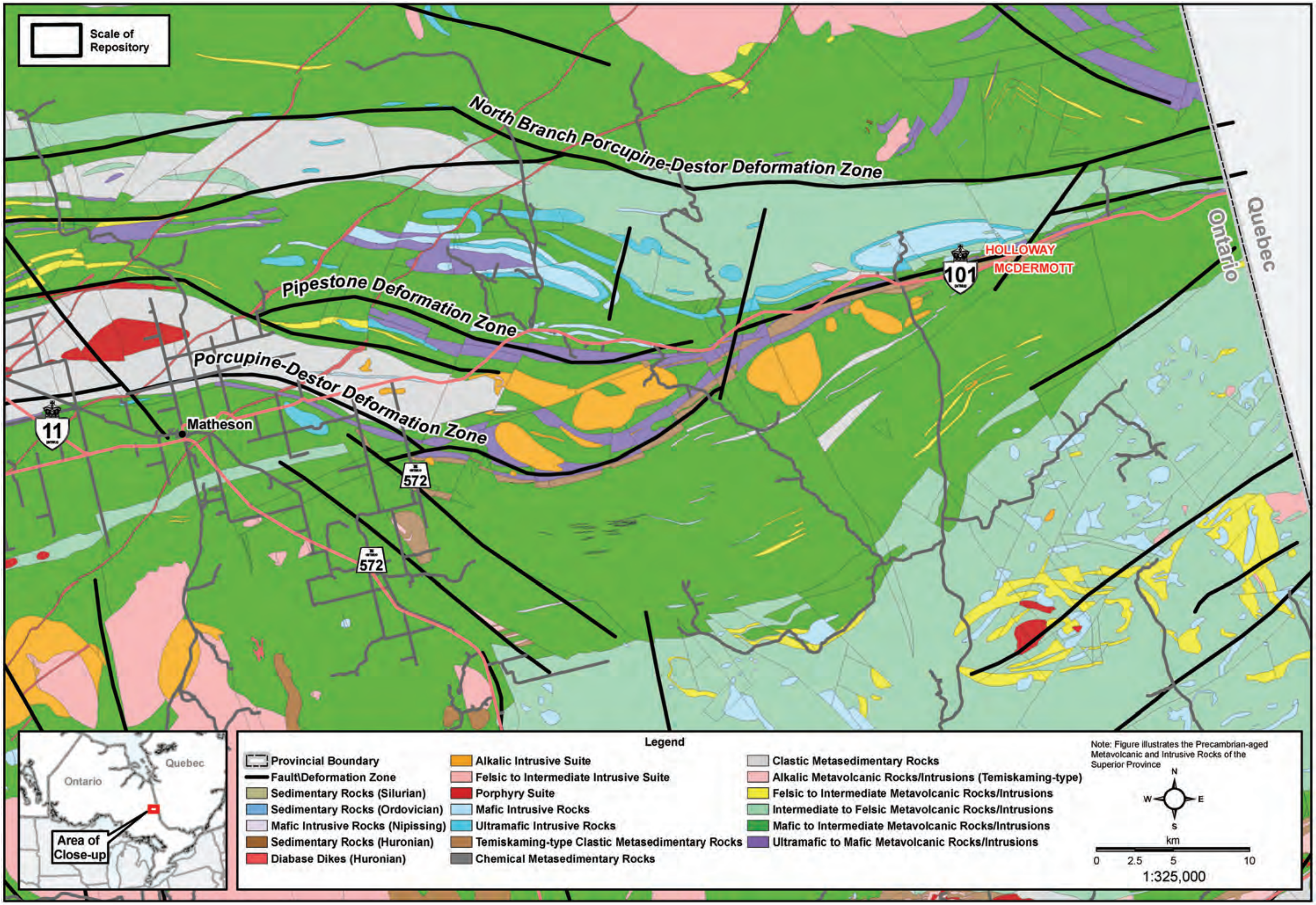


Figure 14: Deformation and Fault Zones in the Porcupine-Destor Deformation Zone, Northeastern Ontario

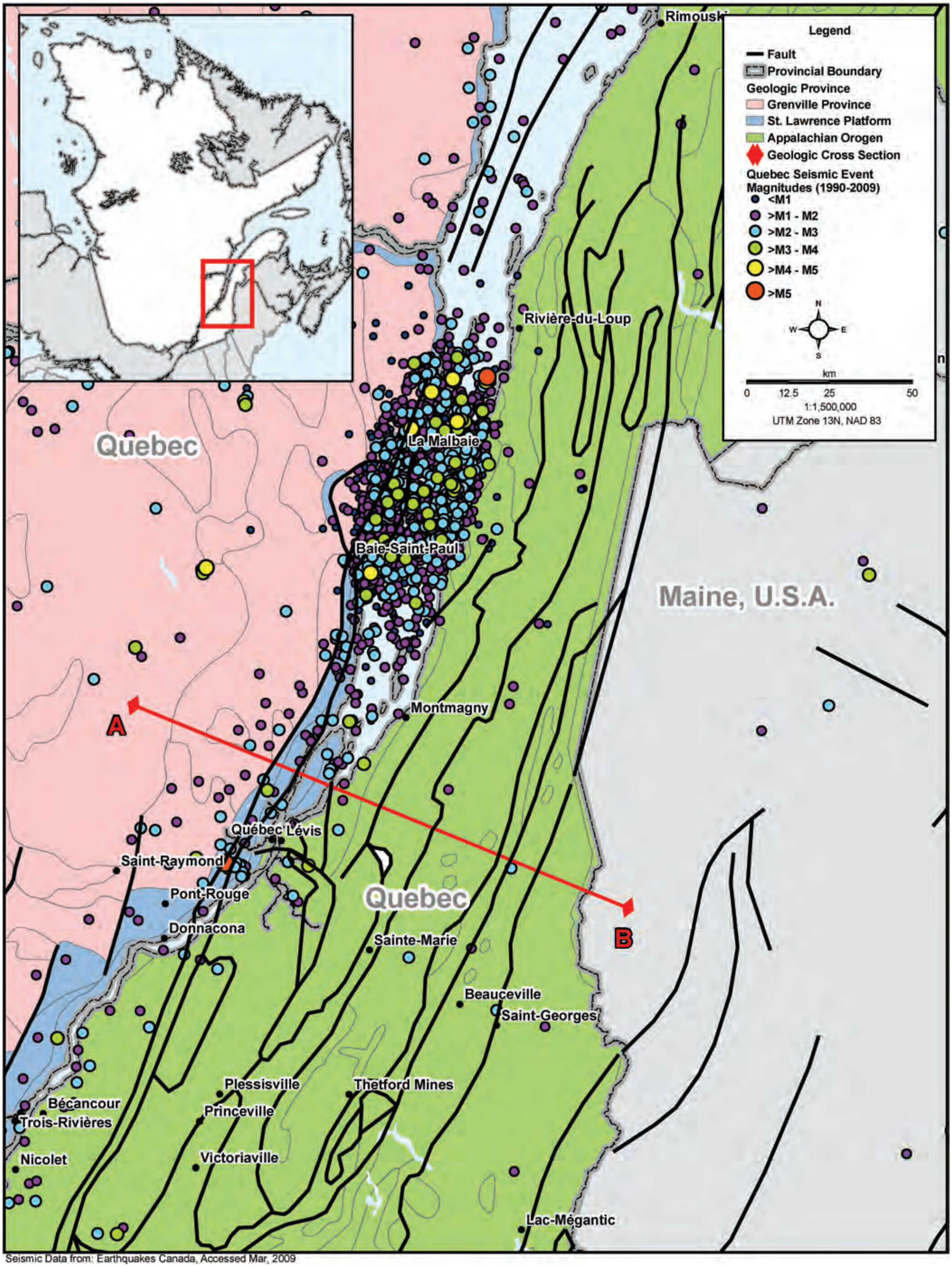
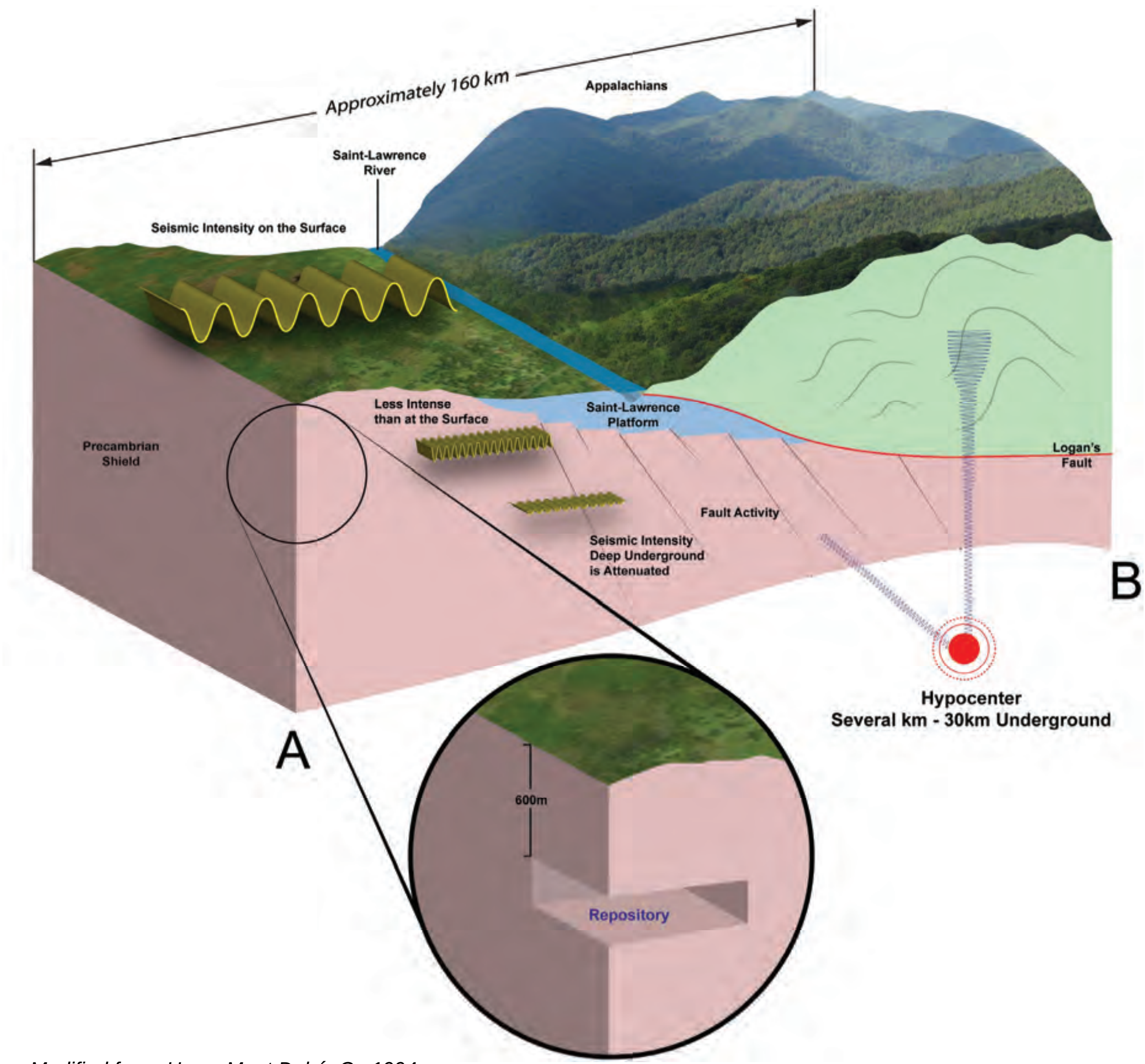


Figure 15: Seismic Activity, Charlevoix Area, Southern Québec

However, the extent to which this can occur will be highly site-specific, depending on the size of active faults in the area, the magnitudes of earthquakes associated with them, the local stress regime in the rock, the properties of the repository host rock, the age and frequency of previous deformation and the distance from the fault.

Another consideration, again highlighted by work done by NUMO in Japan, relates to seismic attenuation with depth. Shaking associated with seismic events (earthquakes) can cause extensive damage to structures at the ground surface above the hypocentre (actual location of the earthquake underground), because these structures can move freely. By contrast, underground structures respond mainly by moving together with the surrounding rock and, as a result, damage is minimal. This effect becomes more attenuated with depth (Figure 16). Seismic shaking at several hundreds of metres depth in competent rocks is of limited concern as it is well known to have little structural impact on underground facilities even in the largest events. Should a repository be contemplated in these areas, surface structures would have to be designed according to the local seismic hazard.



Modified from: Hocq, M. et Dubé, C., 1994

Figure 16: Conceptual Block Model of Southern Québec Illustrating Seismic Attenuation with Depth

Although the Charlevoix Seismic Zone has many faults and is subject to much seismic activity, the area cannot be excluded based on this criteria at a regional scale as that there are areas within the region that contain fewer faults and may have the ability to host a repository.

Most of the area of the four nuclear provinces have a low incidence for seismic activity and together with the uncertainty of the subsurface location of faults indicates that seismicity is not a reliable exclusion factor without significant site specific investigations.

4.1.3 Hydrogeochemical Factors

Hydrogeochemical characteristics of the host rock and the surrounding geological environment play an important role in the long-term performance of the engineered barriers as well as in retarding the transport of radionuclides from the repository to the accessible environment. Hydrogeochemical characteristics of the host rock and deep groundwater systems are also important for developing conceptual models of the site that will be used to build and demonstrate confidence in the long-term stability and resilience of the geosphere.

Hydrogeochemical characteristics of interest include: salinity, pH, redox potential, Eh, conductivity, major and trace element concentrations, and dissolved gases. However, based on limited site specific information, these factors are known to vary considerably over short distances and with depth. In addition, hydrogeochemical parameters are not mapped consistently across the provinces, and not at all for large areas. It is therefore very difficult to consider any pre-screening assessment at a regional scale. Hydrogeochemical characteristics are usually assessed during detailed site evaluations through site specific sampling and testing.

Using hydrogeochemical factors as exclusionary criteria are not possible without detailed site specific studies.

4.1.4 Hydrogeological Factors

The requirement for favourable hydrogeology exists in all guidance documents and is considered by each country with a geological repository program. The importance given to groundwater is because it is the most effective natural carrier of radionuclides.

In general, host rocks with low groundwater velocities along the flow path are favoured as this minimizes the flux of contaminant that can migrate through the geologic materials. For a given site, groundwater velocities are controlled by the hydraulic conductivity of the host rock and the hydraulic gradient. Gradients are the result of topographic variation, past induced hydrogeologic conditions, and the length of the flow path. The hydraulic conductivity depends on the properties of the rock and the nature and density of fractures. These characteristics exhibit considerable variations at both the regional and local scales. For example, numerous field data in Canada and around the world show that hydraulic conductivity can vary by many orders of magnitude over short distances within the same rock type. It is therefore impossible to conduct regional scale pre-screenings based on gradients or hydraulic conductivities. While general areas with likely favourable hydraulic characteristics can be identified, the suitability or exclusion of a particular site needs to be assessed using site specific information gathered through detailed field investigations and analysis.

An important consideration with respect to hydrogeological factors is whether to exclude large areas with potable or fresh groundwater. As noted in Section 3, where fresh water aquifers have been mapped, they occur at relatively shallow depths of less than approximately 150 m, well above the depth of a potential repository. Deeper groundwater at the approximate depth of a potential repository, whether from the Western Canada Basin (WCB), the Canadian Shield, or the Michigan Basin, is saline and not suitable for drinking water purposes. On this basis, the presence of significant fresh water aquifers in the near surface environment should not be used as exclusionary criteria for a large area. Local-scale studies would be required to determine the effects that a potential repository would have on shallow freshwater aquifers.

An example of this is well illustrated by the WCB in Saskatchewan. Figure 17 illustrates the geological and hydrogeological stratigraphy of the WCB and the “repository horizon”, a band at 600 to 800 m BGS where a potential repository could be located. The inset map shows the geographic distribution of aquifers in central and southern Saskatchewan. If siting a repository in an area containing an aquifer was an exclusionary criterion then over half of Saskatchewan could be eliminated from further consideration. However, when considering the third dimension (depth) it can be clearly seen from the cross-section that the potential exists to site a repository at depth below an aquifer where the geology provides the necessary containment. Site specific studies would be required to confirm aquifer properties and those of the formations below the aquifer to ensure long-term protection of the groundwater resource.

Insufficient data are available to exclude large areas based on hydrogeological formation properties that are known to vary over many orders of magnitude over short distances. Further, this study concludes that large areas can not be excluded based on the presence of fresh water aquifer systems. Fresh water aquifers are generally shallow in depth (<150 m) and opportunities exist to site a repository below such near surface resources. However, areas containing extensive groundwater resources should be avoided, specifically at the repository depth.

4.1.5 Natural Resource Related Factors

Consideration of natural resources as a siting factor is important as there is a need to minimise the risk of human intrusion, deliberate or inadvertent, into a repository, particularly during the long post closure period. The siting of a facility should be made with consideration of actual and potential human activities at or near the site. The most likely activities giving rise to such intrusion is considered to be the pursuit of economically exploitable natural resources. As such, preference tends to be given to geological formations that have no great scarcity or economic value.

The ability to exclude a site based on the presence of natural resources varies between resource types, and the amount of existing geoscientific information that exists in a given area. However, based on review of known resources in the four provinces, these deposits are either relatively localized to small areas associated with certain lithological and / or structural terrains, or occur at specific depths. As a result, there may be suitable repository locations within the general area of a known resource but at a different lateral location or at different depths. Therefore such, large areas of natural resources should not automatically be excluded.

As an example, the Western Abitibi Greenstone Belt in northern Ontario along the Porcupine-Destor Deformation Zone (PDDZ) between Timmins and the Québec border is a world-class

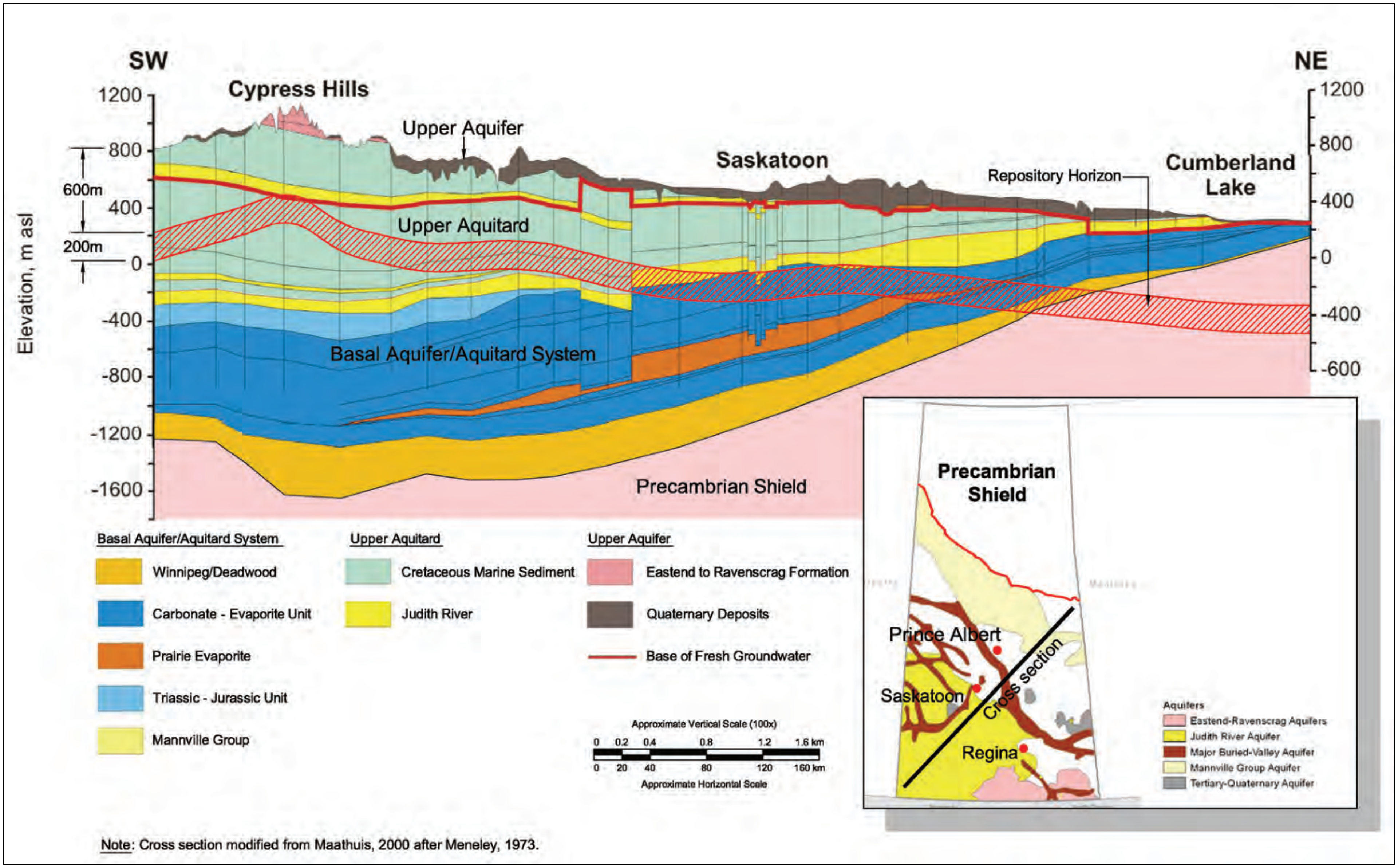


Figure 17: The Geological and Hydrogeological Stratigraphy of the Western Canada Basin, Saskatchewan showing a Hypothetical "Repository Horizon"

gold camp with total production of 2,350 tonnes of gold. In addition to the major and minor gold mines in the area, the region also contains major base metal deposits. The region is comprised of a repetition of similar laterally extensive volcano-sedimentary successions spanning 75 million years. The deformation zone (PDDZ) within this region, as well as the Larder Lake–Cadillac deformation zone to the south, are the most important deformation zones within the Abitibi Greenstone Belt in terms of both structural effect and gold production. The deformation zone occurs principally in ultramafic volcanic rocks and, to a lesser degree, the younger Timiskaming assemblage. The majority of gold deposits occur within the PDDZ or along splay faults to the south. Gold deposits are hosted in a variety of rock types, but are all structurally controlled and spatially associated with alkalic intrusive rocks or lamprophyre dikes.

Figure 18 illustrates that despite the presence of mineral resources and geologic structure (e.g., faults), the entire region cannot be excluded, as at a local scale, a suitably sized area for a repository could be located in the area that is outside the PDDZ, away from faults and shear zones; not near any alkaline intrusive rocks, and in an area without economically exploitable metallic mineral resources. Despite the density of mineral deposits and complexity of structural geology in this area, it should not automatically be excluded as a potential repository site without site-scale investigations. This can only be assessed through local-scale studies.

In general, areas of economically exploitable minerals and other natural resources should be avoided. However, it would be premature to rule out large areas without site specific information.

4.2 INTERNATIONAL EXPERIENCE

The geoscientific siting conditions in Canada are dependant upon specific site, local and regional conditions; therefore care must be taken when considering and transposing international experience. However, international experience is important in the context of “lessons learned” and confirmation that Canada is on the “right track”. All international site selection programs adopt geoscientific criteria as a centre piece of their programs. With few exceptions, the international consensus on applying geoscientific exclusion criteria at a pre-screening level of the site selection process is that it is impractical to exclude large areas from consideration. The reason for this is that acceptable sites may be unnecessarily screened out before such time that detailed investigations can be conducted.

In all countries existing geologic data on a broad scale only exists in two dimensions. Several countries recognize this limitation. Essentially there are no regional / provincial studies that consider the depth dimension, certainly to the depths contemplated for a repository. Therefore the complexity and constraints that may be observed at the surface may not persist to depth, thus highlighting the need for site specific studies. The converse may also be true.

IAEA have provided overview criteria for repository site selection. They indicate that siting must take into account national imperatives and that their document is to provide the responsible parties with a guideline for their approach to site selection, that there is not one approach that fits all, although there are common elements for protecting human health and the environment.

Canada is unique within the international community currently working through repository siting programs. The four nuclear provinces in Canada have a total area of over 3,300,000 km^2,

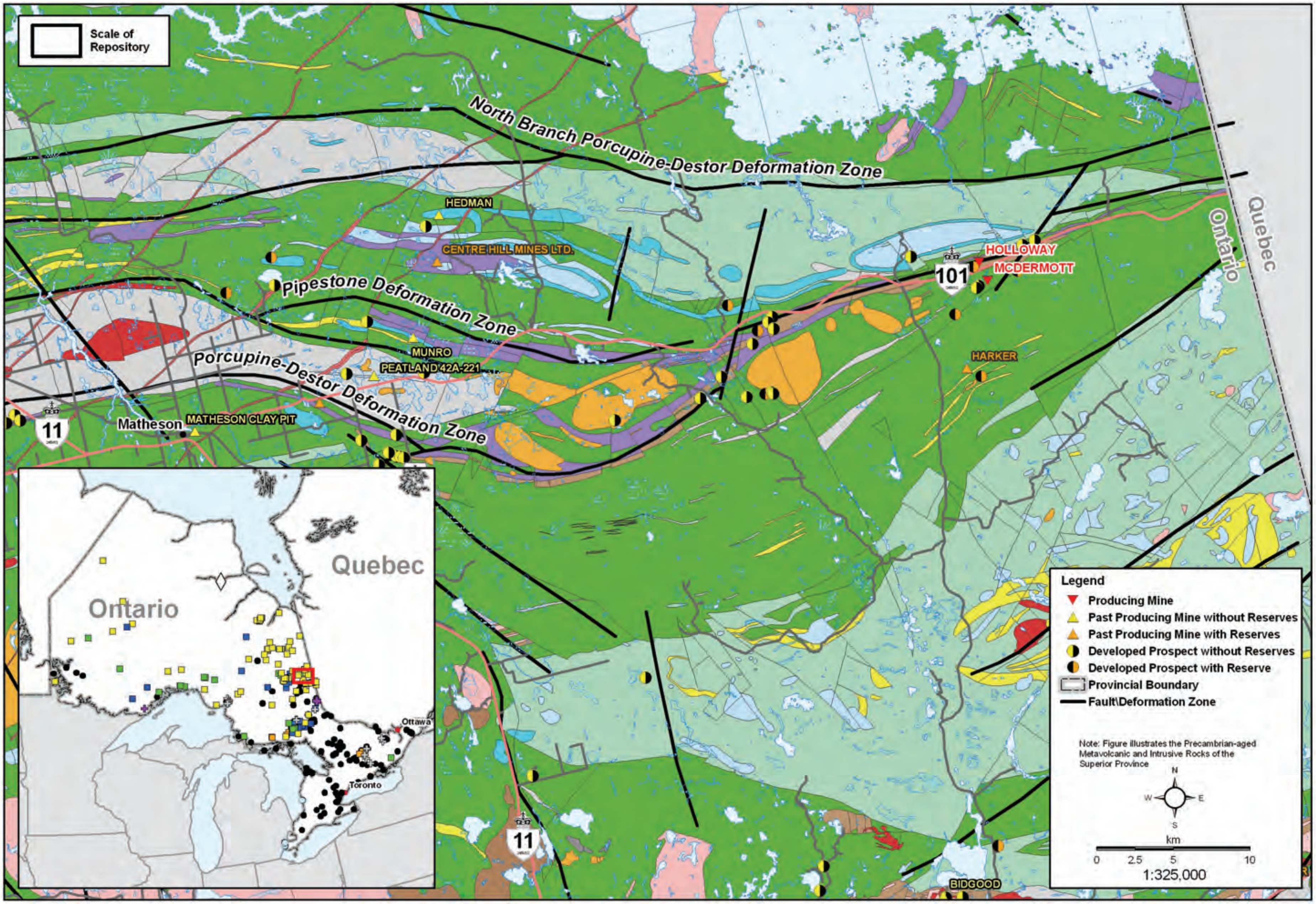


Figure 18: Structural Geology and Economic Resources Related Factors, Porcupine-Destor Deformation Zone, Northeastern Ontario

whereas the six countries described in Section 2.3 have a combined area of 1,800,000 km^2. Their mapping is generally at a more detailed scale than that of most of the Canadian area, yet they still conclude that it is not technically practical to exclude large areas based on regional information. They further conclude that areas that at first glance are of less interest on a national or provincial scale can not be excluded since on a local scale there may be sites of interest which may be rejected when making regional generalizations with incomplete data (Figure 11).

Swedish experience (SKB, 1995) concluded that it is not obvious to completely exclude areas or regions which, on a national scale, appear to be less favourable. They continue; *"whether an area is suitable or not, cannot be determined in a general siting study; more information are necessary for such an evaluation. The suitability is primarily determined in connection with feasibility studies and site investigations."*

The United Kingdom (UK) study had as a mandate the purpose of identifying areas of the UK where it would be difficult to develop a geological repository. The UK study (Department for Environment, 2007), concluded, however; that there are *"few specific geologies that we believe can be excluded from the siting process straightaway".* However, they further concluded that exclusionary factors should include the siting of a repository in freshwater aquifers (to protect water supply) and in natural resources at depths greater than 100 m (to guard against future human intrusion).

The Swiss program for site selection is detailed and also is seeking volunteer communities. However, because of its size (41,300 km^2 just over half the size of New Brunswick 71,000 km^2) it has opted for a site selection process using constraint mapping and site investigations from the beginning.

Of all the countries trying to identify a repository for spent nuclear fuel, perhaps Japan faces the most geoscientific challenges. The country is located at the junction of three tectonic plates, above subductions zones, with hundreds of active volcanoes and faults. In such a setting one would think that it would be easy to exclude large areas. However, the Japanese authority NUMO, which is responsible for siting a repository has essentially identified only two exclusionary criteria. The first being to exclude areas within 15 km of an active volcano; the second factor is to avoid active faults and rocks with high deformation rates. However, even in terms of the later factor, NUMO recognizes the need for site investigations before such areas can be excluded from a siting perspective (NUMO, 2004).

5. CONCLUSIONS AND RECOMMENDATIONS

This report reviewed the geoscientific characteristics of the four nuclear provinces (Saskatchewan, Ontario, Québec and New Brunswick) as well as the proposed geoscientific factors that would need to be considered to ensure the safety of a deep geological repository. The report further assessed whether it is possible to use any of these geoscientific factors to exclude large areas of the four nuclear provinces early in the siting process (pre-screening). The review of the geoscientific factor and their potential use as exclusion criteria was conducted based on Canadian regulatory requirements, international guidance and experience in other countries pursuing the development of deep geological repositories. In considering the suitability of the various geoscientific factors for pre-screening, it was assumed that the "exclusion of large areas" would only be feasible if there was certainty that excluded areas would not contain local areas that could be potentially suitable to safely host a geological repository.

A summary of the proposed geoscientific factors that would need to be considered to ensure safety of repository was provided in Table 6. These factors are based on the main safety functions that a repository needs to achieve in order to ensure safe containment and isolation of used nuclear fuel. They cover characteristics related to geology, geomechanics, seismicity, hydrogeology, hydrogeochemistry and natural resources.

The assessment of whether geoscientific factors could be used to exclude larges geographic areas of the four nuclear provinces highlighted two main challenges. First, most of the geoscientific factors that could be used as exclusion criteria require site specific information at depth which is typically lacking at early stages in the siting process. The other challenge is associated with the large geographic extent of the four nuclear provinces (3,300,000 km^2) compared to the typical repository scale at which site specific geoscientific information is needed (~6 km^2). After reviewing the international literature and the available geoscientific information from the four provinces, it is concluded that:

> *It is not practical to exclude large areas of the four nuclear provinces early in the siting process (pre-screening) based on the geoscientific factors identified herein. However, some of the geoscientific factors may be used as exclusion factors at later stages of the site evaluation process as more local scale and site specific information becomes available such as during screening studies, feasibility studies and detailed field investigations. This conclusion is consistent with international experience and the outcome of general siting studies conducted in other countries.*

The conclusions associated with each factor considered are as follows:

- **Geological factors** - given the different scales and detail on existing geological maps and the uncertainty of regional information on geological conditions at repository scale and depth, there is no reason to exclude large areas based on geological factors.
- **Geomechanical factors** - based on available information on geomechanical rock properties across the four nuclear provinces and the variability of regional information, there is insufficient information to exclude large areas at a pre-screening stage using geomechanical factors.
- **Seismic factors** - most of the area of the four nuclear provinces have a low incidence for seismic activity and together with the uncertainty of the subsurface location of faults

indicates that seismicity is not a reliable exclusion factor without significant site specific investigations.

- **Hydrogeochemical factors** - using hydrogeochemical factors as exclusionary criteria are not possible without detailed site specific studies. This finding is consistent with other international projects.
- **Hydrogeological factors** - insufficient data are available to exclude large areas based on hydrogeological formation properties that are known to vary over many orders of magnitude over short distances. Further, this study concludes that large areas cannot be excluded based on the presence of fresh water aquifer systems. Fresh water aquifers are generally shallow in depth (<150 m) and opportunities exist to site a repository below such near surface resources. However, areas containing extensive groundwater resources should be avoided, specifically at the repository depth.
- **Natural resource factors** - in general, areas of exploitable mineral and other natural resources should be avoided. However, it would be premature to rule out large areas without site specific information.

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