Regional Geologic Evaluations for Disposal of HLW and SNF: Archean Crystalline Rocks of the North-Central United States

Fuel Cycle Technology

Prepared for
U.S. Department of Energy
Used Fuel Disposition Campaign
Frank V. Perry, Richard E. Kelley, Damien M. Milazzo
Los Alamos National Laboratory
October, 2016
FCRD-UFD-2016-000634
Los Alamos Unlimited Release LA-UR-16-27845

SUMMARY

This report documents a regional evaluation of the geologic and hydrologic environment of the western Superior Province of the north-central US. This region is one of several major crystalline rock terranes in the US that could potentially host a deep geologic repository for radioactive waste. Neoarchean (Neoarchean = 2.5-2.8 Ga) granitic plutons and batholiths intruded much of the region in the late Archean (Archean = 2.5-4.0 Ga) and are a potentially suitable host-rock for a repository in granite host rock. Analogous granites in the western Superior Province of Canada and other similar tectonic settings in the world have fracture systems characterized by highly fractured low-angle deformation zones (thrust faults) that accommodated strain during regional continental accretion. Rock domains bounded by the deformation zones remained relatively undeformed and sparsely fractured through deformation and cooling of the plutons and may be suitable domains for repository construction. Available geotechnical information and GIS methods were used to evaluate a number of features, events and processes that could affect long-term repository performance in the region. Groundwater conditions at depths below several hundred meters are likely to be saline, reducing and static, but establishing the depth at which these conditions occur will require site-specific studies that document local differences in fracture systems, groundwater recharge/discharge zones, and other factors that influence the relationship between depth, groundwater chemistry and groundwater age. Glacial events may affect groundwater chemistry through infiltration of meltwater, but the impact on groundwater will depend on site-specific conditions of groundwater infiltration. Other external events such as seismicity and human intrusion through mineral exploration are not significant in the region due to the historically low frequency and magnitude of earthquakes and the absence of economic mineral deposits in the Neoarchean granites. Sedimentary overburden in the form of glacial deposits that cover most of the region would pose challenges to site characterization and repository construction. If glacial deposits were found to be desirable as an additional waste isolation barrier above the granite host rock, site-specific studies would be necessary to understand the isolation properties of these deposits.

CONTENTS

FIGURES

TABLES

ACRONYMS

AECL	Atomic Energy Canada Limited
DEM	Digital Elevation Model
DOE	Department of Energy
EDP	Eye-Dashwa Pluton
FY	Fiscal Year
Ga	Giga-annum (units of billions of years before the present)
GIS	Geographic Information System
GLTZ	Great Lakes Tectonic Zone
HLW	High-Level Waste
LANL	Los Alamos National Laboratory
LDB	Lac du Bonnet (Batholith)
Ma	Mega-annum (units of millions of years before the present)
NWMO	Nuclear Waste Management Organization (Canada)
R&D	Research and Development
SMU	Southern Methodist University
SNF	Spent Nuclear Fuel
UFDC	Used Fuel Disposition Campaign
US	United States
USGS	United States Geological Survey

Regional Geologic Evaluations for Disposal of HLW and SNF: Archean Crystalline Rocks of the North-Central United States

1. Introduction

The U.S. DOE's UFDC is supporting research on crystalline rock, shale (argillite) and salt as potential host rocks for disposal of HLW and SNF in a deep geologic repository. The distribution of these three potential repository host rocks is limited to specific regions of the US and to different geologic and hydrologic settings (Perry et al., 2014), any of which may be technically suitable as a site for deep geologic disposal. However, this report is intended to support a generic reference case (Mariner et al., 2016) representing the technical feasibility and performance of a repository in crystalline host rock.

In this report, we present a regional geologic evaluation, based on available data, of the western Superior Province of the north-central US. The western Superior Province is one of several major crystalline rock terranes exposed at the surface in the conterminous US (see Figure 2-1). The Superior Province in this region consists of Archean crystalline rocks with ages of ~3.6 – 2.6 Ga (Sims, 1995; Jirsa et al., 2013). Early Proterozoic (~2.5 – 1.8 Ga) crystalline rocks are exposed primarily to the east of the Archean rocks. The Archean crystalline rocks of the north-central US occur primarily in the state of Minnesota, with lesser areas of exposure in Wisconsin and the Upper Peninsula of Michigan. The Superior Province extends in the subsurface westward beneath North Dakota and South Dakota where it is covered by thick deposits of Mesozoic sedimentary rocks.

For this regional evaluation, we focus on the Archean crystalline rocks that form the western Superior Province and constitute the greatest area of exposed crystalline rocks within the north-central US (Sood et al., 1984). A large amount of relatively recent geoscientific information and data is available for this region from the published literature and from data maintained by state and national agencies. These data include a recently published geologic map of the crystalline basement rocks of Minnesota that is available in digital format, lending use of the data as part of a GIS database. Data and topics reviewed for this regional evaluation include geologic mapping, aeromagnetic and gravity data, sedimentary overburden, fracture systems in granitic rocks, hydrology and hydrogeochemistry, glacial events, seismicity and mineral exploration as it relates to the possibility of human intrusion. Although the western Superior Province is evaluated for this report, suitable crystalline rocks to host a repository are likely present in numerous other regions of the US.

In this evaluation, we focus on a group of Neoarchean (2.6-2.7 Ga) syn- to late-tectonic granite plutons that are widespread throughout the western Superior Province. These granites are relatively undeformed compared to other Archean crystalline rocks of the region. Analogous well-studied granites in the crystalline terranes of other countries suggest that the Neoarchean granites in the US are a potentially suitable host rock for a repository primarily because of their fracture characteristics.

Granitic rocks and the geologic environment of the western Superior Province share some characteristics with the granitic terrane at Forsmark, Sweden, which has been extensively studied and characterized as part of Sweden's HLW disposal program. These characteristics include a history of glacial cycles, glacial overburden on the granitic bedrock, and granite fracture domains that are both highly fractured and sparsely fractured. A Neoarchean batholith in the Canadian portion of the western Superior Province has been extensively studied for the Canadian HLW waste program and shares these characteristics. These two well-characterized granitic host-rock systems can be viewed as analogs to granites in the US portion of the Superior Province and provide an aid in evaluating the features and processes that would affect long-term repository performance in the crystalline terrane of the north-central US.

In this regional evaluation, we use GIS as the basis for examining existing data to document and understand the geologic and hydrologic environment of the Neoarchean granites. The data sets and methodology included in this evaluation extend the methodology incorporated in the LANL Regional Geology GIS database (Perry et al. 2014) to focus more on detailed studies of specific regional geologic environments. All of the maps in this report (except Figures 5-1 and 5-14) were produced at LANL using GIS software (ArcGIS 10) and GIS data listed in Table 3-1.

2. Crystalline (Granitic) Terranes in the US

The term "granite" used in this report is a general term describing medium to coarse-grained crystalline rocks, including intrusive igneous rocks and high-grade metamorphic rocks of felsic to intermediate composition (~65-75 weight percent SiO_2; Harrison et al., 1983, Sood et al., 1984). Granite, using this broad definition, is a potential host rock for a mined repository in crystalline rock. Crystalline rock terranes include granitic rocks as well as more mafic and finer grained igneous and metamorphic rocks. A guideline for siting a mined repository in crystalline rock is that the rock must be exposed at the surface or be present reasonably near the surface (covered by no more than ~100-300 meters of overburden) to allow site characterization and construction of the repository at a depth of ~400-800 meters. This may limit potential repository sites to regions of the US where crystalline rocks are near or at the surface (Figure 2-1).

Exposed or near-surface granitic rocks in the US occur in several terranes with different geologic and hydrologic environments (Table 2-1), but can be grouped more generally into three main geographic and tectonic terranes within the conterminous US (Figure 2-1). The largest of these general groupings includes Cenozoic to Archean granites of the western US that occur within the North American Cordillera, which as a whole is characterized by active tectonics and high hydraulic gradients relative to the rest of the US. The north-central US contains Archean granites that are part of the Superior Province of the Canadian Shield as well as early Proterozoic crystalline terranes accreted to the southern margin of the Superior Province between ~2.4 – 1.8 Ga (Sims, 1995). Proterozoic and Paleozoic granites of the eastern US occur in the southern and northern Appalachians from the southeastern US to New England.

Each of these three general groupings is located in a different geologic and hydrologic environment as highlighted at the national scale in Figure 2-2. Granites of the western Cordilleran are in a geologic environment characterized by high topographic relief and high hydraulic gradient, reflecting active faulting and uplift, as well as significant areas of high to moderate seismicity. Granites of the north-central US are in a region characterized by subdued topography, low seismicity and a history of Quaternary glaciation (Harrison et al., 1983). Granites of the southern and northern Appalachian Mountains of the eastern US are within regions characterized by moderate to high topography and hydraulic gradients, moderate to low seismicity and a history of glaciation in the northern Appalachian Mountains. The crystalline rock terrane of the north-central US is unique among the three major regions in having a combination of subdued topography and low hydraulic gradients, low seismicity, and a history of glaciation. These characteristics are similar to the geologic and hydrologic environment of granites in Finland and Sweden that are being studied as host rocks for HLW waste disposal.

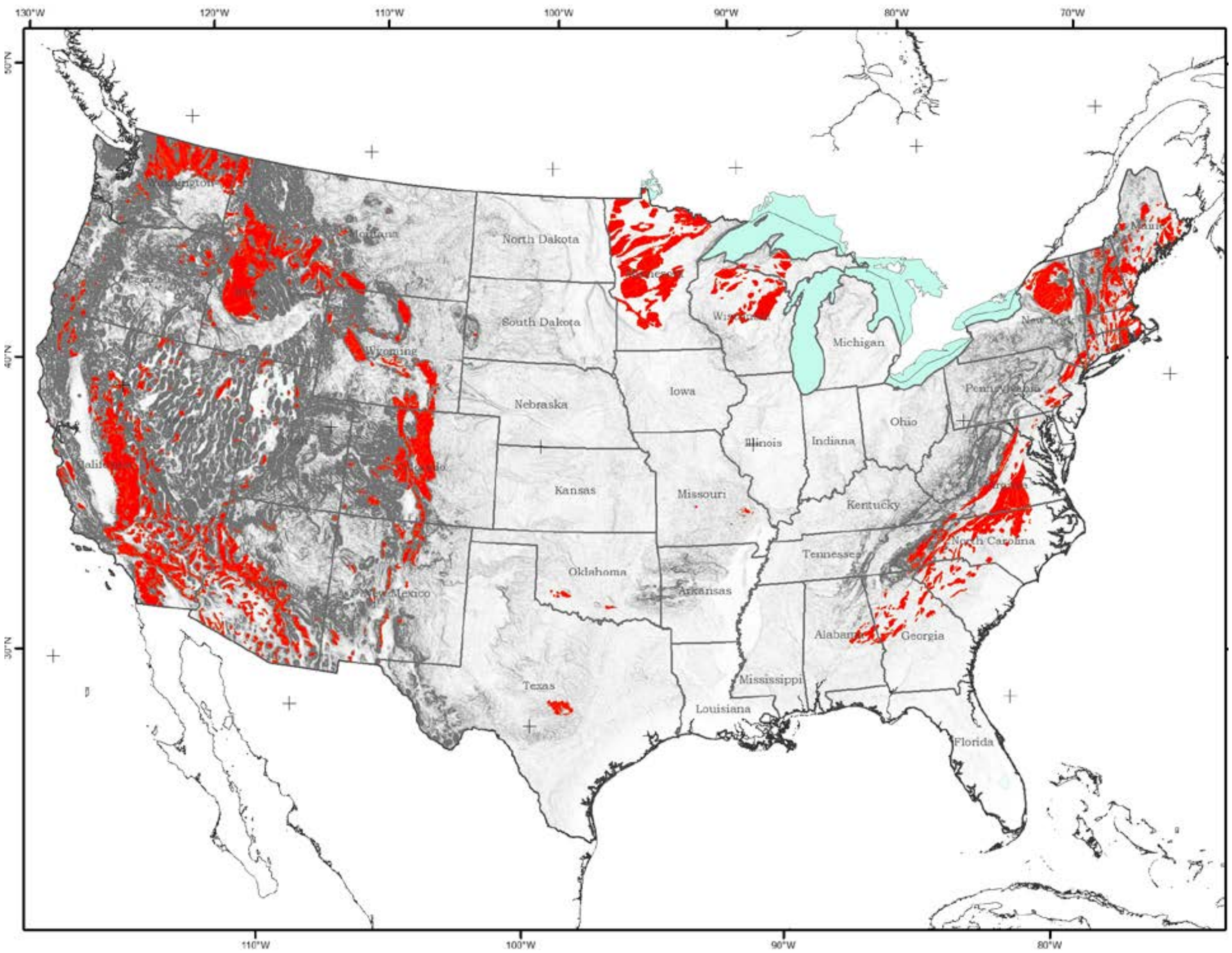

Figure 2-1. Distribution of exposed or near-surface crystalline rocks (red) in the conterminous US. Major crystalline terranes include the crystalline rocks of the Western Cordillera, the northern and southern Appalachians and the Superior Province of the Canadian Shield in the north-central US.

Table 2-1. Crystalline Terranes in the US from Mariner (2011). The Lake Superior Region corresponds to the north-central US or Superior Province described in this report..

Location	Units	Attributes	Comments
Pacific Border Region	Triassic, Jurassic, and Cretaceous granites, California, Oregon, and Washington	Very high hydraulic gradient. Large vertical movement along the Sierra Nevada and Cascade Range. Large horizontal movement along the coast range. High seismic and volcanic activity. Regions of large expanses of granite.	
Basin and Range Region	Precambrian granites, Arizona, Jurassic and Triassic granites east of Sierra Nevada. Cretaceous granites in Nevada, California, and Arizona.	High hydraulic gradient. Large vertical movement. Many active faults, Major mining for mineral deposits. High heat flow region.	Some granitic areas in Arizona and Nevada have a relatively low incidence of seismicity, when compared to the California granites.
Rocky Mountain Region	Archean granite, Wyoming, and southern Montana. Precambrian granites, Front Range, Colorado. Mesozoic granite, Idaho batholiths, and Montana.	High hydraulic gradient. Large vertical movement. Moderate seismic activity. Large faults bound uplifted blocks. Major mineral deposits. Occurrence of large homogeneous masses of granite.	
Lake Superior Region	Precambrian granites, Minnesota, Wisconsin, and Michigan.	Low hydraulic gradient. Little vertical relief. Small number of faults. Very low seismic activity. No volcanic activity.	The most stable region of granite outcrops in the U.S. – part of the N. American Continent stable craton
Northern Appalachian and Adirondack Region	Precambrian crystalline rocks, New England and the Adirondacks.	Moderate to low hydraulic gradients. Moderate vertical uplift. No modern fault movement. Low seismic activity. No volcanic activity	
Southern Appalachian Region	Precambrian granite, Blue Ridge and Piedmont provinces.	High hydraulic gradient in the Blue Ridge. Intermediate to low hydraulic gradient in the Piedmont. Moderate vertical movement. Very few recent faults. Low seismicity. No volcanic activity. Large masses of granite.	

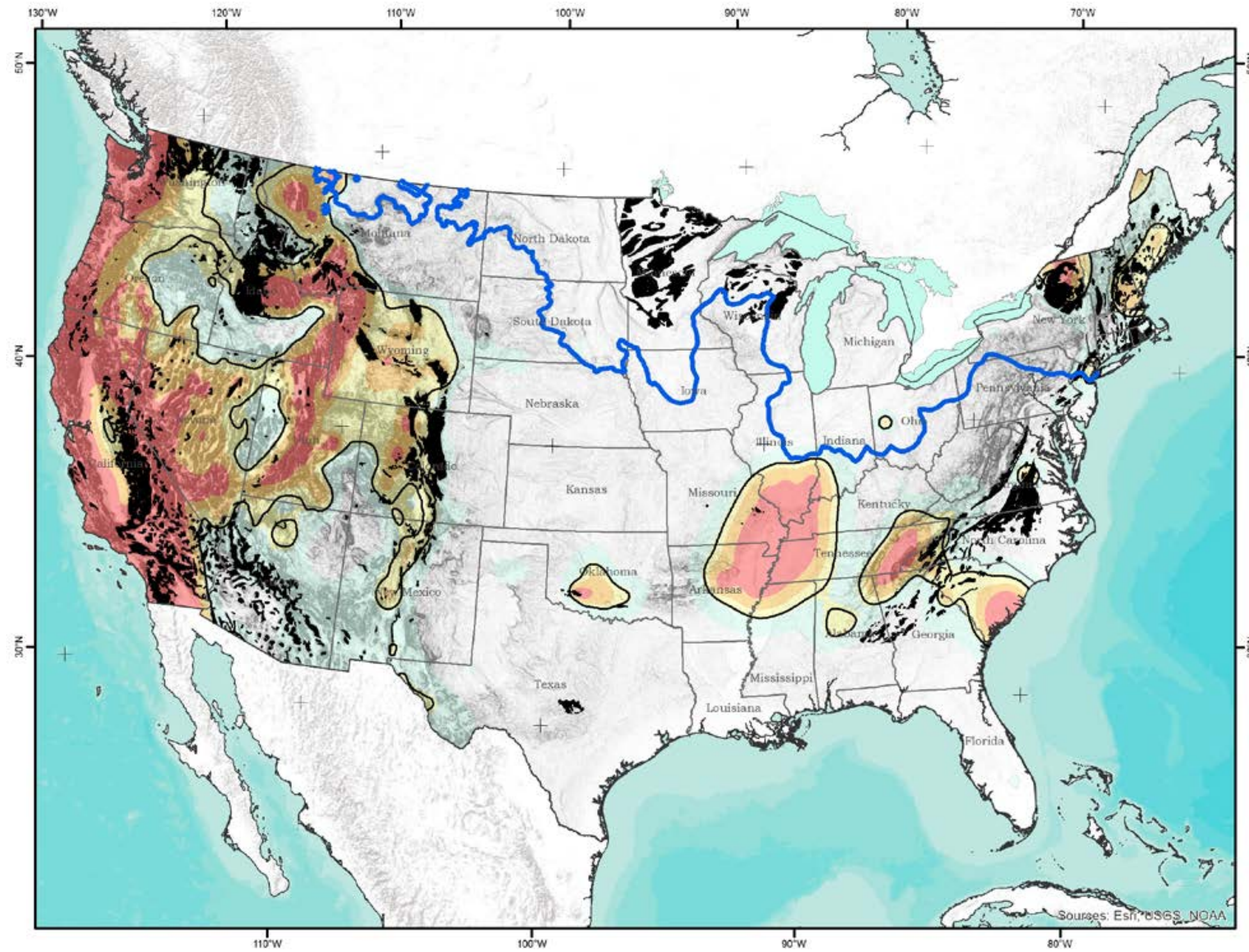

Figure 2-2. Distribution of exposed or near-surface crystalline rocks (black) in the conterminous US. Features shown at this scale that could influence siting of a repository include topography, maximum extent of the last glaciation (blue line) and seismic ground motion hazard. Red color shading indicates areas of the US with the highest seismic hazard. The black lines enclose areas with a 2% probability in 50 years of exceeding a peak ground acceleration of 0.16 g, an indicator of tectonically active regions of the US.

3. Approach and Limitations of the Regional Geologic Evaluation

This report presents an introductory regional geologic evaluation of the western Superior Province in the north-central US. We evaluate the geologic and hydrologic setting of the region in relation to a population of potential granitic host rocks that are widespread throughout the region in order to understand some of the features, events and processes that might affect the long-term performance of a mined geologic repository. We chose the Superior Province for this evaluation in part because the region's geologic and hydrologic setting is similar to that being studied by several other international HLW programs and can thus provide analogous information for an evaluation.

Analogous granitic sites in southern Ontario and Manitoba that lie within 150 km of the US-Canada border provide information on regional and site geology that can be compared to the Superior Province in the US. Preliminary evaluations of one of these sites in 2013 also provide an example of methodologies that are being used to conduct regional evaluations in other countries and serve as a point of reference for comparison to the regional evaluation presented in this report (Golder Associates, 2013).

The HLW disposal program in Canada managed by NWMO is conducting several site evaluations in southern Ontario as part of a consent-based process that started in 2010 (NWMO, 2010). In addition, the AECL operated a URL in granite in at the Whiteshell research area in southeastern Manitoba in the 1980s and 1990s. These sites are within the western Superior Province of Canada, part of the same crystalline terrane as in the north-central US. These sites are the source of additional information by providing both geotechnical data and approaches to regional and site evaluations that are helpful in framing the evaluation approach used in this report. The closest Canadian site to the region evaluated in this report is the Ignace Township site in southern Ontario (Golder and Associates, 2013; Figure 5-1).

The NWMO evaluations are based on five safety factors that are intended to insure the safe containment and isolation of nuclear waste (NWMO, 2010):

1. Safe containment and isolation characteristics of the host rock;
2. Long-term stability of the site, including future geologic processes and events such as earthquakes, glaciation, uplift and erosion;
3. Safe construction, operation and closure of the repository, based on the surface and underground characteristics of the site;
4. Isolation of waste from future human activities such as exploration for mineral resources or use of groundwater resources;
5. Amenable to site characterization, based on the practicality of studying and describing the site.

The safety goals are consistent with safety factors used in other countries. Following initial site screening, NWMO evaluates the potential suitability of a site against the safety factors through a preliminary site assessment, the “Phase 1 Desktop Geoscientific Preliminary Assessment” based on available geotechnical data (Golder Associates, 2013). The assessment includes the following activities:

1. Detailed review of available geoscientific information such as geology, structural geology, natural resources, hydrogeology and overburden deposits;
2. Interpretation of available geophysical surveys (magnetic, gravity, radiometric, electromagnetic);
3. Lineament studies using available satellite imagery, topography and geophysical surveys to provide information on characteristics such as location, orientation and length of interpreted structural bedrock features;
4. Terrain analysis studies to help assess factors such as overburden type and distribution, bedrock exposures, accessibility constraints, watershed and subwatershed boundaries, groundwater discharge and recharge zones; and
5. The identification and evaluation of general potentially suitable areas based on key geoscientific characteristics and the systematic application of NWMO’s geoscientific site evaluation factors.

The preliminary desktop assessments carried out by NWMO are similar to the regional evaluation documented in this report with the major difference being the scale and focus of the assessment, namely whether the assessment is for a region, as in this report with no specific site identified, or for a specific site as is the case in the NWMO assessments.

The scope of the regional evaluation reported here is significantly less detailed compared to the site-specific assessments carried out by NWMO. The NWMO assessments, because they are site specific, involve teams of specialists and use of analysis software to conduct data processing and interpretation of existing data such geophysics, remote sensing, terrain analysis and lineament studies. The NWMO assessments produce multiple reports for any one potential site and hundreds of pages of documentation. In comparison, we use comparatively simple GIS techniques to combine available data in ways that aid analysis and visualization to support a regional geologic evaluation.

For this regional evaluation, we focus on review and analysis of available geoscientific information relevant to granitic plutons and their geologic environment (the geosphere) in the western Superior

Province (Table 3-1). This information encompasses aspects of the natural barrier system and potential external factors within a FEPs framework (Freeze et al., 2011). We assess how this information might potentially bear on the long-term performance of a HLW repository located within the crystalline rock the crystalline rock of this region or elsewhere.

The DOE is pursuing a strategy for repository siting based on consent of a host community. This evaluation focuses on the technical perspective but is broadly applicable in understanding how existing geologic, geophysical and hydrologic data could be used for evaluation of site suitability for any future consent-based siting plan.

Table 3-1. Available data used for regional geologic evaluation of the western Superior Province of the US

Data Type	**Reference (complete reference descriptions in Section 7)**	**Comments**
Minnesota Well Index	Johnson et al. 2016. Minnesota Well Index. Minnesota Department of Health, 01 Aug. 2016. Web. 26 Aug. 2016. http://www.health.state.mn.us/divs/eh/cwi/	
Map of Minnesota Precambrian Bedrock Geology	Jirsa et al. 2013. S-22, Geologic Map of Minnesota, Precambrian Bedrock Geology. Retrieved from the University of Minnesota Digital Conservancy.	
Depth to Bedrock	Jirsa et al., 2010. OFR10-02, Preliminary Bedrock Geologic Map of Minnesota. Minnesota Geological Survey. Retrieved from the University of Minnesota Digital Conservancy,	
Minnesota Bouguer Gravity Map	Kucks, 1999. Bouguer Gravity Anomaly Data Grid for the Conterminous US. U.S. Geological Survey. Retrieved from the USGS Mineral Resources On-Line Spatial Data Repository. http://mrdata.usgs.gov/gravity/bouguer.	Updated gravity data for Minnesota is available (Chandler and Lively, 2014) but not used in this report.
Minnesota Aeromagnetic Map	Chandler and Lively, 2007. Revised Aeromagnetic Data for Minnesota. Minnesota Geological Survey Open File Report OFR07-06. http://www.mngs.umn.edu/magnetics.htm#Revised.	
Bedrock Sediment Thickness	Southern Methodist University Geothermal Laboratory, courtesy of Maria Richards	
Seismic ground motion hazard	Petersen, 2014. Documentation for the 2014 update of the United States national seismic hazard maps: U.S. Geological Survey Open-File Report 2014–1091, 243 p.	
Earthquake history of Minnesota	Chandler, 1994. Earthquakes in Minnesota. Minnesota Geological Survey, 4 p.	
Exploration Drill Core Locations	Minnesota Department of Natural Resources Drill Core Library web site http://mcc.mn.gov/gis.html.	Core stored at Minnesota Department of Natural Resources Drill Core Library
Distribution of crystalline rocks and glacial maximum in the US	Garrity and Soller, 2009. Database of the Geologic Map of North America. U.S. Geological Survey Data Series 424.	

4. Relevant Features, Events and Processes (FEPs) for the Natural System in a Crystalline Basement Terrane

Examination and evaluation of geologic data as part of a regional geologic evaluation is a first step towards identifying FEPs that are relevant to understand issues and types of data needed (DOE 2012) to understand the long-term performance of a HLW repository (Appendix A). At this preliminary stage of regional evaluation, we identify FEPs that are relevant to the geologic/hydrologic environment (geosphere) as well as external events that could affect repository performance. These FEPs are listed in Appendix A, and are based on the FEPs analysis of Freeze et al. (2011). We do not address topics related to FEPs for the engineered barrier systems, waste types and repository design.

5. Regional Evaluation of the Archean Crystalline Terrane in the North-Central US

In this report, we use available geologic, geophysical and hydrologic data to evaluate crystalline rocks of the western Superior Province. Archean-age crystalline rocks in the north-central US are exposed or near the surface in the western portion of the Superior Province, primarily in Minnesota, and to a lesser extent in Wisconsin and the Upper Peninsula of Michigan (Figure 2-1; Harrison et al., 1983; Sood et al., 1984). Proterozoic crystalline rocks are more prevalent in eastern Minnesota and in Wisconsin but are not being evaluated in this report, as this report focuses on the Archean granitic rocks of the Superior Province.

Much of the relevant data needed to conduct a regional evaluation, such as geologic mapping, borehole and water well databases, and geophysical data is available on a state by state basis from state geological surveys or departments of natural resources. The quality, format and ease of access to these data vary by state. For the state of Minnesota, a large amount of data is available in digital format, including a recent geologic map of the crystalline basement that represents the newest and most comprehensive mapping of crystalline basement in the north-central US (Jirsa et al., 2013). Numerous studies for HLW disposal have been conducted over the past 30 years in the Canadian portion of the Superior Province immediately north of Minnesota (Figure 5-1). These studies provide analogous information on granitic rocks for this regional assessment

It is likely that suitable host rocks are present in all of the granitic terranes discussed in Section 2 of this report. Evaluations in other regions of the US would involve consideration of a different set of features and processes inherent in their different geologic environments. The regional evaluation focused on the western Superior Province is an R&D effort to further the methodology of evaluating specific regions of the US based on available geologic data.

This regional geologic evaluation concentrates on a specific population of potential granitic host rocks. These are the Neoarchean plutons and batholiths emplaced throughout the Archean terrane during a relatively brief geologic interval between 2.6 and 2.7 billion years ago, part of a regional episode of deformation, heating and anatexis. Many of these plutons are relatively undeformed and lithologically homogeneous compared to the older rocks they intrude, and are a plausible potential host rock within the western Superior Province (Sood et al., 1984). Other potential host rocks in the region include Archean gneisses and a number of relatively undeformed Proterozoic plutons and batholiths that are present in Wisconsin (Sood et al., 1984).

5.1 Overview of the Geologic and Tectonic History of the Western Superior Province

The western portion of the Superior Province is exposed at or near the surface in Minnesota and in the Canadian provinces of Manitoba and Ontario (Figure 5-1). This part of the Superior Province was assembled by the accretion and suturing of several island arc and continental terranes starting at about 2.7

billion years ago (Percival et al., 2006). These accretionary episodes are represented today by a series of generally east-west belts or subprovinces defined by changes in lithology, metamorphic grade and structural style separated by major faults and shear zones (Card, 1990 and Figure 5-1). The Great Lakes Tectonic Zone (GLTZ) in central Minnesota is a major suture zone that separates subprovinces with island-arc characteristics (greenstone-granite terrane) to the north from a continental gneissic terrain (the Minnesota River Valley subprovince) to the south (Sims and Day, 1993). The accretion and suturing of the gneissic block to the southern edge of the Superior Province along the GLTZ marked the final assemblage of the Superior Province near the end of the Archean and resulted in a widespread episode of deformation, metamorphism and emplacement of granitic plutons throughout much of the western and southern Superior Province (Sims and Day, 1993).

From north to south, the US portion of the western Superior Province consists of four subprovinces as illustrated in Figure 5-1 and described by Card (1990) and Southwick (1993):

Wabigoon – a volcano-plutonic terrane consisting of about 65% plutonic rocks with lessor metamorphosed arc-like volcanic rocks and minor metasediments.

Quetico – a metasedimentary terrane consisting primarily of metamorphic schists and gneisses intruded by granitic plutons. It has been interpreted as an accretionary prism that was compressed between the Wabigoon subprovince to the north and the Wawa subprovince to the south.

Wawa – a volcano-plutonic terrane consisting of major batholith complexes (e.g., Giants Ridge) with lessor amounts of metavolcanic and metasedimentary rocks.

Minnesota River Valley – a high-grade, granulite facies gneiss terrane that represents an older Archean continental terrane that accreted to the younger island-arc/volcano-plutonic terranes to the north.

The Wabigoon, Quetico and Wawa subprovinces are a series of classic “greenstone-granite” belts that are characteristic island-arc terranes made up of typically mafic and moderately metamorphosed metavolcanic and metasedimentary rocks intruded by later granitic plutons. Most of the Neoarchean granite plutons intruded the greenstone belts north of the GLTZ with a smaller number of plutons intruding the southern Minnesota River Valley gneiss terrane (Figures 5-1 and 5-2).

The subprovinces north of the GLTZ, including the English River subprovince in Canada (Figure 5-1), were sequentially accreted from the (current) south in ~ 10 Ma intervals to assemble the final Superior Craton within a relatively short geologic period from ~2700 - 2600 Ma (Morey and Van Schmus, 1988; Percival et al., 2006). During this same interval, late tectonic, syn-deformational Neoarchean granitic plutons were intruded throughout all of the subprovinces (Figure 5-2). The origin of these plutons is attributed to partial melting of aluminous metasediment or quartzofeldspathic gneiss, or in the case of tonalites of more intermediate composition, partial melting of tholeiitic basalt (summarized in Card, 1990 and Southwick, 2014). The Neoarchean granites are described as being relatively undeformed with massive or weakly foliated fabric. They extend from the Minnesota River Valley subprovince in the south to at least as far north as the English River subprovince in Canada.

Two post-Archean regional events are of potential significance in understanding the subsurface hydrologic characteristics of the region. The first was the intrusion of a giant dike swarm (hundreds to thousands of dikes) at about 2 Ga. The second was a series of glacial events and ice sheets that covered the region during the Quaternary with the last glacial maximum at about 18,000 years ago. The geologic recency of the last glaciation indicates that additional glaciations will occur in the next million years. These two events are discussed in the following sections of this report.

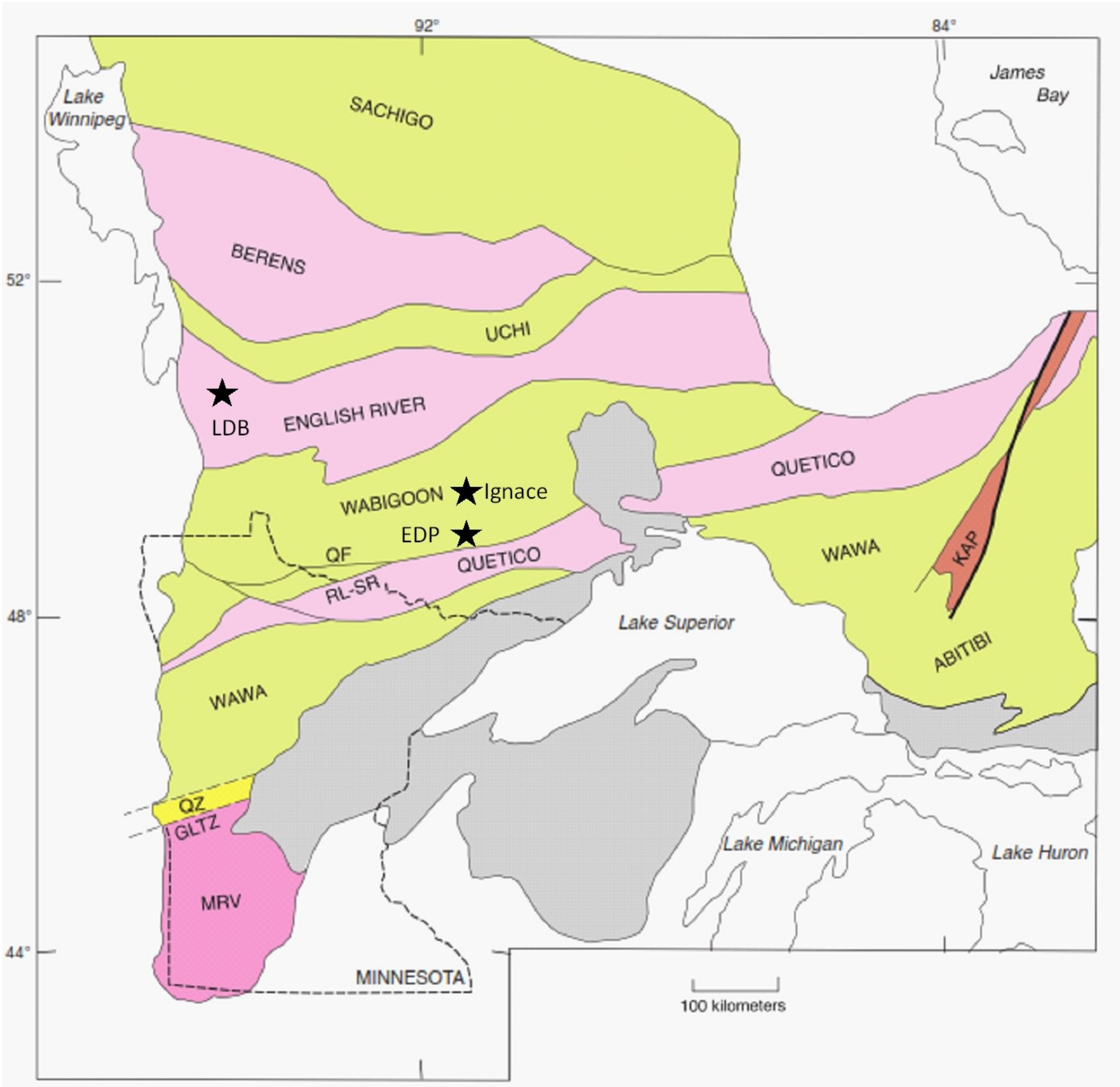

Figure 5-1. Map of subprovinces of the western Superior Province from Southwick (2014). Sites indicated by stars in southern Canada are the Lac du Bonnet (LDB) batholith, site of the Whiteshell URL operated by the AECL, the Eye Dashwa Pluton (EDP) and the Ignace Township, an area of recent site evaluations carried out by NWMO. Note that the English River subprovince is further subdivided into the Winnipeg and Bird River subprovinces in much of the Canadian literature. Gray shading represents areas of Proterozoic crystalline rocks. “QZ” north of the GLTZ is a magnetically quite zone on the southern margin of the Wawa subprovince (Southwick, 2014). “MRV” is the Minnesota River Valley subprovince.

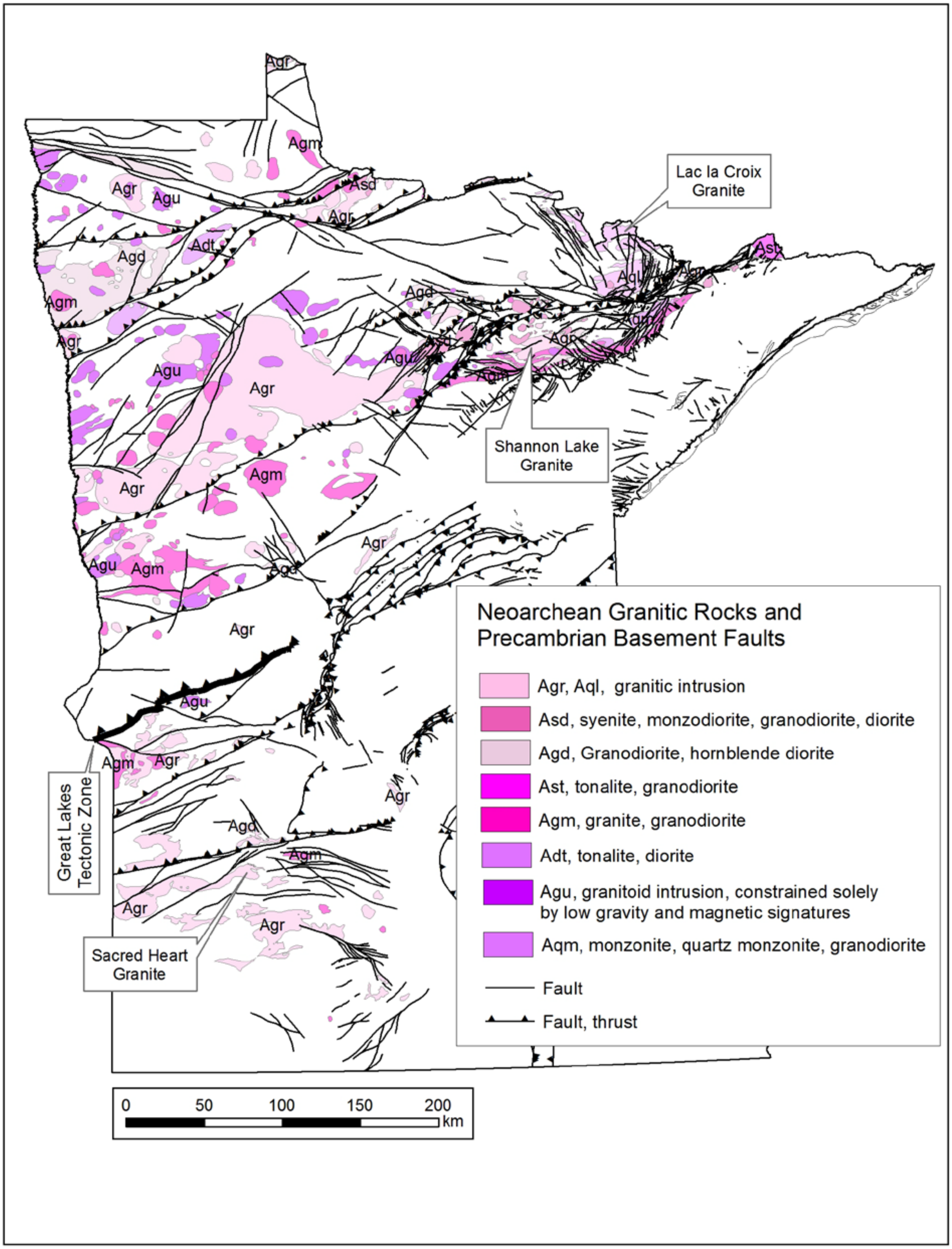

Figure 5-2. Distribution of Neoarchean granites and Archean/Proterozoic basement faults in the western Superior Province. Neoarchean granitic rocks are described as nonfoliated to weakly foliated or lineated plutons. Data for geologic contacts, granitic lithology and fault locations are from Jirsa et al. (2013).

5.2 Geologic Environment/Natural Barrier System

This regional geologic evaluation does not consider every geologic or hydrologic feature or process that could affect the long-term performance of a HLW repository. It focuses on several features of the geologic environment where relevant data and information has become available, preferably in digital form, over the past 10-15 years. As such, it includes evaluation of geologic mapping, geophysical data, potentially suitable granitic host rocks, the nature of sedimentary overburden above the granitic bedrock, hydrologic features and fracture characteristics of potential host rocks. Data discussed in this report to evaluate the geologic environment of the late Archean granitic rocks of the Superior Province are listed in Table 3-1.

5.2.1 Geologic Mapping and Geophysical Data

The basis for geologic mapping of crystalline basement in this region is (1) mapping of surface rock exposures, or outcrops, which are relatively sparse in the region, (2) borehole data and cores (which provide samples for identification of lithologies, lithologic correlation and age-dating), and (3) interpretation of geophysical data. A recent geologic map of the crystalline basement uses these methods to document the location, extent, lithology and age of crystalline rock units as well as the location of basement faults in the region (Figure 5-3, based on GIS data from Jirsa et al., 2013). We use the geologic mapping data to highlight features in the geologic environment that are relevant to long-term repository performance. These data include the distribution of Neoarchean granites and their relationship to other features in the geologic environment, such as location of faults, dikes, depth to the water table, thickness of sedimentary overburden, and location of boreholes for past mineral exploration.

Aeromagnetic and gravity surveys use magnetic and density properties of rocks to delineate the boundaries of rock masses. These boundaries can represent either lithologic boundaries (e.g., intrusion boundaries) or faults that juxtapose different lithologies against each other (Figures 5-4 and 5-5). Geophysical surveys have been a critical tool in mapping lithologic boundaries and structures in crystalline terranes that are hidden beneath magnetically transparent sedimentary deposits (Holm et al., 2007).

The most prominent feature of the regional aeromagnetic map is the high-amplitude magnetic high in eastern Minnesota that marks the Proterozoic Midcontinent Rift and the Duluth Complex. Magnetic anomalies in the Archean terrane predominantly strike northeast, reflecting the regional trend of the subprovinces. Broad moderate amplitude anomalies reflect granitic bodies while more subdued magnetic signatures reflect belts of metasedimentary rocks (Chandler, 1993). Interpretation of aeromagnetic data is the only method in many cases to define margins of intrusive bodies, and is particularly definitive for more mafic intrusions and dikes (Jirsa et al., 2013).

The most prominent feature seen at the regional scale in the gravity data is the prominent density high in far eastern Minnesota due to the presence of Proterozoic mafic lavas and intrusions of the Midcontinent Rift and Duluth Complex (Figure 5-5). To the west of the Midcontinent Rift, sharp boundaries between positive and negative gravity anomalies coincide with major faults or major accretionary terrane boundaries. Broad gravity minimums coincide with areas dominated by low-density granitic intrusions (Figure 5-5).

5.2.1.1 Neoarchean Granites

Many of the Neoarchean granites have poor exposure at the surface and are covered by significant overburden, which is discussed in more detail later in this report. They also tend to have low gravity and magnetic signatures (Jirsa et al., 2013). Despite these mapping challenges, their locations and boundaries are constrained from a combination of information obtained from outcrop exposures, borehole data, and geophysical interpretations including the contrasting geophysical signatures of the crystalline rock they intrude (Jirsa et al., 2013; Figure 5-4 and 5-5).

The margins of Neoarchean granites are commonly bounded by basement faults or they are in relatively close proximity to faults (Figure 5-2). Historic earthquakes probably involved reactivation of these faults (Chandler 1994, 1995). These earthquakes have been minor and infrequent and are discussed later in this report. These basement faults are not considered "active" as they would be in the case of faults with Quaternary offset. The faults may however represent potential groundwater flow pathways that would have to be evaluated, if present.

Studies of the Neoarchean granitic bodies that include information pertinent to HLW disposal are few within the north-central US with the exception of surveys carried out by DOE in the 1980s (Harrison et al., 1983; Sood et al., 1984). Examples of Neoarchean granites that have been relatively well studied in terms of geochemistry, geochronology and origin include (Figure 5-2):

Sacred Heart Granite of the Minnesota River Valley subprovince (2603 Ma): medium-grained, pink, and homogeneous to weakly foliated, virtually undeformed (Sims, 1993; Schmitz et al., 2006).

Shannon Lake Granite of the Giants Ridge Batholith of the Wawa subprovince (2674 Ma): medium grained pinkish-gray, weakly foliated muscovite biotite granite and pink, weakly to nonfoliated, coarse-grained granite (Boerboom and Zartman, 1993).

Lac la Croix Granite of the Vermillion Granitic Complex of the Quetico subprovince (2700 Ma): medium to coarse grained grayish-pink biotite granite, massive in interior of batholith (Day and Weiblen, 1986).

5.2.1.2 Dike Swarms

After consolidation of the Superior Province at about 2.6 Ga, a giant radial dike swarm, the Kenora–Kabetogama dikes of tholeiitic basalt composition, was emplaced at about 2076 - 2067 Ma (Schmitz et al., 2006). This regional intrusive event was related to rifting and extension on the southern margin of the Superior Province (Schmitz et al., 2006; Schultz and Cannon, 2007). The location and orientations of these dikes are determined primarily from high-precision aeromagnetic data using the first vertical derivative of the total magnetic field (Southwick, 2014). The dike swarm consists of hundreds or thousands of dikes that are dominantly northwest-trending to the north of the GLTZ and more east-west trending within and south of the GLTZ (Figure 5-6). Dike widths range from less than a meter to as much as 120 meters with dike separations that are typically on the order of 1 or 2 km (Southwick and Day, 1983). Most of the Neoarchean granitic plutons are intruded by these dikes and they would likely factor into any future more detailed evaluations (Figure 5-6). The geology, age relationships and origin of these dikes are described in detail by Southwick and Day (1983) and Southwick (2014).

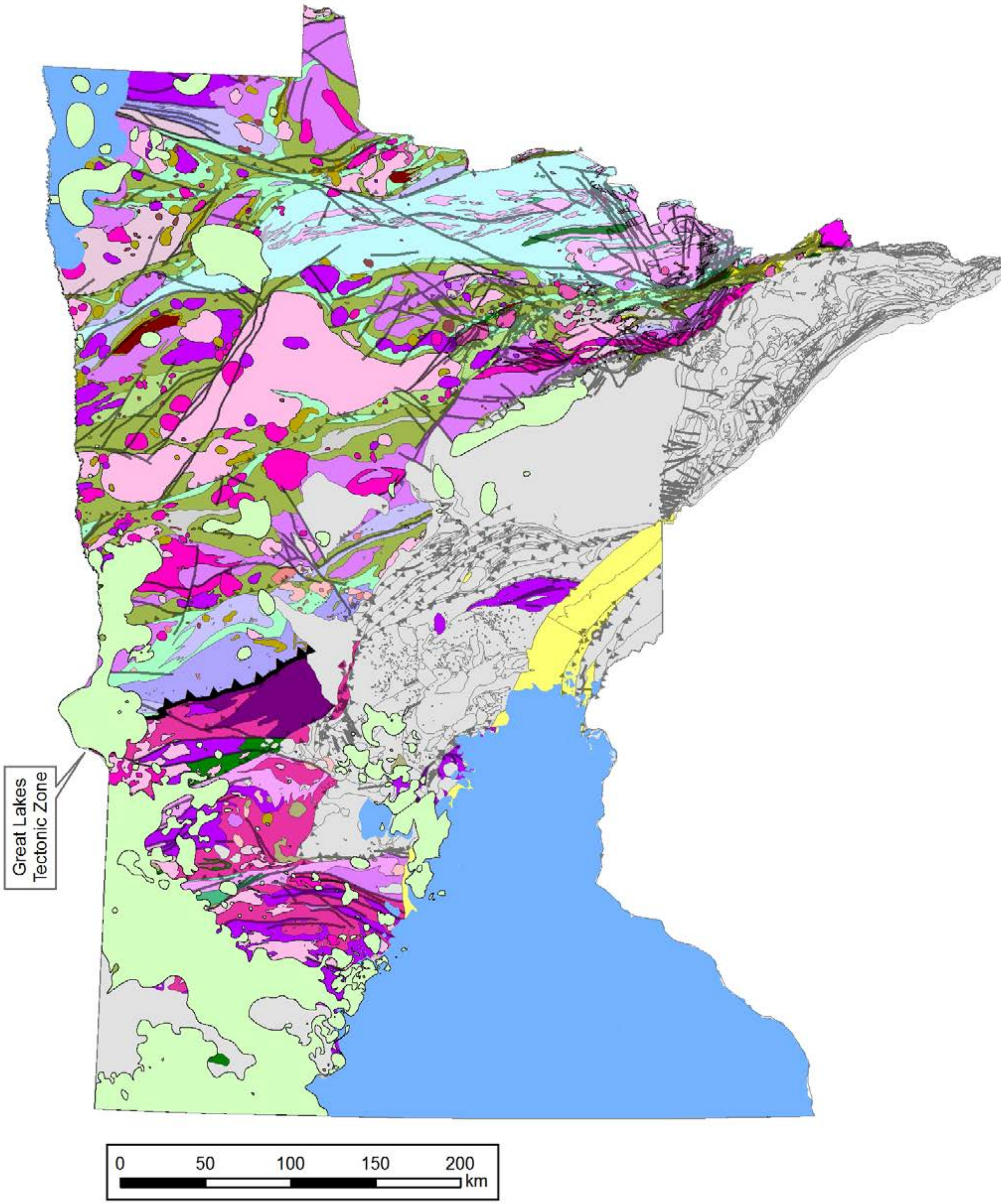

Figure 5-3. Geologic map of crystalline basement rocks and Mesozoic/Paleozoic sediments based on data from Jirsa et al. (2013). Grayed out rocks in the southwestern and eastern parts of the state are Proterozoic crystalline rocks; multi-color patterned rocks to the northwest and west of the Proterozoic rocks are Archean crystalline rocks. Light green patterned rocks in the southwest and western parts of state are mostly Cretaceous shales and sandstones. Blue patterned rocks in the southeastern and northwestern parts of the state are mostly Paleozoic carbonates. Yellow patterned rocks in the east-central part of the state are rift-filling sediments of the Midcontinent rift that are covered by Paleozoic carbonates to the south.

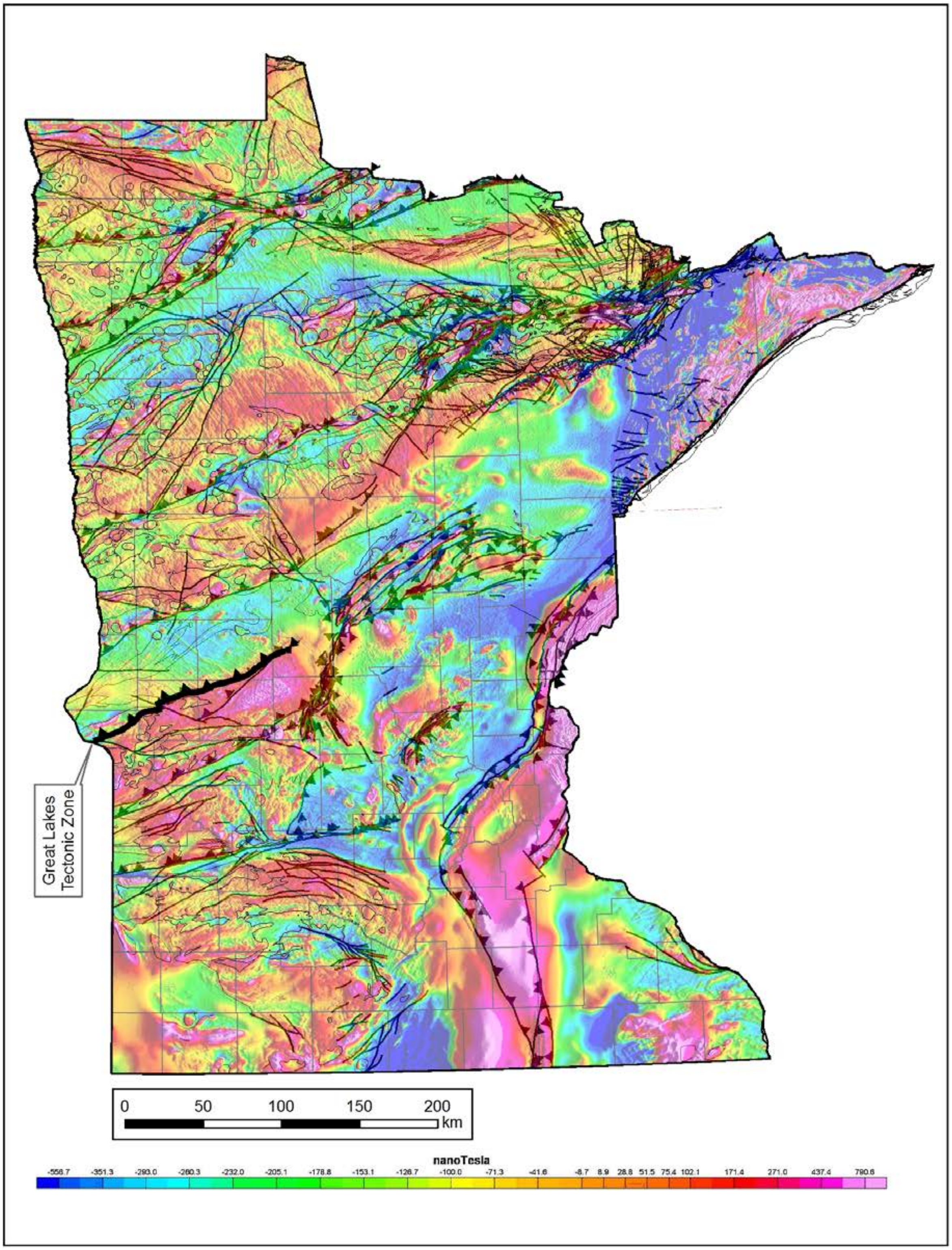

Figure 5-4. Aeromagnetic anomaly map and Precambrian basement faults of Minnesota. Geologic contacts for Neoarchean granitic plutons are shown as faint gray lines. Aeromagnetic data is from a PDF image created by Chandler and Lively (2007) and processed at LANL for use in GIS. Image obtained at: http://www.mngs.umn.edu/magnetics.htm#Revised.

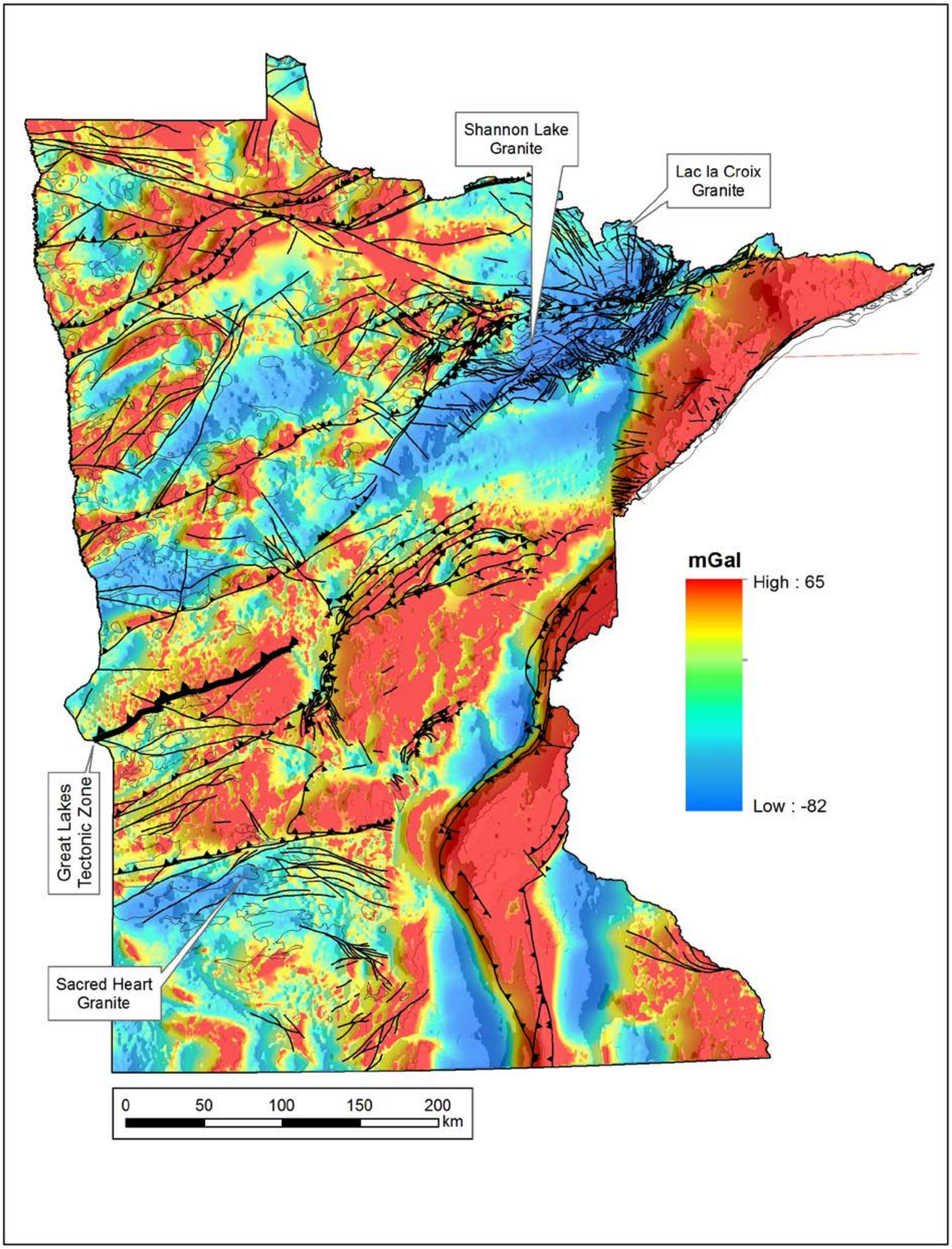

Figure 5-5. Bouguer gravity map and Precambrian basement faults of Minnesota. Gravity data from Kucks (1999). Geologic contacts for Neoarchean granitic plutons are shown as faint gray lines. Locations of three Neoarchean granites from Figure 5-2 are shown to illustrate their association with gravity lows.

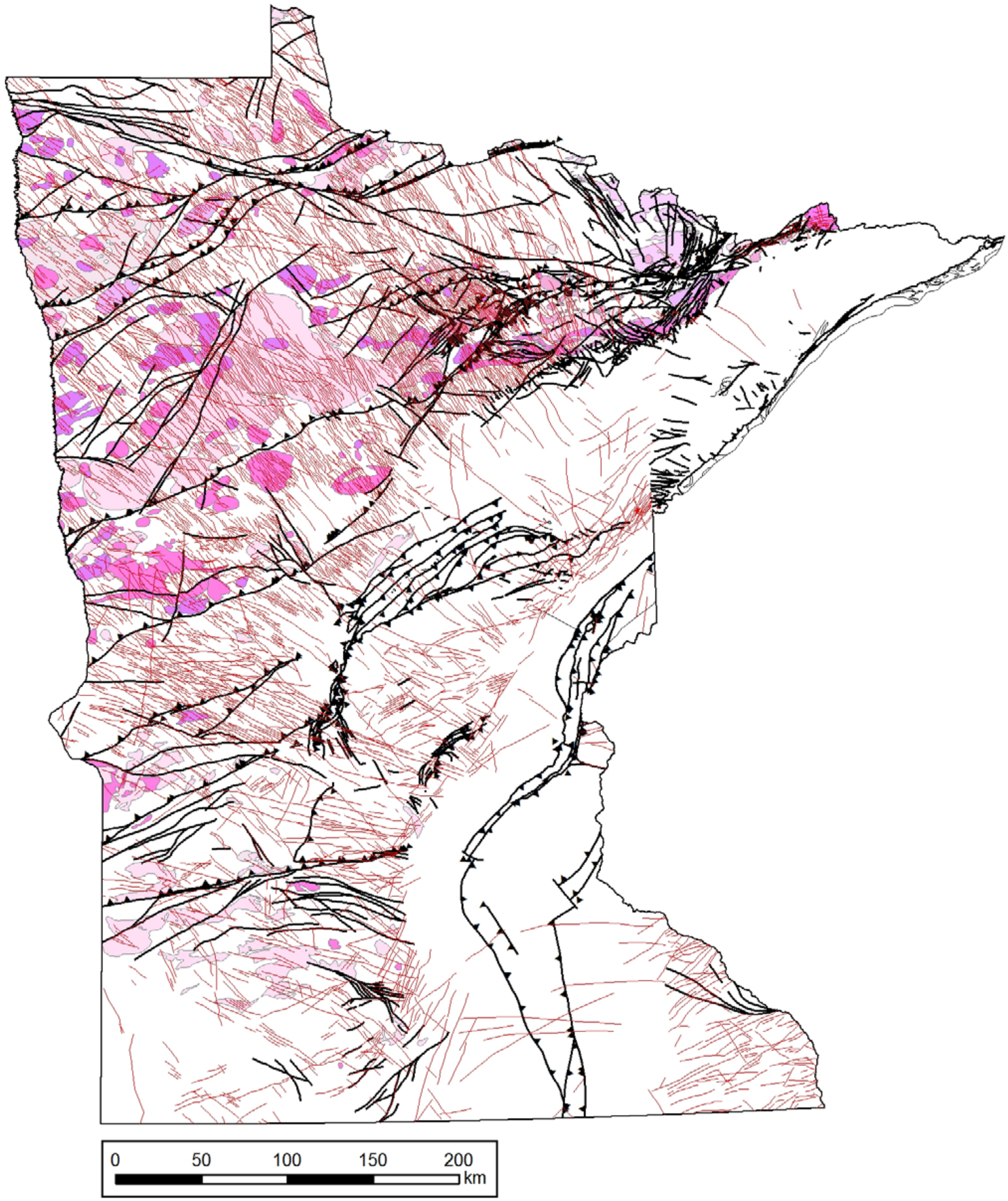

Figure 5-6. Distribution of mafic dikes (red lines), Neoarchean granites and Archean/Proterozoic basement faults in the western Superior Province. Data from Jirsa et al. (2013). Intrusions of dikes was related to an episode of rifting and extension to the west of the map area (Schmitz et al., 2006; Schultz and Cannon, 2007).

5.2.2 Sediment Overburden on Crystalline Basement Rocks

The Archean crystalline rocks in Minnesota are largely covered by Quaternary glacial deposits or Mesozoic and Paleozoic sedimentary rocks, collectively referred to as overburden (Figures 5-7 and 5-8). The Quaternary glacial deposits are the most widespread and lie on top of crystalline basement rocks. The interface between solid crystalline basement rock and glacial deposits is a horizon of variable thickness referred to as saprolite, which is derived from weathering and alteration of the crystalline bedrock. Thickness of the saprolite is uneven and can range from zero to >100 meters, but is typically 5-10 meters thick where it exists (Martin et al., 1989; Martin et al., 1991).

Glacial deposits vary in thickness in the region from almost none to more than 100 meters in some areas (Figure 5-7). Mesozoic (shale and sandstone) and Paleozoic sediments (carbonates) occur primarily in the southern and far western parts of Minnesota and reach thicknesses of >300 meters (Figure 5-8). Exposed granitic rocks generally occur in the northeastern part of Minnesota and along river valleys such as the Minnesota River in the southwestern part of the state (Figure 5-7, inset).

In some repository safety scenarios, overburden of a confining sedimentary rock such as shale has been considered as an additional barrier for HLW isolation that lies between the granite host rock and the human environment. In this scenario, the required thickness of the sediment would lie somewhere between 50 and 300 m (Figure 5-8). In the western Superior Province, only a few Neoarchean granitic plutons are known to lie beneath Cretaceous shales, therefore the conditions that meet the assumptions for this scenario (Neoarchean granites with a confining sedimentary cover), are not prevalent within this region (Figure 5-8).

Glacial overburden containing minerals such as clay (illite), ferrihydrite and calcium carbonate has been quantitatively evaluated as a retardation barrier above granite by the Swedish HLW program (Grandia et al., 2007). Based on a reactive transport model, Grandia et al. (2007) concluded that glacial deposits can act as an effective reactive barrier that is able to retain several key radionuclides including uranium, cesium, strontium and iodine.

Except for the study discussed above, we are not aware of any HLW literature that suggests sedimentary overburden is desirable or necessary as an additional isolation barrier for a granite repository. Metcalfe and Watson (2009) discuss hard fractured rock overlain by a sedimentary rock sequence containing at least one significant low-permeability formation as one of nine geologic environments identified in England. They note that they have not identified any organization that is currently developing a safety case in this type of environment and note that the overburden would make it more difficult to characterize the host rock.

Golder Associates (2013) considered overburden thickness as an important site characteristic in their preliminary suitability assessment of the Ignace area in southern Ontario (Figure 5-1). They concluded that areas with overburden (in this case glacial deposits) of greater than 2 m would not be amenable to geologic and structural mapping and gave preference to areas with greater bedrock exposures.

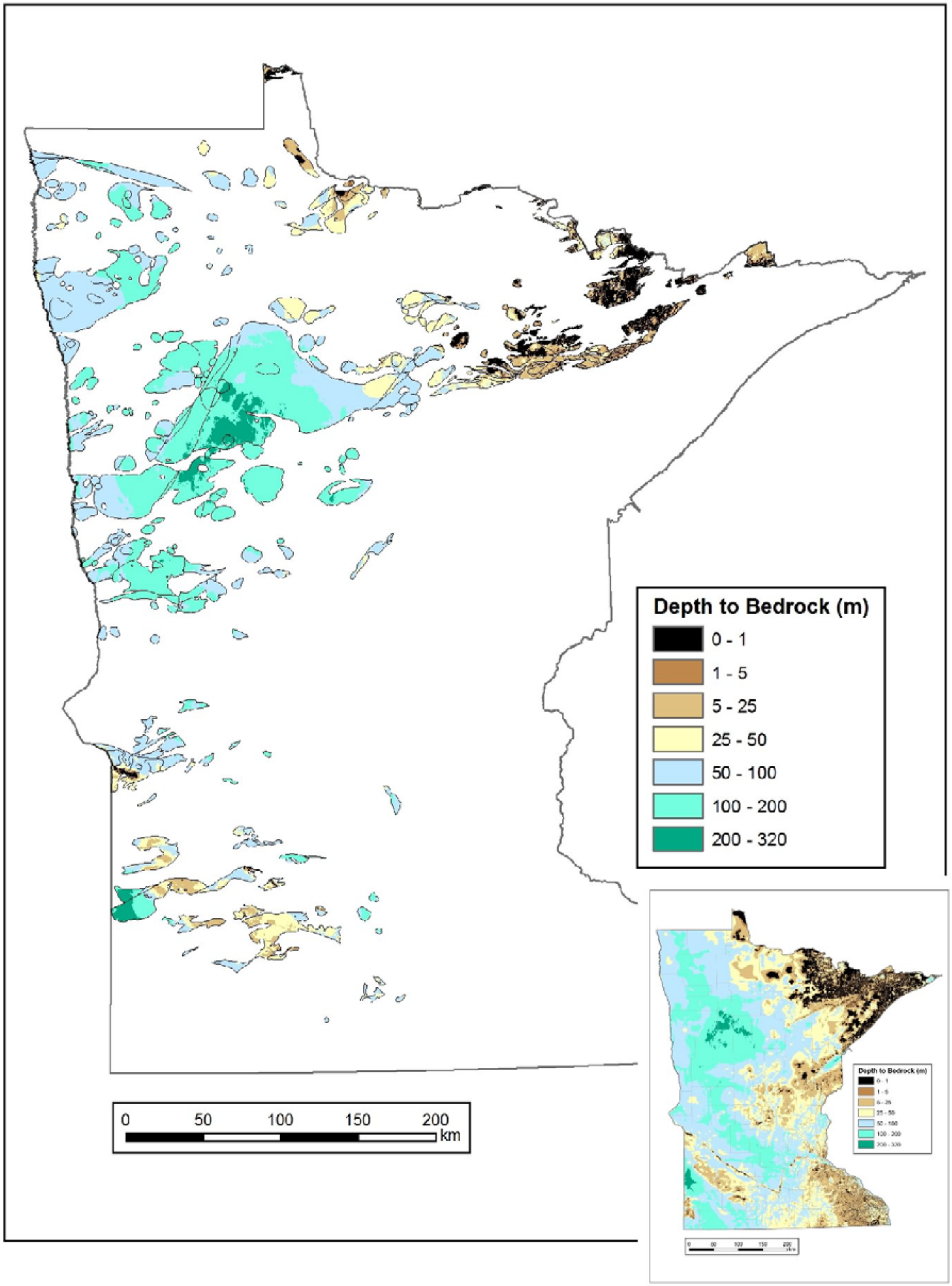

Figure 5-7. Thickness of glacial overburden above Neoarchean plutons obtained using GIS. Overburden data from Jirsa et al. (2010). Inset map shows depth to bedrock (both Mesozoic and Paleozoic sedimentary rocks and crystalline basement) for all of Minnesota. Thin overburden in the southeastern part of state overlies Paleozoic carbonates.

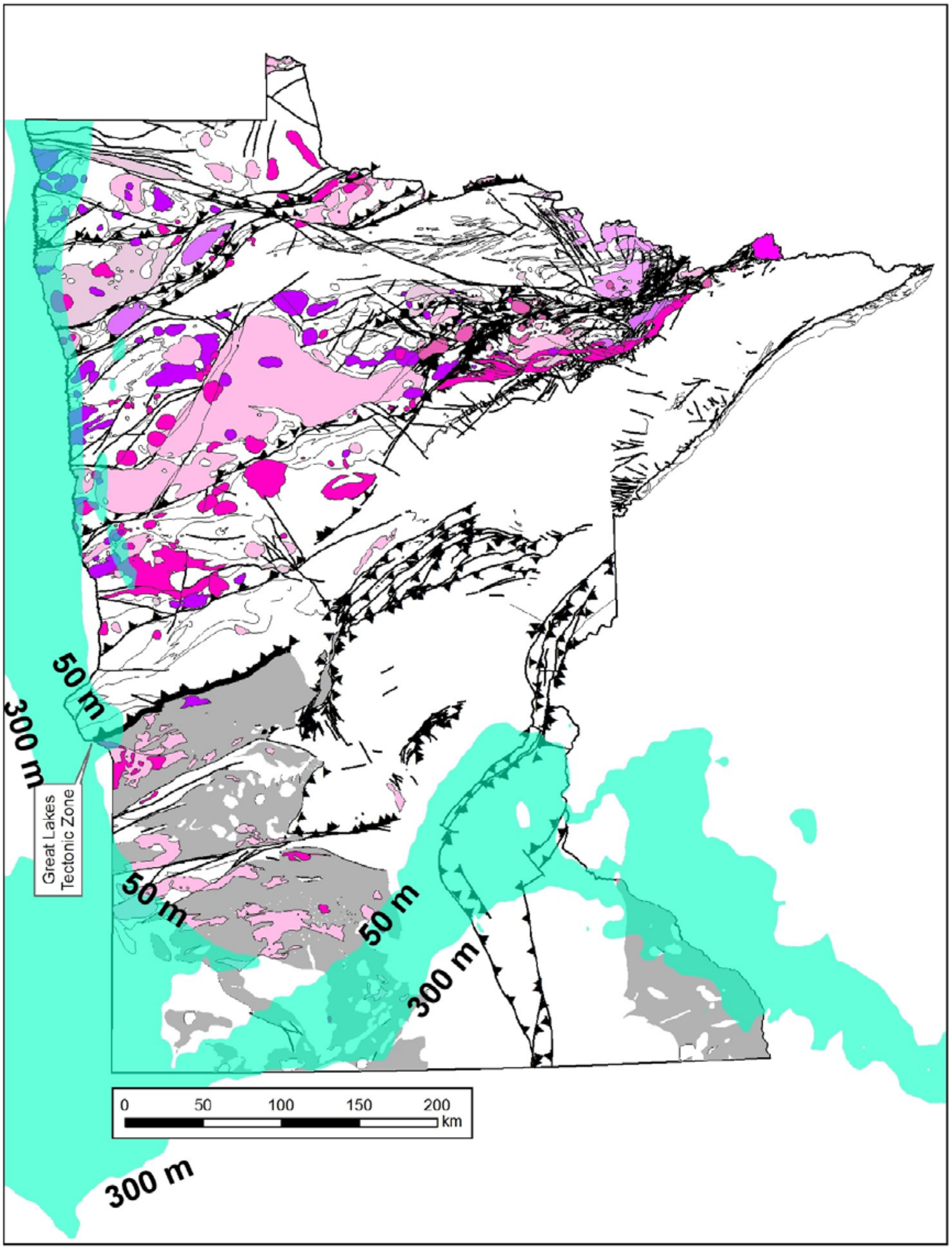

Figure 5-8. Mesozoic and Paleozoic sediments with thickness of between 50 and 300 meters (transparent green) illustrating the thickness of bedrock sedimentary cover over Neoarchean granites. Sediments in the western half of the region are primarily Cretaceous shale and sandstone, while sediments in the southeastern part of the region are Paleozoic carbonates (see Figure 5-3). Sediment thickness data obtained from the SMU Geothermal Lab (Table 3-1).

5.2.3 Fracture Systems in Granitic Rocks

The flow of water in granitic rocks is dominantly through fracture flow. A key factor for the long-term performance of a HLW repository in granitic host rocks is the nature of the fracture systems, including their aperture and connectivity to create flow paths. To our knowledge, no data is available on fracture systems for granitic rocks in the western Superior Province of the US that would compare to the level of detailed data typically collected for HLW programs. In almost all descriptions of granites, fractures are not mentioned and the granites are typically described as massive, relatively undeformed and weakly foliated (Day and Weiblen, 1986; Southwick, 2002; Satkoski, 2013; Southwick, 2014).

Analogous Neoarchean granites do exist, however, in the western Superior Province of southeastern Manitoba and southwestern Ontario where fracture systems have been characterized as part of the Canadian HLW program (Figure 5-1). The Lac du Bonnet batholith is a Neoarchean biotite granite and is the site of the Canadian (AECL) URL that has been well characterized beginning with studies in the early 1980s. It was emplaced at about 2665 Ma during the same episode as other Neoarchean granites throughout the region (Stone et al., 1989). The Lac du Bonnet granite, as well as two similarly sized granite bodies to the south, are sparsely fractured throughout much of their volumes. This is attributed to their emplacement at a relative late stage of regional deformation and their relatively large size, which delayed the onset of brittle deformation and fracturing (Brown et al., 1989; Everitt et al., 1996).

Stone et al. (1989) compared fracture styles in two plutons of different size within the western Superior Craton (Figure 5-9). The Lac du Bonnet batholith (LDB) has a minimum calculated volume of ~9000 km^3 while the volume of the Eye-Dashwa pluton (EDP), 300 km to the southeast, has a calculated volume range of ~120-375 km^3. The two plutons have distinctly different fracture styles with fractures in the LDB strongly localized in shallow-dipping (10-30 degrees) fracture zones that indicate thrust faults with displacements of several meters or less (Brown et al., 1989; Everitt et al. 1996). The rock domains between fracture zones are sparsely fractured with very low permeabilities ($< 10^{-19}$ m^2) and domain thicknesses of > 500 meters (Stone et al., 1989; Lodha et al., 1998). In contrast, the EDP fractures are more closely spaced, subvertical fractures that are pervasive throughout the rock mass (Figure 5-9). Stone et al. (1989) attribute the differences in fracture style to the volume difference between the two plutons that led to substantially different cooling histories and timing of the transition from a ductile regime to a brittle fracture regime during regional deformation. During regional deformation, the LDB was hotter and ductile throughout much of the period of regional compression. The smaller EDP cooled more quickly and deformed in a pervasive brittle fashion throughout the period of deformation (Figure 5-9). In the case of the larger LDB, strain within the pluton was accommodated through ductile deformation that occurred within deformation zones that may have been localized at subtle compositional and mineralogical boundaries (Brown et al., 1989; Stone et al., 1989). As the rock mass cooled through the ductile-brittle transition, the deformation zones became the locus of intense fracturing during continued regional deformation. Large rock domains between the intensely fractured deformation zones remained relatively intact and sparsely fractured (Figure 5-9).

A remarkable similarity exists between fracture styles at the large volume, late-tectonic LDB batholith in the Superior Province and the granite repository host rock at Forsmark, Sweden. Both rock masses are characterized by sparsely fractured domains bounded by highly fractured, gently-dipping deformation zones (Figure 5-10). The origin of the highly fractured deformation zones at Forsmark has also been attributed to a transition from ductile to brittle deformation with localized deformation zones that accommodate the majority of strain during regional compression, leaving intervening rock domains relatively intact and sparsely fractured (e.g., Stephens, 2010).

The relationship between pluton size, deformation and cooling history and fracture characteristics suggests that the larger Neoarchean plutons of the western Superior Province in the US are likely to contain sparsely fractured domains. This would have to be established through site-specific studies.

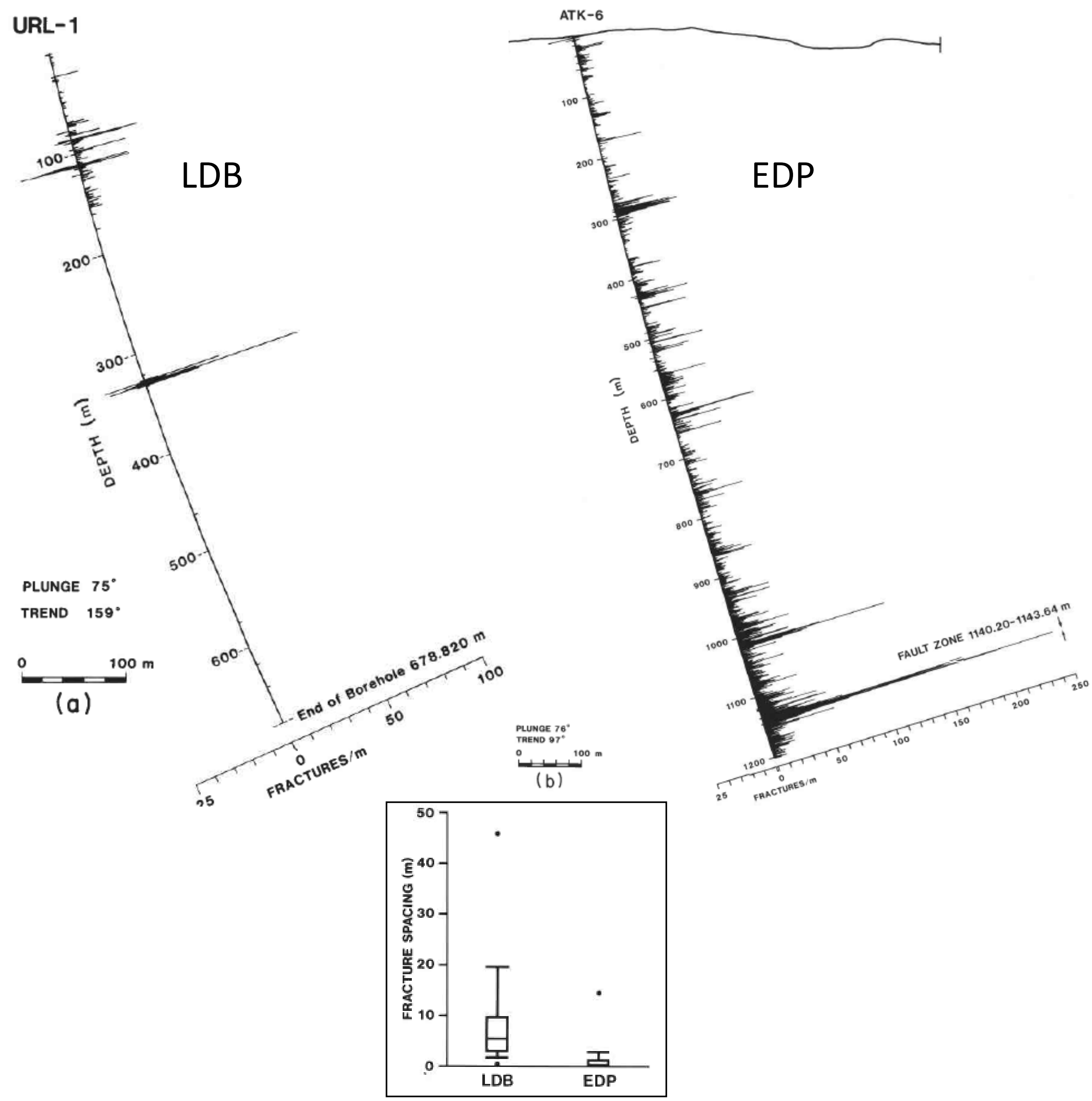

Figure 5-9. Borehole traces from the Lac du Bonnet (top left) and Eye-Dawsha granites (right). Bars along the depth trace indicate the fracture density in fractures/meter. Lower diagram is a box and whisker plot comparing fracture spacing for the two granites. Figures from Stone et al. (1989).

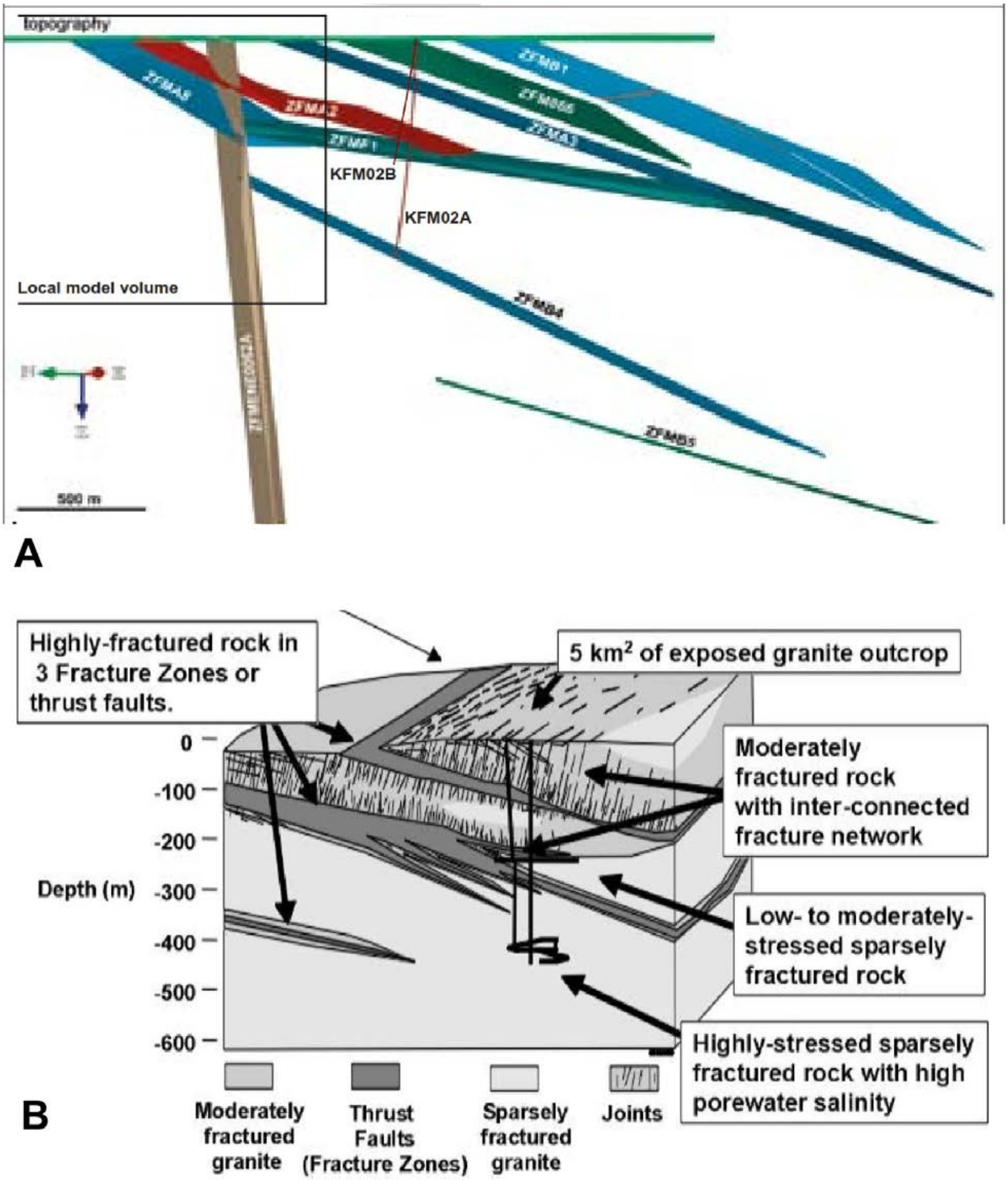

Figure 5-10. Comparison of the geometry of highly fractured deformation zones and sparsely fractured domains at Forsmark (A) and the Lac du Bonnet Batholith (B). Figures from Stephens (2010) and Chandler (2003).

5.2.4 Regional Hydrology and Hydrogeochemistry

Two groundwater systems are relevant to this regional evaluation. The first are the shallow aquifers within glacial deposits that supply the largest proportion of drinking water to the region. These aquifers are stratified gravel or sand deposits or lens separated by confining glacial sediments with high clay content (e.g., Lindgren. 1996). Topography in the region is relatively subdued, but regional groundwater flow is largely controlled by topography and drainage basin divides with flow moving from high areas (sometimes glacial moraine features) to major river valleys such as the Mississippi, Minnesota and Red River or, more locally, major lakes (Winter, 1974).

Water well data for depth to the water table is available from the Minnesota County Well Index database (Table 3-1). For most of the state, the water table is encountered at a depth of 25 meters or less (Figure 5-11). The depth to water table above the Neoarchean granitic plutons is generally 25 meters or less with a few instances as great as 50-100 meters, indicating that a repository in the crystalline basement at a depth of 400-500 meters would be saturated.

The main groundwater system of interest for repository siting is the fracture system of the crystalline basement. Crystalline basement lies directly beneath the glacial aquifers throughout most of the region. The crystalline basement represents a low-yield aquifer in some parts of the state where water is drawn from fractures in the upper few 10s of meters of the crystalline basement.

Little is known about the deep groundwater system in the crystalline basement or Neoarchean granitic rocks of the western Superior Province of the US (Harrison et al. 1983). Fracture studies in Neoarchean granites in the western Superior Province of Canada have focused on the Lac du Bonnet (LDB) batholith (Stone et al., 1989; Everitt et al., 1996). These studies indicate that larger granitic bodies in the western Superior Province are characterized by a moderately fractured zone of subvertical fractures to a depth of ~100- 200 meters (Figure 5-10). Below the near-surface fractured zone, water would flow dominantly in the highly fractured, low-angle deformation/fracture zones that dominate the overall groundwater movement in the granite (Stone et al., 1989; Everitt et al., 1996). Tiren (1991) argues that the low-angle fractured deformation zones are a common feature in crystalline shield provinces and serve as major groundwater pathways, an idea supported by the similarity of these features in Sweden and Canada (Figure 5-10).

Permeability in the LDB batholith generally decreases with depth in both the sparsely fractured domains and the highly fractured deformation zones. Permeability values for the highly fractured domains are primarily in the range of 10^{-11} to below 10^{-16} while permeability values for sparsely fractured domains are primarily in the range of 10^{-16} to less than 10^{-20} (Stevenson et al. 1996a; 1996b).

Salinity increase with depth in crystalline rocks world-wide is a well-established phenomenon (Frape et al., 2003; Figure 5-12). The origins and systematics of saline waters in crystalline rock have been reviewed by many sources, including Frape et al. (2003) and Gascoyne (2004), and can grouped into mechanisms that involve a long history of rock-water interactions or intrusion of marine waters or brine from external sources. Once present in the deep crystalline rock environment (several hundred meters or more), saline waters will tend to remain saline and stagnant because their higher density makes them resistant to mixing with more dilute waters from meteoric sources (Phillips and Castro, 2003), and because of the low permeability of the rock and closed fractures at depth that limit connectivity and mixing with shallower meteoric waters (Frape et al., 2003).

Groundwater in the LDB batholith is fresh to a depth of 250-300 meters and becomes more saline with depth, reaching the salinity of seawater at 1000 meters depth. At potential repository depths of ~400-500 meters, groundwater is brackish to saline with chloride concentrations of between 1200-6000 mg/L (Frape et al. (2003); Figure 5-12). In other parts of the Canadian Shield, groundwater in crystalline rock reaches highly saline concentrations of >100,000 mg/L at depths of 1200-1800 meters (Frape et al. (2003); Figure 5-12).

Redox potential (measured as Eh) measured in the LDB batholith changes from primarily oxidizing in the upper 200 meters to mildly oxidizing or reducing at a depth of ~200-400 meters (Figure 5-13, from Gascoyne, 1996). Consistently reducing groundwater conditions were measured at a depth greater than about 600 meters. Gascoyne (1996) attributes this trend to the location of the rock mass relative to recharge and discharge zones. The AECL URL at the LDB batholith is located in a recharge zone consisting of exposed bedrock on a ridge of modest relief. Gascoyne (2004) concludes that the location of the URL below a recharge area allows active circulation of modern meteoric water in fractures down to a depth of about 200 meters. From ~200-400 meters, which is described as a transition zone, the groundwater is moderately saline and isotopic evidence indicates a component of glacial melt water, indicating that shallow, fresh groundwater has circulated to these depths. Below a depth of about 500-600 meters, groundwater in fractures and pores is reducing, highly saline and has isotopic compositions indicative of stagnant water with long residence times. The depth at which groundwater transitions to reducing, saline conditions likely varies from pluton to pluton depending on location relative to recharge and discharge zones and the details of fracture systems among other potential factors. Determining groundwater chemistry and flow paths relative to repository location would require site-specific studies and characterization.

An additional feature that could affect groundwater flow in the western Superior Province is the presence of mafic dikes that intrude most of the Neoarchean plutons of the region (Figure 5-6). It is not clear what impact dikes might have on the hydrologic system of a granitic pluton. Dikes may act as either groundwater pathways or low-permeability barriers in the overall groundwater system (Golder Associates, 2013 and references therein). Understanding their role at a specific site would require information on their hydrologic properties relative to those of the host rock.

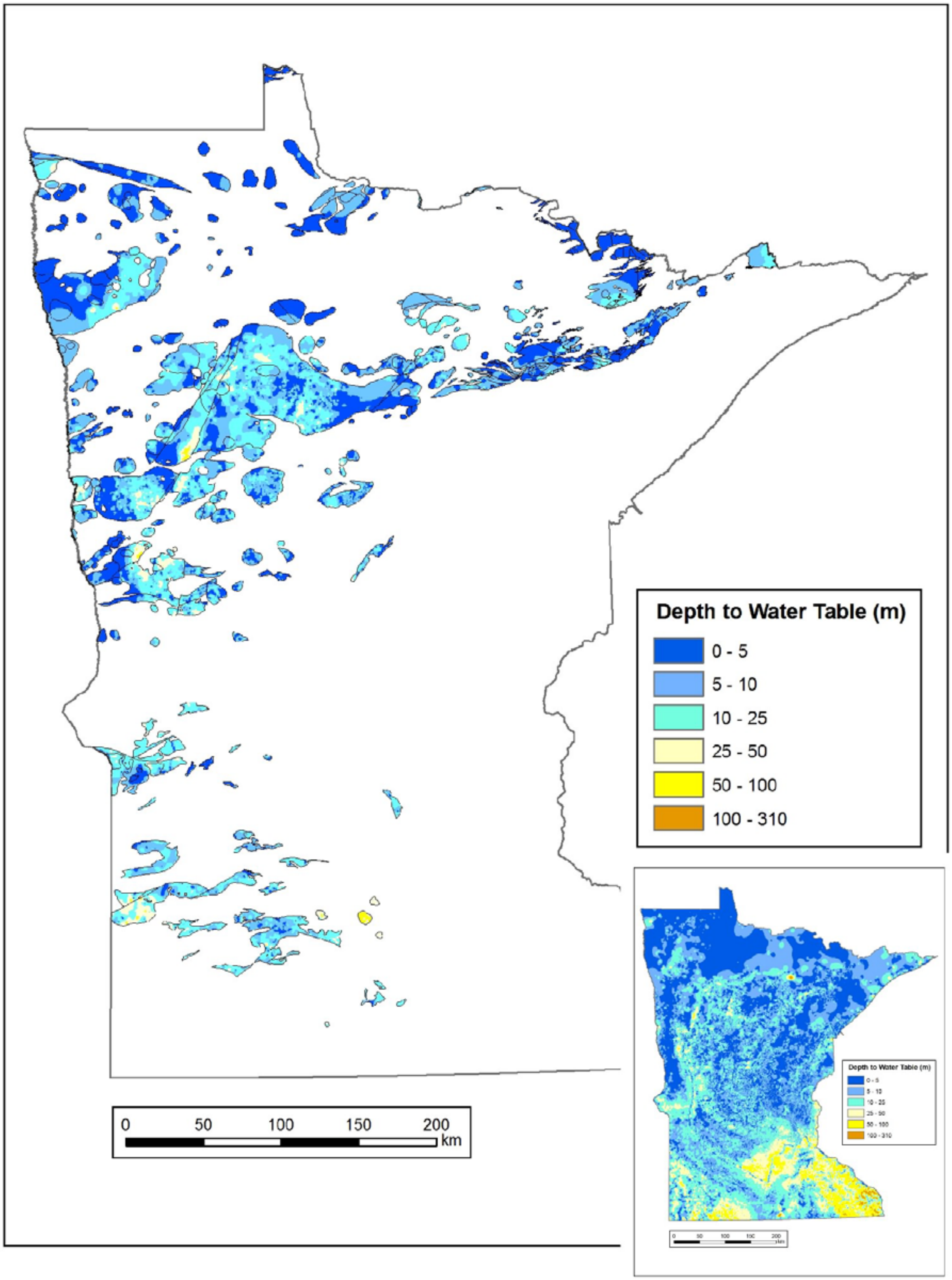

Figure 5-11. Depth to the water table above Neoarchean granitic plutons obtained using GIS. Water table data obtained from the Minnesota Well Index (Table 3-1). Inset map shows depth to water table for all of Minnesota.

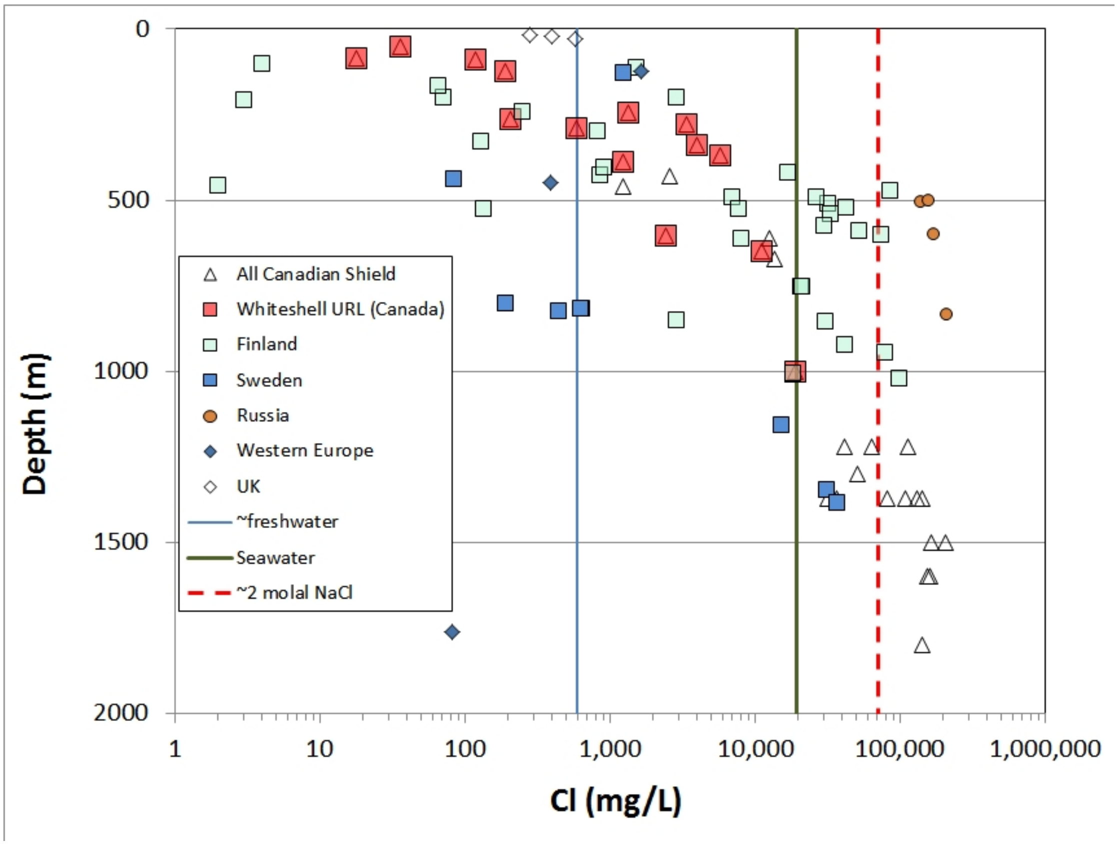

Figure 5-12. Chloride concentration and depth relationships for the Canadian Shield. Whiteshell is the AECL URL located within the Lac du Bonnet (LDB) Batholith. Data from Frape et al. (2003). Figure from Perry (2014).

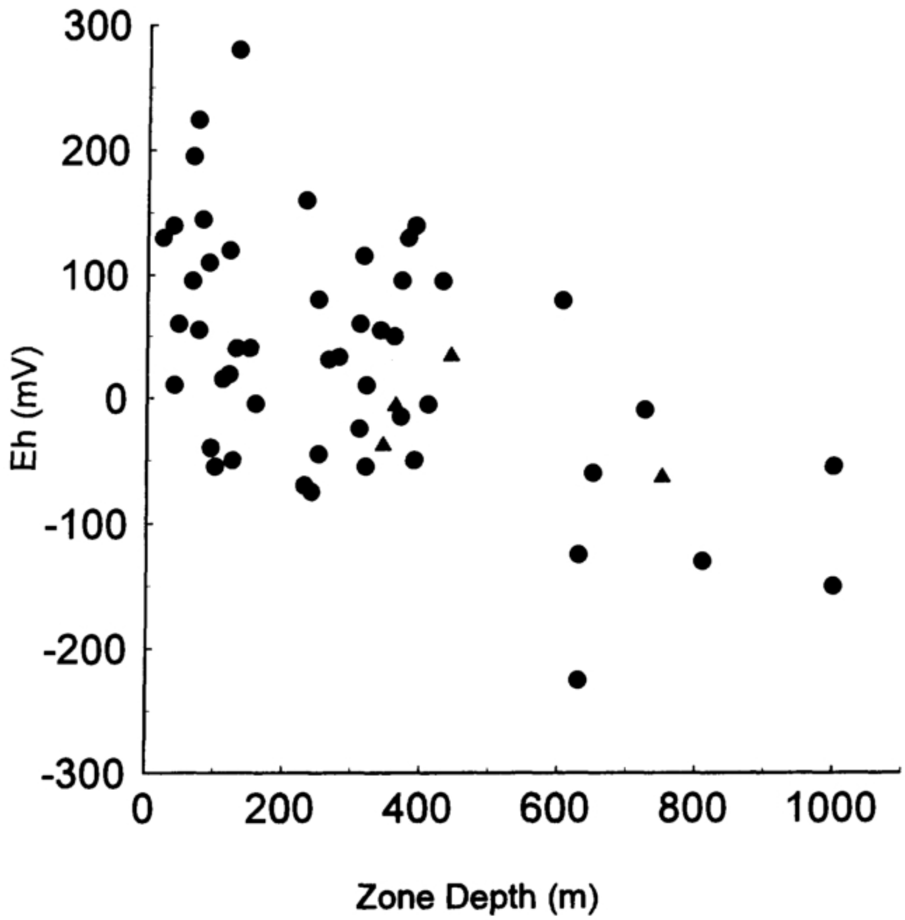

Figure 5-13. Variation of redox potential with depth at the Lac du Bonnet (LDB) batholith. Figure from Gascoyne (1996).

5.3 External Factors

5.3.1 Glacial Events

The western Superior Province is located at high latitudes and has been glaciated and deglaciated several times during the Quaternary (Figure 3-2). The last glacial maximum occurred about 18,000 years ago, and given the frequency of glaciation in the last ~2.5 Ma, it is likely that additional glaciation events will occur over the next 100,000 to 1 million years (Forsstrom, 1999; Johnson et al. 2016).

The advance and retreat of large ice sheets can impact a repository system in several ways including downwarping and rebound of crust with changes in stress conditions, changes to rock porosity, pore pressure and permeability, as well as changes in the groundwater system (Forsstrom, 1999; Holmlund et al., 2006). The most significant impacts on groundwater chemistry are possible changes in salinity and redox conditions caused by mixing with low-salinity and oxidizing meltwater (McMurry and Bertetti, 2014). Low-salinity, oxidized groundwater can corrode waste packages and erode bentonite buffers if meltwater is able to penetrate to repository depths through fracture zones (Auqué et al.; 2006; Neretnieks et al., 2009). Oxidation of groundwater at repository depths may be transitory due to the reducing capacity of the rock mass as oxygenated water moves through the rock mass (Auqué et al.; 2006).

The potential impact of future glacial cycles on a repository system in the western Superior Province would depend on specific features of the host rock, including the characteristics of fracture systems, as well as the initial conditions of the groundwater systems, among many other possible factors that could influence rock properties and the hydrologic system during glacial events. The glacial processes that could impact a repository system would need to be examined as part of site-specific studies.

5.3.2 Seismicity

The western Superior Province is one of the least seismically active regions of the US (Moony, 1979). The historical earthquake record dates from 1860, with about 20 moderate earthquakes recorded since that time (Chandler, 1994; Figure 5-14). The largest recorded earthquakes had a magnitude approaching 5.0 with most in the 3.0-4.8 range (Chandler, 1994). Harrison et al. (1993) calculate a maximum magnitude earthquake of 5.3 for the region. Most historical earthquakes occurred in west-central Minnesota and are associated spatially with the GLTZ (Moony, 1979). Earthquakes in the region are generally attributed to reactivation of faults in the Archean and Proterozoic crystalline basement (Chandler, 1994; 1995). The low frequency and magnitude of earthquakes in this region do not represent a significant safety factor for the long-term performance of a potential repository.

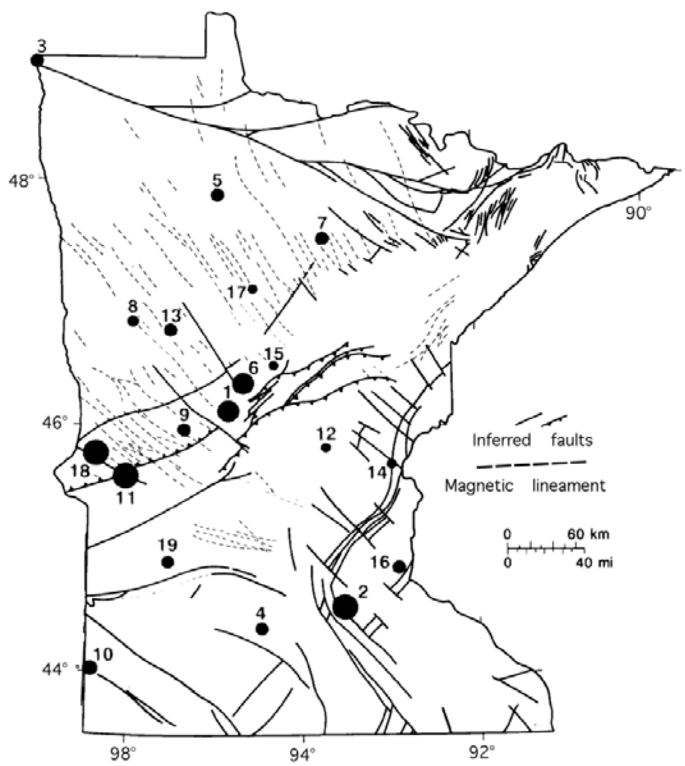

Figure 5-14. Locations of historical earthquakes of moderate intensity in Minnesota. Figure from Chandler (1994). The strongest instrumently recorded earthquake was the Morris earthquake of 1975 earthquake (#11 on figure) with a magnitude of 4.6-4.8 (Chandler 1994).

5.3.3 Human Intrusion – Exploration of Natural Resources

Mineral exploration and production in the western Superior Province is primarily for iron. Exploration activities have also targeted nickel, copper, zinc, gold and platinum-group metals. Copper, nickel, zinc (base metals) and platinum-group metals are usually associated with the mafic Duluth complex in northeastern Minnesota or metavolcanic rocks of the northern greenstone belts (Morey and Sims, 1993; Figure 5-14). Diamonds found in glacial deposits originated from erosion of Mesozoic kimberlite intrusions identified by aeromagnetic surveys (Morey and Sims, 1993). The Neoarchean granitic plutons of the region are not known to be metal bearing and few have been the target of exploratory drilling (Figure 5-15). Golder Associates reached the same conclusion for analogous granites in the Ignace area of southwestern Ontario (Figure 5-1) where mineralization occurs in the intruded metavolcanic greenstone belts, but not in the granitic plutons.

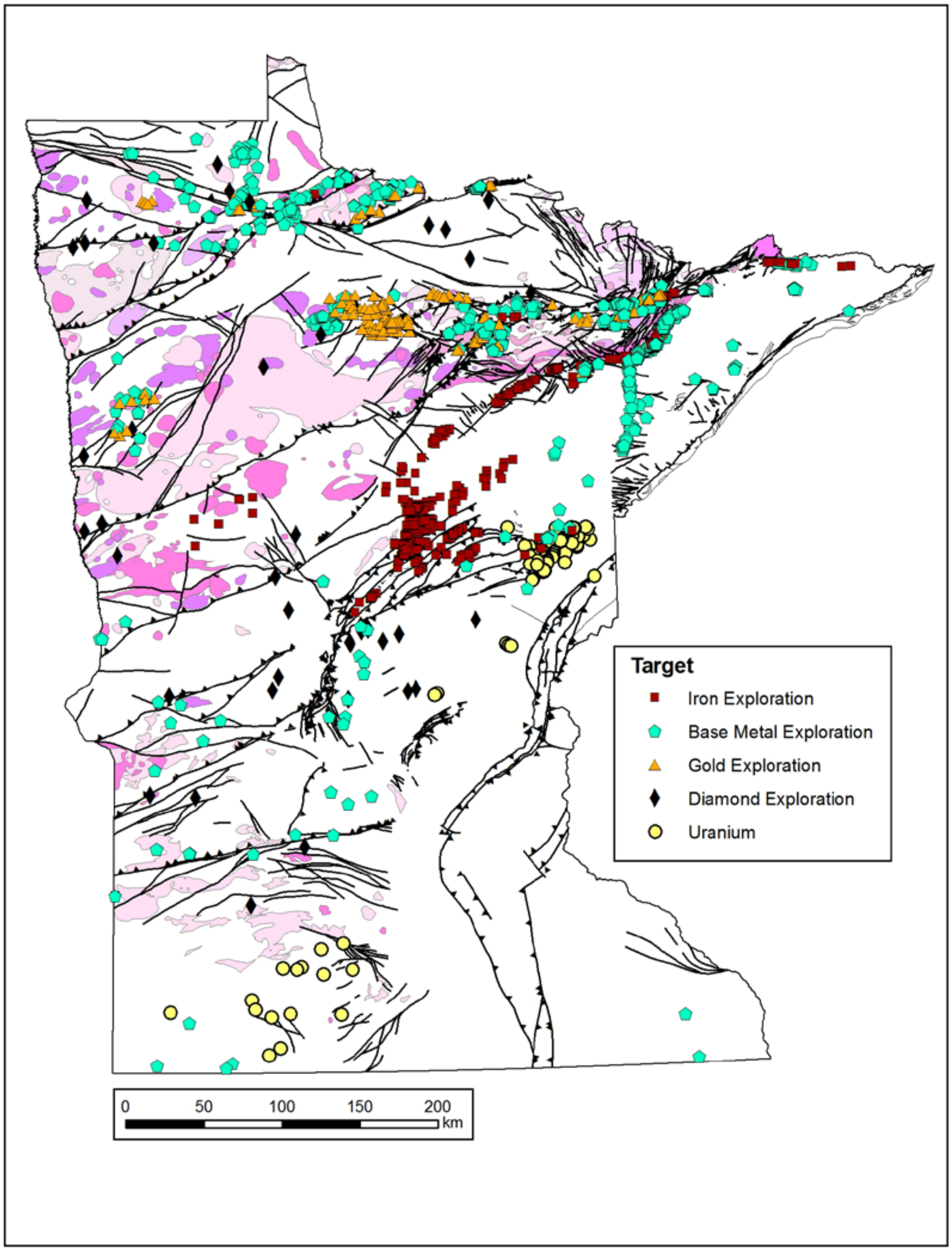

Figure 5-15. Location of mineral exploration boreholes drilled between 1910 and 2005 illustrating their location relative to Neoarchean granites. Mineral exploration borehole data from Minnesota Department of Natural Resources Drill Core Library (Table 3-1).

6. Conclusions

We have completed a regional geologic evaluation of the western Superior Province in the north-central US. This evaluation was focused on the geologic and hydrologic environment (i.e., the natural system or geosphere) as well as three external events, glaciation, seismic activity, and human intrusion in the form of mineral exploration. Neoarchean granitic plutons emplaced during late deformation of the western Superior Province are a potential host-rock for a deep geologic repository for radioactive waste (Sood et al., 1984).

From the regional geologic evaluation, we conclude the following:

Host Rock/Fracture Systems – Neoarchean granite intrusions are widespread throughout the western Superior Province and represent a potential granitic host rock. Data from analogous granitic intrusions within the western Superior Province of Canada and from the crystalline terrane in Sweden suggest that the Neoarchean intrusions of larger volume are characterized by highly fractured deformation zones (thrust faults) that separate relatively intact and sparsely fractured rock masses. The latter rock domains would be desirable for repository siting in a flow-restricted groundwater environment. Documentation of these features would require characterization at specific sites to confirm their presence in the US.

Hydrology and Hydrogeochemistry – Based on the analog fracture systems in Canada described above, and data from groundwater systems in crystalline rock from other parts of the world, groundwater conditions change with increasing depth, becoming more saline, reducing, and less capable of mixing with modern meteoric water because of density differences and restricted fracture flow. The transition to deep groundwater conditions takes place over several hundred meters and likely varies in detail from pluton to pluton but appears to reach highly saline and reducing conditions below a depth of ~500-600 meters.

Seismicity and Faulting – The western Superior Province has one of the lowest rates of seismic activity in the US with no record of major earthquakes. The largest historical earthquakes since 1860 had a magnitude of less than 5.0. Earthquakes, therefore, do not represent a significant event in terms of repository performance. Historical earthquakes are associated Precambrian basement faults suggesting the faults are periodically reactivated because of crustal stress conditions. Faults may represent potential groundwater flow pathways or zones of mechanical weakness that would have to be evaluated, if present, if site characterization were carried out at specific sites.

Overburden – For the Neoarchean plutons, only glacial deposits are relevant overburden as Mesozoic sediments overlie only a few plutons or portions of plutons in the western part of the region. Neoarchean plutons are covered by significant thickness of glacial deposits (>25 meters) except in the northeastern part of the region. Overburden may be an impediment to site characterization because of difficulties in accessing the potential host rock. In some safety scenarios, overburden is desirable as an additional HLW isolation barrier. In these scenarios, site-specific data would be necessary to determine the radionuclide retention characteristics of glacial deposits.

Glaciation – Glaciation is an expected future event in the western Superior Province. Evaluating the impact of future glaciation/deglaciation events on a deep geologic repository for radioactive waste would require site-specific studies of fracture systems and hydrogeochemistry.

Seismicity – the low frequency and magnitude of earthquakes in the western Superior Province indicate that seismicity would not play a role in the long-term performance of a deep geologic repository for radioactive waste.

Human Intrusion – Mineral exploration in the western Superior Province is primarily for metals associated with greenstone belts and mafic intrusions. Neoarchean granitic rocks are not expected to be a future target for exploration of mineral resources.

7. References

Auqué, L.F., Gimeno, M.J., Gomez, J.B., Puigdomenech, I., Smellie, J. and Tullborg, E.L., 2006. Groundwater chemistry around a repository for spent nuclear fuel over a glacial cycle: evaluation for SR-Can, SKB (Sweden), TR-06-31. 118 p.

Boerboom, T.J. and Zartman, R.E., 1993. Geology, geochemistry, and geochronology of the central Giants Range batholith, northeastern Minnesota. Canadian Journal of Earth Sciences, v. 30, p. 2510-2522.

Brown, A.N., Soonawala, M., Everitt, R.A. and Kamineni. D. C., 1989. Geology and Geophysics of the Underground Research Laboratory Site, Lac Du Bonnet Batholith, Manitoba. Canadian Journal of Earth Sciences v.26, p. 404-425.

Card, K.D. 1990. A review of the Superior Province of the Canadian Shield, a product of Archean accretion. Precambrian Research, v. 48, p. 99-156.

Chandler, N. A., 2003. Twenty Years of Underground Research at Canada's URL. WM'03 Conference, Tucson, Arizona, 15 p.

Chandler, V.W., 1993. Gravity and Magnetic Studies Conducted Recently; in P.K. Sims and L.M.H. Carter, eds., Archean and Proterozoic Geology of the Lake Superior Region, U.S.A., 1993; U.S. Geological Survey Professional Paper 1556, p. 76-87.

Chandler V.W., 1994. Earthquakes in Minnesota. Minnesota Geological Survey, 4 p.

Chandler, V.W., 1995. The west-central Minnesota earthquake of June 5, 1993: an opportunity to re-examine seismicity near the Morris fault. Seismological Research, v. 66, p. 113 -121.

Chandler, V.W., 2007. Upgrade of Aeromagnetic Databases and Processing Systems at the Minnesota Geological Survey. Minnesota Geological Survey Open File Report OFR07_06.

Chandler, V.W.; Lively, R.S., 2014. Upgrade of the Gravity Database. Retrieved from the University of Minnesota Digital Conservancy, http://hdl.handle.net/11299/163539.

Day, W., and Weiblen, P., 1986. Origin of Late Archean Granite: Geochemical Evidence from the Vermilion Granitic Complex of Northern Minnesota. Contributions to Mineralogy and Petrology v. 93, p. 283-296.

DOE (U.S. Department of Energy) 2012. Used Fuel Disposition Campaign Disposal Research and *Development Roadmap.* FCR&D-USED-2011-000065, REV 1, U.S. DOE Office of Nuclear Energy, Used Fuel Disposition, Washington, D.C., September 2012.

Everitt, R. 1996. Geology of the Lac Du Bonnet Batholith, Inside and Out: AECL's Underground Research Laboratory, Southeastern Manitoba Field Trip B5. Winnipeg: Geological Association of Canada, Winnipeg Section, 72 p.

Forsstrom, L., 1999. Future glaciation in Fennoscandia. POSIVA 99-30 (Finland), 42 p.

Frape, S., Blyth, A., Blomqvist, R., McNutt, R., and Gascoyne, M./ 2003. Deep Fluids in the Continents: II. Crystalline Rocks. In Treatise on Geochemistry, Eds. H. Holland, and K. Turekian. pp. 541-580.

Freeze, G., Mariner, P., Blink, J.A., Caporuscio, F.A., Houseworth, J.E., and Cunnane, J.C., 2011. Disposal System Features, Events, and Processes (FEPs): FY11 Progress Report. DOE Used Fuel Disposition Campaign, FCRD-UFD-2011-000254.

Garrity and Soller, 2009. Database of the Geologic Map of North America; adapted from the map by J.C. Reed, Jr. and others 2005. U.S. Geological Survey Data Series 424.

Gascoyne, M., 2004. Hydrochemistry, groundwater ages and sources of salts in granitic batholith on the Canadian Shield, southeastern Manitoba. Applied Geochemistry, v.19, p. 519-560.

Gascoyne, M. 1996. The Evolution of Redox Conditions and Groundwater Geochemistry in Recharge-Discharge Environments on the Canadian Shield. Atomic Energy Canada Limited, AECL-11682, COG-96-500. 48 p.

Golder Associates, 2013. Phase 1 Geoscientific Desktop Preliminary Assessment of Potential Suitability for Siting a Deep Geological Repository for Canada's Used Nuclear Fuel, Township of Ignace, Ontario. Report submitted to NMWO (Canada), NWMO Report No: APM-REP-06144-0011, Toronto, Ontario. www.nwmo.ca. 147 p.

Grandia, F., Sena, C., Arcos, D., Molinero, Jorge, D., L. and Bruno, J., 2007. Quantitative assessment of radionuclide retention in the near-surface system at Forsmark: Development of a reactive transport model using Forsmark 1.2 data, SKB (Sweden), R-07-64. 90 p.

Harrison, W., Edgar, D., Van Luik, A., Hinze, W., Braile, L., Kalliokoski, J., Pfannkuch, H., Wright, H., Tisue M. and Sood, M., 1983. Geology, Hydrology, and Mineral Resources of Crystalline Rock Areas of the Lake Superior Region, United States, Argonne National Laboratory Report ANL/ES-134. 427 p.

Holm, D.K., Anderson, R., Boerboom, T.J., Cannon, W.F., Chandler, V., Jirsa, M., Miller, J., Schneider, D.A., Schulz, K.J. and Van Schmus.W.R., 2007. Reinterpretation of Paleoproterozoic Accretionary Boundaries of the North- Central United States Based on a New Aeromagnetic-Geologic Compilation. Precambrian Research v.157. p. 71-79.

Holmund, P, Caroline C, and Blomdahl K., 2016. The Effect of a Glaciation on East Central Sweden: Case Studies on Present Glaciers and Analyses of Landform Data. Research, Technical Note 2016:21. Swedish Radiation Safety Authority. 75 p.

Jirsa, M.A.; Bauer, E.J.; Boerboom, T.J.; Chandler, V.W.; Lively, R.S.; Mossler, J.H.; Runkel, A.C.; Setterholm, D.R., 2010. Preliminary Bedrock Geologic Map of Minnesota. Minnesota Geological Survey OFR10-02. Retrieved from the University of Minnesota Digital Conservancy, http://hdl.handle.net/11299/98043.

Jirsa, M.A.; Boerboom, T.J.; Chandler, V.W., 2013. S-22, Geologic Map of Minnesota, Precambrian Bedrock Geology. Retrieved from the University of Minnesota Digital Conservancy, http://hdl.handle.net/11299/154540.

Johnson, B. and Wahl, T., 2016. Minnesota Well Index. Minnesota Department of Health, 01 Aug. 2016. Web. 26 Aug. 2016. http://www.health.state.mn.us/divs/eh/cwi/ .

Johnson, M. D., Adams, R. S., Gowan, A.S., Harris, K.L., Hobbs, H.C., Jennings, C. E., Knaeble, A.R., Lusardi, B.A., Meyer, G.N., 2016. Quaternary Lithostratigraphic Units of Minnesota. Minnesota Geological Survey, RI-68. Retrieved from the University of Minnesota Digital Conservancy, http://hdl.handle.net/11299/177675.

Kucks, R.P., 1999 Bouguer Gravity Anomaly Data Grid for the Conterminous US. U.S. Geological Survey. Retrieved from the USGS Mineral Resources On-Line Spatial Data Repository. http://mrdata.usgs.gov/gravity/bouguer.

Lodha, G.S., Davison, C.C. and Gascoyne, M., 1998. Characterizing fractured plutonic rocks of the Canadian shield for deep geological disposal of Canada's radioactive wastes. In Characterization and Evaluation of Sites for Deep Geological Disposal of Radioactive Waste in Fractured Rocks: Proceedings from The 3rd ÄSPÖ International Seminar Oskarshamn, June 10–12, 1998. SKB (Sweden) TR-98-10. P.1-14.

Lundgren, R.J., 1996. Hydrogeology and Ground-Water Quality of Glacial-Drift Aquifers, Leech Lake Indian Reservation, North-Central Minnesota. U.S. Geological Survey Water-Resources Investigations Report 95-4077. 86 p.

Mariner, P.E., Lee, J.H., Hardin, E.L., Hansen, F.D., Freeze, G.A., Lord, A.S., Goldstein, B., and Price, R.H., 2011. Granite Disposal of U.S. High-Level Radioactive Waste. Sandia National Labs, Sandia Report SAND2011-6203, 114 p.

Mariner, P. E., E. R. Stein, J. M. Frederick, S. D. Sevougian, G. E. Hammond, and D. G. Fascitelli, 2016. *Advances in Geologic Disposal System Modeling and Application to Crystalline Rock*, FCRD-UFD-2016-000440, SAND2016-96107R. Sandia National Laboratories, Albuquerque, NM, September 22, 2016.

Martin, D. P., Meyer, G., Cartwright, D. F., Lawler, T. L., Pastika, T., Jirsa, M. A., Boerboom, T. J. and Streitz. A. R., 1989. Regional Geochemistry Survey of Glacial Drift Drill Samples over Archean Granite- Greenstone Terrane in the Effie Area, Northern Minnesota. Minnesota Department of Natural Resources, Division of Minerals, Report 263. 70 p.

Martin, D.P., Dahl, D.A., Cartwright, D.F. and Meyer, G.N., 1991. Regional Survey of Buried Glacial Drift, Saprolite, and Precambrian Bedrock in Lake of the Woods County, Minnesota. Minnesota Department of Natural Resources, Division of Minerals, Report 280. 203 p.

McMurry, J. and Bertetti, F.P., 2016. Review of Long-Term Redox Evolution of Groundwater and Potential Influence of Oxygenated Glacial Meltwater in SR-Site, Technical Note 2014:08. Swedish Radiation Safety Authority. 50 p.

Metcalfe, R. and Watson, S.P., 2009. Technical issues associated with deep repositories for radioactive waste in different geological environments, Science Report: SC060054/SR1.Environmental Agency (England). 224 p.

Minnesota Department of Natural Resources Drill Core Library web site http://mcc.mn.gov/gis.html#exploration_head. Retrieved October 3, 2016

Mooney, H. M., 1979. Earthquake History of Minnesota. Minnesota Geological Survey, Report of Investigations 23. 31 p.

Morey G.B. and Sims, P.K., 1993. Metallogeny; in P.K. Sims and L.M.H. Carter, eds., Archean and Proterozoic Geology of the Lake Superior Region, U.S.A., 1993; U.S. Geological Survey Professional Paper 1556, p. 87-94.

Morey, G.B., and Van Schmus, W.R., 1988. Correlation of Precambrian Rocks of the Lake Superior Region, United States. US Geological Survey Professional Paper 1241-F. 39 p.

Neretnieks, I., Liu, L. and Moreno, L., 2009. Mechanisms and models for bentonite erosion. SKB (Sweden) TR-09-35. 160 p.

NWMO (Nuclear Management Waste Organization, Canada), 2010. Moving Forward Together: Process for Selecting a Site for Canada's Deep Geological Repository for Used Nuclear Fuel.. Toronto, Ontario. www.nwmo.ca. 52 p.

Percival, J., Sanborn-Barrie, M., Skulski, T., and Stott, G., 2006. Tectonic Evolution of the Western Superior Province from NATMAP and Lithoprobe Studies. Canadian Journal of Earth Sciences, v.43. p. 1085-117.

Perry, F.V., Kelley, R.E., Dobson, P.F., and Houseworth, J.E., 2014. Regional geology: A GIS database for alternative host rocks and potential siting guidelines. DOE Used Fuel Disposition Campaign, FCRD-UFD-2014-000068.

Petersen, M.D. et al., 2014. Documentation for the 2014 update of the United States national seismic hazard maps: U.S. Geological Survey Open-File Report 2014–1091, 243 p. http://dx.doi.org/10.3133/o fr20141091.

Phillips, F., and Castro, M., 2003. Groundwater Dating and Residence-time Measurements. In Treatise on Geochemistry, Eds. H. Holland, and K. Turekian, p. 452-497.

Satkoski, A.M., Bickford, M.E. Samson, S.D., Bauer, R.L., Mueller, P.A. and Kamenov. G.D., 2013. Geochemical and Hf– Nd Isotopic Constraints on the Crustal Evolution of Archean Rocks from the Minnesota River Valley, USA. Precambrian Research, v.224. p. 36-50.

Schmitz, M.D., Bowring, S.A., Southwick D.L., Boerboom T.J. and Wirth. K.R., 2006. High- Precision U- Pb Geochronology in the Minnesota River Valley Subprovince and Its Bearing on the Neoarchean to Paleoproterozoic Evolution of the Southern Superior Province. Geological Society of America Bulletin, v. 118. p. 82-93.

Schulz, K.J., and Cannon, W.F., 2007. The Penokean Orogeny in the Lake Superior Region. Precambrian Research v.157. p. 4-25.

Sims, P.K. 1993. Minnesota River Valley Subprovince Archean Gneiss Terrane; in P.K. Sims and L.M.H. Carter, eds., Archean and Proterozoic Geology of the Lake Superior Region, U.S.A., 1993; U.S. Geological Survey Professional Paper 1556, p. 14-23.

Sims, P.K., Day, W.C., 1993. The Great Lakes tectonic zone - Revisited. U.S. Geol. Surv. Bull. 1904-S. 20 p.

Sims, P.K., 1995. Archean and Early Proterozoic Tectonic Framework of North-Central United States and Adjacent Canada. U.S. Geol. Surv. Bull. 1904-T. 18 p.

Sood, M.K., Flower, M.F.J., & Edgar, D.E., 1984. Characterization of crystalline rocks in the Lake Superior region, USA: implications for nuclear waste isolation.. Waste Management '84, CONF-840307-20. Tucson, Arizona. 14 p.

Southwick, D.L., 2002. Geologic map of pre-Cretaceous bedrock in southwest Minnesota. Minnesota Geological Survey, Miscellaneous Map Series Map M-121.

Southwick, D. L., and Day, W. C., 1083. Geology and Petrology of Proterozoic Mafic Dikes, North-Central Minnesota and Western Ontario. Canadian Journal of Earth Sciences, v.20. p. 622-638.

Southwick, D.L., 1993. Archean Superior Province. In P.K. Sims and L.M.H. Carter, eds., Archean and Proterozoic Geology of the Lake Superior Region, U.S.A., 1993; U.S. Geological Survey Professional Paper 1556, p. 6-13.

Southwick, D.L., 2014. Reexamination of the Minnesota River Valley Subprovince with emphasis on Neoarchean and Paleoproterozoic events. Minnesota Geological Survey, Report of Investigations 69, 52p.

Stephens M.B, 2010. Forsmark site investigation: Bedrock geology – overview and excursion guide. SKB (Sweden) R-10-04. 47 p.

Stevenson, D.R., Brown, A., Davison, C.C., Gascoyne, M., McGregor, R.G., Ophori, D.U., Scheier, N.W., Stanchell, F.W., Thome, G.A. and Tomsons, D.K., 1996a. A revised conceptual model of a crystalline rock environment, Whiteshell Research Area, Southeastern Manitoba, Canada. Atomic Energy of Canada Limited Report AECL-11331/COG-95-271. 37 p.

Stevenson, D.R., Kozak, E.T., Davison, C.C., Gascoyne, M and Broadfoot, R.A., 1996b. Hydrogeologic Characteristics of Domains of Sparsely Fractured Rock in the Granitic Lac du Bonnet Batholith, Southeastern Manitoba, Canada. Atomic Energy of Canada Limited Report AECL-11558/COG-96-117. 36 p.

Stone, D., Kamineni, D. C., Brown, A. and Everitt, R., 1989. A Comparison of Fracture Styles in Two Granite Bodies of the Superior Province. Canadian Journal of Earth Sciences, v.26. p. 387-403.

Tirén, S.A., 1991. Geological Setting and Deformation History of a Low- Angle Fracture Zone at Finnsjön, Sweden. Journal of Hydrology, v. 126. P. 17-43.

Winter, T.C., 1974. The natural quality of ground water in Minnesota. Minnesota Department Of Natural Resources, Bulletin 26. 16 p.

APPENDIX A

IDENTIFICATION OF FEPS FOR EVALUATION OF THE GEOLOGIC ENVIRONMENT AND EXTERNAL FACTORS IN CRYSTALLINE TERRANES (MODIFIED FROM FREEZE ET AL., 2011)

UFD FEP Number	Description	Associated Processes	Related YMP FEPs
0.0.00.00	0. ASSESSMENT BASIS		
0.1.02.01	Timescales of Concern		0.1.02.00.0A
0.1.03.01	Spatial Domain of Concern		0.1.03.00.0A
1.0.00.00	1. EXTERNAL FACTORS		
1.2.00.00	2. GEOLOGICAL PROCESSES AND EFFECTS		
1.2.01.00	2.01. LONG-TERM PROCESSES		
1.2.01.01	Tectonic Activity – Large Scale	- Uplift - Folding	1.2.01.01.0A
1.2.03.00	2.03.SEISMIC ACTIVITY		
1.2.03.02	Seismic Activity Impacts Geosphere - Host Rock - Other Geologic Units	- Altered flow pathways and properties - Altered stress regimes faults, fractures) [see also Alterations and Impacts in 2.2.05.01, 2.2.05.02, 2.2.05.03, 2.1.07.01, and 2.1.07.02]	1.2.03.03.0A 1.2.10.01.0A 2.2.06.01.0A 2.2.06.02.0A 2.2.06.02.0B 2.2.06.03.0A
1.2.04.00	2.04. IGNEOUS ACTIVITY		
1.2.04.02	Igneous Activity Impacts Geosphere - Host Rock - Other Geologic Units	- Altered flow pathways and properties - Altered stress regimes faults, fractures) - Igneous intrusions - Altered thermal and chemical conditions	1.2.04.02.0A 1.2.10.02.0A
1.3.00.00	3. CLIMATIC PROCESSES AND EFFECTS		
1.3.04.01	Periglacial Effects	- Permafrost - Seasonal freeze/thaw	1.3.04.00.0A
1.3.05.01	Glacial and Ice Sheet Effects	- Glaciation - Isostatic depression - Melt water	1.3.05.00.0A
1.4.00.00	4. FUTURE HUMAN ACTIONS		

UFD FEP Number	Description	Associated Processes	Related YMP FEPs
1.4.02.01	Human Intrusion - Deliberate - Inadvertent	- Drilling resource exploration, …) - Mining / tunneling - Unintrusive site investigation airborne, surface-based, …)	1.4.02.01.0A 1.4.02.02.0A 1.4.03.00.0A 1.4.04.00.0A 1.4.04.01.0A 1.4.05.00.0A 3.3.06.01.0A
2.0.00.00	2. DISPOSAL SYSTEM FACTORS		
2.2.00.00	2. GEOLOGICAL ENVIRONMENT		
2.2.02.00	2.02. HOST ROCK		
2.2.02.01	Stratigraphy and Properties of Host Rock	- Rock units - Thickness, lateral extent, heterogeneities, discontinuities, contacts - Physical properties - Flow pathways [see also Fractures in 2.2.05.01 and Faults in 2.2.05.02]	2.2.03.01.0A 2.2.03.02.0A
2.2.03.00	2.03. OTHER GEOLOGIC UNITS		
2.2.03.01	Stratigraphy and Properties of Other Geologic Units Non-Host-Rock) - Confining units - Aquifers	- Rock units - Thickness, lateral extent, heterogeneities, discontinuities, contacts - Physical properties - Flow pathways	2.2.03.01.0A 2.2.03.02.0A
2.2.05.00	2.05. FLOW AND TRANSPORT PATHWAYS		
2.2.05.01	Fractures - Host Rock - Other Geologic Units	- Rock properties [see also Stratigraphy and Properties in 2.2.02.01 and 2.2.03.01]	1.2.02.01.0A 2.2.07.13.0A
2.2.05.02	Faults - Host Rock - Other Geologic Units	- Rock properties [see also Stratigraphy and Properties in 2.2.02.01 and 2.2.03.01]	1.2.02.02.0A 2.2.07.13.0A
2.2.05.03	Alteration and Evolution of Geosphere Flow Pathways - Host Rock - Other Geologic Units	- Changes In rock properties - Changes in faults - Changes in fractures - Plugging of flow pathways - Changes in saturation	2.2.12.00.0A 2.2.12.00.0B

UFD FEP Number	Description	Associated Processes	Related YMP FEPs
2.2.07.00	2.07. MECHANICAL PROCESSES		
2.2.07.01	Mechanical Effects on Host Rock	- From subsidence - From salt creep - From clay deformation - From granite deformation rockfall / drift collapse into tunnels) - Chemical precipitation / dissolution - Stress regimes [see also Subsidence in 1.2.02.01, Thermal-Mechanical Effects in 2.2.11.06 and Thermal-Chemical Alteration in 2.2.11.07]	2.2.06.04.0A 2.2.06.05.0A
2.2.07.02	Mechanical Effects on Other Geologic Units	- From subsidence - Chemical precipitation / dissolution - Stress regimes [see also Subsidence in 1.2.02.01, Thermal-Mechanical Effects in 2.2.11.06 and Thermal-Chemical Alteration in 2.2.11.07]	2.2.06.04.0A
2.2.08.00	2.08. HYDROLOGIC PROCESSES		
2.2.08.01	Flow Through the Host Rock	- Saturated flow - Fracture flow / matrix imbibition - Unsaturated flow fingering, capillarity, episodicity, perched water) - Preferential flow pathways - Density effects on flow - Flow pathways out of Host Rock [see also Influx/Seepage into EBS in 2.1.08.09, Alteration of Flow Pathways in 2.2.05.03, Thermal Effects on Flow in 2.2.11.01, Effects of Gas on Flow in 2.2.12.02]	2.2.07.02.0A 2.2.07.03.0A 2.2.07.04.0A 2.2.07.05.0A 2.2.07.07.0A 2.2.07.08.0A 2.2.07.09.0A 2.2.07.12.0A
2.2.08.02	Flow Through the Other Geologic Units - Confining units - Aquifers	- Saturated flow - Fracture flow / matrix imbibition - Unsaturated flow fingering, capillarity, episodicity, perched water) - Preferential flow pathways - Density effects on flow - Flow pathways out of Other Geologic Units [see also Alteration of Flow Pathways in 2.2.05.03, Thermal Effects on Flow in 2.2.11.01, Effects of Gas on Flow in 2.2.12.02]	2.2.07.02.0A 2.2.07.03.0A 2.2.07.04.0A 2.2.07.05.0A 2.2.07.07.0A 2.2.07.08.0A 2.2.07.09.0A 2.2.07.12.0A

UFD FEP Number	Description	Associated Processes	Related YMP FEPs
2.2.08.03	Effects of Recharge on Geosphere Flow - Host Rock - Other Geologic Units	- Infiltration rate - Water table rise/decline [see also Infiltration in 2.3.08.03]	1.3.07.01.0A 1.3.07.02.0A 1.3.07.02.0B
2.2.08.08	Groundwater Discharge to Biosphere Boundary	- Surface discharge water table, capillary rise, surface water) - Flow across regulatory boundary	2.2.08.11.0A 2.3.11.04.0A
2.2.09.00	2.09.CHEMICAL PROCESSES - CHEMISTRY		
2.2.09.01	Chemical Characteristics of Groundwater in Host Rock	- Water composition radionuclides, dissolved species, …) - Water chemistry temperature, pH, Eh, ionic strength …) - Reduction-oxidation potential - Reaction kinetics - Interaction with EBS - Interaction with host rock	2.2.01.02.0B 2.2.08.01.0B
2.2.09.02	Chemical Characteristics of Groundwater in Other Geologic Units Non-Host-Rock) - Confining units - Aquifers	- Water composition radionuclides, dissolved species, …) - Water chemistry temperature, pH, Eh, ionic strength …) - Reduction-oxidation potential - Reaction kinetics - Interaction with other geologic units	2.2.08.01.0A
2.2.09.03	Chemical Interactions and Evolution of Groundwater in Host Rock	- Host rock composition and evolution granite, clay, salt ...) - Evolution of water chemistry in host rock - Chemical effects on density - Interaction with EBS - Reaction kinetics - Mineral dissolution/precipitation - Redissolution of precipitates after dry-out	2.2.01.02.0B 2.2.07.14.0A 2.2.08.03.0B 2.2.08.04.0A
2.2.09.04	Chemical Interactions and Evolution of Groundwater in Other Geologic Units Non-Host-Rock) - Confining units - Aquifers	- Host rock composition and evolution granite, clay, salt ...) - Evolution of water chemistry in host rock - Chemical effects on density - Reaction kinetics - Mineral dissolution/precipitation - Recharge chemistry	2.2.07.14.0A 2.2.08.03.0A
2.2.09.05	Radionuclide Speciation and Solubility in Host Rock	- Dissolved concentration limits [controlled by Chemistry in Host Rock in 2.2.09.01]	2.2.08.07.0B

UFD FEP Number	Description	Associated Processes	Related YMP FEPs
2.2.09.06	Radionuclide Speciation and Solubility in Other Geologic Units Non-Host-Rock) - Confining units - Aquifers	- Dissolved concentration limits [controlled by Chemistry in Other Geologic Units in 2.2.09.02]	2.2.08.07.0A
2.2.09.50	2.09. CHEMICAL PROCESSES - TRANSPORT		
2.2.09.51	Advection of Dissolved Radionuclides in Host Rock	- Flow pathways and velocity - Advective properties porosity, tortuosity) - Dispersion - Matrix diffusion - Saturation	2.2.07.15.0B 2.2.08.08.0B
2.2.09.52	Advection of Dissolved Radionuclides in Other Geologic Units Non-Host-Rock) - Confining units - Aquifers	- Flow pathways and velocity - Advective properties porosity, tortuosity) - Dispersion - Matrix diffusion - Saturation	2.2.07.15.0A 2.2.08.08.0A
2.2.09.53	Diffusion of Dissolved Radionuclides in Host Rock	- Gradients concentration, chemical potential) - Diffusive properties diffusion coefficients) - Flow pathways and velocity - Saturation	2.2.08.05.0A
2.2.09.54	Diffusion of Dissolved Radionuclides in Other Geologic Units Non-Host-Rock) - Confining units - Aquifers	- Gradients concentration, chemical potential) - Diffusive properties diffusion coefficients) - Flow pathways and velocity - Saturation	2.2.07.17.0A
2.2.09.55	Sorption of Dissolved Radionuclides in Host Rock	- Surface complexation properties - Flow pathways and velocity - Saturation	2.2.08.09.0B
2.2.09.56	Sorption of Dissolved Radionuclides in Other Geologic Units Non-Host-Rock) - Confining units - Aquifers	- Surface complexation properties - Flow pathways and velocity - Saturation	2.2.08.09.0A

UFD FEP Number	Description	Associated Processes	Related YMP FEPs
2.2.09.59	Colloidal Transport in Host Rock	- Flow pathways and velocity - Saturation - Advection - Dispersion - Diffusion - Sorption - Colloid concentration	2.2.08.10.0B
2.2.09.60	Colloidal Transport in Other Geologic Units Non-Host-Rock) - Confining units - Aquifers	- Flow pathways and velocity - Saturation - Advection - Dispersion - Diffusion - Sorption - Colloid concentration	2.2.08.10.0A
2.2.09.62	Dilution of Radionuclides in Groundwater - Host Rock - Other Geologic Units	- Mixing with uncontaminated groundwater - Mixing at withdrawal well	2.2.07.16.0A
2.2.09.63	Dilution of Radionuclides with Stable Isotopes - Host Rock - Other Geologic Units	- Mixing with stable and/or naturally occurring isotopes of the same element	3.2.07.01.0A
2.2.09.64	Radionuclide Release from Host Rock - Dissolved - Colloidal - Gas Phase	- Spatial and temporal distribution of releases to the Other Geologic Units or to the Biosphere due to varying flow pathways and velocities, varying transport properties)	
2.2.09.65	Radionuclide Release from Other Geologic Units - Dissolved - Colloidal - Gas Phase	- Spatial and temporal distribution of releases to the Biosphere due to varying flow pathways and velocities, varying transport properties)	1.4.07.02.0A 2.2.08.11.0A 2.3.11.04.0A 2.3.13.04.0A
2.2.11.07	Thermal-Chemical Alteration of Geosphere	- Mineral precipitation / dissolution - Altered properties of fractures, faults, rock matrix - Alteration of minerals / volume changes - Formation of near-field chemically altered zone rind)	2.1.09.12.0A 2.2.10.06.0A 2.2.10.07.0A 2.2.10.08.0A 2.2.10.09.0A
2.3.00.00	3. SURFACE ENVIRONMENT		
2.3.01.00	3.01. SURFACE CHARACTERISTICS		
2.3.01.01	Topography and Surface Morphology	- Recharge and discharge areas	2.3.01.00.0A

UFD FEP Number	Description	Associated Processes	Related YMP FEPs
2.3.02.01	Surficial Soil Type	- Physical and chemical attributes	2.3.02.01.0A
2.3.04.01	Surface Water	- Lakes, rivers, springs - Dams, reservoirs, canals, pipelines - Coastal and marine features - Water management activities	1.4.07.01.0A 2.3.06.00.0A
2.3.07.00	3.07. MECHANICAL PROCESSES		
2.3.07.01	Erosion	- Weathering - Denudation - Subsidence [see also Subsidence in 1.2.02.01, Periglacial Effects in 1.3.04.01, Glacial Effects in 1.3.05.01, Surface Runoff in 2.3.08.02, and Soil and Sediment Transport in 2.3.09.53]	1.2.07.01.0A 2.2.06.04.0A
2.3.07.02	Deposition	- Weathering	1.2.07.02.0A
2.3.08.00	3.08. HYDROLOGIC PROCESSES		
2.3.08.01	Precipitation	- Spatial and temporal distribution	2.3.11.01.0A
2.3.08.02	Surface Runoff and Evapotranspiration	- Runoff, impoundments, flooding, increased recharge - Evaporation - Condensation - Transpiration root uptake)	2.3.11.02.0A 2.2.06.04.0A
2.3.08.03	Infiltration and Recharge	- Spatial and temporal distribution - Effect on hydraulic gradient - Effect on water table elevation	2.3.11.03.0A
2.3.09.50	3.09. CHEMICAL PROCESSES - TRANSPORT		
2.3.09.53	Soil and Sediment Transport Through Biosphere	- Radionuclide transport in or on soil and sediments - Processes include: fluvial runoff, river flow), eolian wind), saltation, glaciation, bioturbation animals)	2.3.02.03.0A 2.3.09.01.0A