Title: Geosynthesis for WR-1 Environmental Impact Statement			Date: 2022/01/10
Prepared by:			
Section Head, WR-1/WMA Senior Geotechnical Engineer	Jason Martino		2022-01-10
TITLE	NAME	SIGNATURE	DATE
Prepared by:			
Project Professional	Iouri Minenkov		2022-01-10
TITLE	NAME	SIGNATURE	DATE
Reviewed by:			
Acting Regulatory Approval Manager	Jeff Miller		2022-01-10
TITLE	NAME	SIGNATURE	DATE
Approved by:			
Acting GM, Decomm. & ERM	Brian Wilcox		2022-01-10
TITLE	NAME	SIGNATURE	DATE

Table of Contents

Section **Page**

Table **Page**

Figure **Page**

1. Introduction

1.1 Background

Canadian Nuclear Laboratories (CNL) is preparing an Environmental Impact Statement (EIS) [1] for the safe decommissioning of the Whiteshell Reactor #1 (WR-1) located at the Whiteshell Laboratories (WL) near Pinawa, Local Government of District (LGD) of Pinawa, Manitoba. The purpose of the decommissioning is to ensure a reduction of Canadian legacy long-term liabilities and elimination of interim waste storage, while reducing worker risk and transport/waste handling risk [2]. WR-1 is located approximately 500 m from the Winnipeg River, about 15 km south and upstream from Lac du Bonnet, Manitoba and approximately 14 km west and slightly north of Pinawa, Manitoba. Figure 1-1 shows the location of the WL site.

Figure 1-1: Location of Whiteshell Laboratories, Arrow Indicates the Approximate Location of WR-1

This Geosynthesis summarizes the geologic background information used in the WR-1 in situ decommissioning EIS [1] and licence amendment application.

A Geosynthesis report is a compilation of geoscientific information that summarizes the overall understanding of site characteristics, attributes and evolution (past and future) that are relevant to demonstrating long-term performance and safety of an undertaking that relies on geoscientific information [3] [4], which in the current context is the in situ decommissioning of WR-1.

For the in-situ decommissioning of WR-1, this Geosynthesis is the integration and presentation of site geological, hydrogeological and geomechanical data and information within the broader context of regional geoscientific data based on research completed on the Lac du Bonnet Batholith for research related to the Canadian Nuclear Fuel Waste Management Program (CNFWMP); in support of site operations and the safe storage of nuclear wastes held at the WL site. The Geosynthesis places the detailed geoscientific description of the site within the broader geoscientific understanding.

WR-1 is proposed to be decommissioned in situ to contain and isolate the contaminated systems and components below grade. The below grade structure extends from ground surface to a depth of 16 m. The structure is largely located in the overburden at the WL site with its base slightly inset into the bedrock. The in situ disposal involves filling the in situ disposal envelope with grout. The proposed grout is a mixture of fly ash, Portland cement, admixtures, fine aggregate and water that produces a highly flowable, concrete-like material to help the filling of voids throughout the facility. The East Annex and Service Wing (Figure 1-2) of the building will be remediated and demolished, the waste removed and the space backfilled with clay-based material. Contaminated or radioactive components of the building above the in situ disposal envelope will be placed in the below grade portion of the structure where suitable to do so. Non-contaminated structural material will be recycled or disposed as appropriate. An engineered barrier consisting of a reinforced concrete cap and overlying clay-based cover will be installed over the in situ disposal envelope. WR-1 site will then be graded, fenced and restored in preparation for long-term care and maintenance activities carried out under an amendment of the current decommissioning licence.

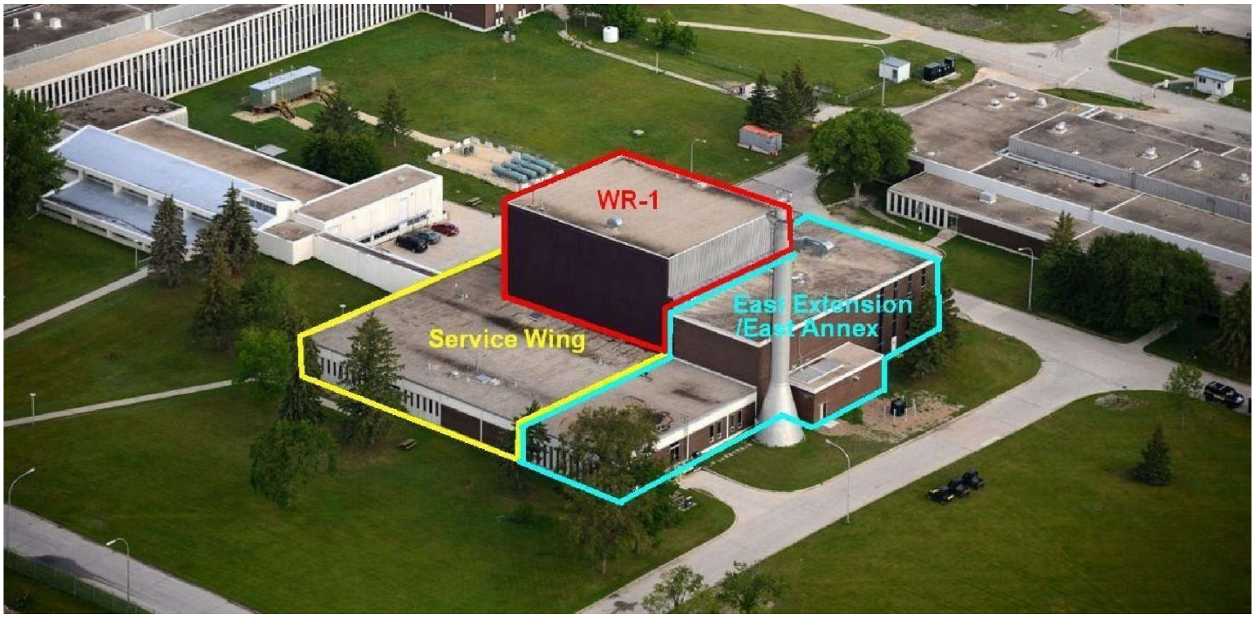


Figure 1-2: In Situ Decommissioning Envelope of WR-1, shown in red, marked as WR-1. Other portions of the building will be decommissioned, demolished and the excavated void backfilled with clay-based material.

1.2 Scope

This report provides information to support the WR-1 In Situ Decommissioning Project, in three areas:

1. A Geosynthesis of the information used to support the EIS and licence amendment application for decommissioning of WR-1.
2. Ensuring that CNSC EIS regulatory baseline geological and hydrogeological requirements of Appendix B.4 of Regulatory Document 2.9.1 [5] and Section 7.3.1 of Regulatory Document 2.11.1 Volume III [6] are met.
3. Identification of geoscientific data uncertainties and an assessment of their relevance/ significance to the decommissioning project.

This Geosynthesis provides a review and summary of available geological, hydrogeological and geomechanical information, including published scientific literature, WL site characterization reports, and information on the regional and local geology developed during the CNFWMP.

Regional Characterization (Manitoba and Central Canada):

The Geosynthesis relies on a number of industry publications for regional macro-geological and lithographical information. These include references dealing with Superior province geology, tectonic evolution of central Canada, geological surveys of Canadian regions, government documentation of area soil, and drawing upon mapping data from the Manitoba Geological Survey and Earthquakes Canada.

Local Characterization (Lac du Bonnet Batholith):

A number of reports dealing directly with the locality of the WL site were also referenced. These include investigations of the Lac du Bonnet batholith on which the WL site is situated, including rock mechanics studies performed by Atomic Energy of Canada Limited (AECL) during operation of the Underground Research Laboratory (URL) northeast of the WL site and investigations prepared to support operations at the WL Waste Management Area. These reports are typically dated from 1980 to 2007. The hydrogeology of the overall WL site has been monitored in annual hydrogeological assessments performed as part of the Environmental Assessment Follow-Up Program, the results of which were used to confirm the site-specific groundwater trends using the 2014-2019 data and reports [7] [8] [9] [10] [11].

Site Specific Characterization (WR-1 Project Site)

For the purposes of this report and the environmental assessment work, “site-specific” indicates the area within the Local Study Area, centered on the WR-1 location.

There are several key references that provide information specifically about the WR-1 location, including investigations directly related to the WR-1 reactor. The two original studies are the Shawinigan Engineering Report from 1960 [12] and the Pre-operational Environmental Survey Report by J.E. Guthrie and G.A. Scott from 1988 [13]. Both of these provide geological, hydrological, and biophysical information about the WL site prior to or during operation of the WL site. In 2001, AECL prepared a Comprehensive Study Report (CSR) [14] that captured all historic reports and investigations as part of the Environmental Assessment for the overall site decommissioning. The CSR was accepted by CNSC in 2002 and forms the basis of the current decommissioning licence.

Further to the CSR, the following investigations were carried out at the WR-1 site to support the In Situ Decommissioning Environmental Impact Statement:

2016 – KGS Engineering – Comprehensive report [15] on the installation of 31 overburden boreholes (29 monitoring wells, 2 survey benchmark wells across 7 Well Nests) around the WR-1 Local Study Area, including report on the drilling program, field notes, recovery of soil samples, soil stratigraphy analysis, groundwater levels, groundwater chemistry analysis, field hydraulic conductivity testing, and particle size analysis.

2016-2018 – Dillon Consulting – Hydrogeological Study Report for the WR-1 site [16], including installation of 4 additional boreholes around the WR-1 reactor (3 as monitoring wells completed at 10 m into the bedrock, 1 borehole drilled 30 m into the bedrock left open), 2 new monitoring wells installed at Building 505 near the WR-1 reactor, stratigraphic analysis of core logs, soil and water analysis for baseline radiological constituents and ions. Dillon Consulting also developed site groundwater elevation and flow maps and provided data for conceptual hydrogeological model for the site.

1.3 Report Organization

This report is organized by section sections.

Section 1 provides a brief project overview including the objectives and scope of the work.

Section 2 describes the geologic framework of the WL site including a summary review of available regional and local geological information, and reference to lineament studies done for the CNFWMP. In addition, Section 2 discusses physiography and geomorphology, Quaternary geology and history, bedrock structural geology and lithology, economic geology, and development of a descriptive geological model based on these data.

Section 3 summarizes the hydrogeological framework for the WL site based on work done for the WR-1 Hydrogeological Study Report [16] and provides a descriptive hydrogeological model based on these data.

Section 4 describes the geomechanical framework for the WL site based on assembly and review of available regional and local geomechanical information. This includes overburden geotechnical properties and hazards, intact rock properties, rock mass properties, major structural discontinuities and structural features, in-situ stresses, seismicity, seismic hazard assessment and development of a descriptive geomechanical model based on these data.

Section 5 presents the future evolution of the WL site considering Winnipeg River flooding, glaciation, geological disturbances and hazards.

Section 6 provides summary and conclusions, including description of the geosphere site model, and a comparison of EIS and Geosynthesis information and CNSC REGDOC 2.9.1 Appendix B.4 [5] requirements for geological and hydrogeological baselining for environmental assessments under the Canadian Environmental Assessment Act. Section 6 also identifies and rationalizes geoscience data uncertainties identified as part of completion of the Geosynthesis, and presents a proposed Geoscience Verification Plan to address data uncertainties and summarizes overall Geosynthesis conclusions.

Section 7 lists references cited in the Geosynthesis Report.

2. Geological Framework

2.1 Introduction

The WL site is located in southeastern Manitoba and is situated on glacial Quaternary sediments unconformably underlain by Precambrian rock of the Lac du Bonnet Batholith. The Precambrian rock is ancient, and in the vicinity of the WL site is in the range of 2.6 billion years old [17]. The regional and local geological framework for the WL site is based on provincial and federal government, as well as Atomic Energy of Canada Limited overburden and bedrock geological mapping and lineament studies.

2.2 Physiography and Geomorphology

Table 2-1: Sources of Information

Reference Study	Regional Reference	Site/Local Reference
Physiography, **Topography,** **River Bathymetry**	Agriculture and Agri-Food Canada, Municipality of Pinawa, Information Bulletin 99-25, 1999.	R.A. Everitt, A. Brown, C.C. Davison, M. Gascoyne, and C.D. Martin, Regional and local setting of the Underground Research Laboratory, In Proceedings of the Symposium on Unique Underground Structures, Denver, Colorado, pp. 64-1 to 64-23, 1990.
	Canada-Manitoba Soil Survey, 1980 - Canada-Manitoba Soil Survey, Physiographic Regions of Manitoba, Ellis Bldg., University of Manitoba, Winnipeg, Revised, 1980. Unpublished Report.	Agriculture and Agri-Food Canada, Rural Municipality of Lac du Bonnet Information Bulletin 99-26.
	Natural Resources Canada, The National Atlas of Canada, 5th edition, 1985.	
	S. St. George, Hydrological Dynamics in the Winnipeg River Basin, Manitoba; in Report of Activities 2006, Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, p. 226-230, 2006.	
	www.charts.gc.ca, Canadian Hydrographic Service maps 6205 and 6206.	

2.2.1 Terrain Physiographic Features

Whiteshell Laboratories is located in the very west portion of the LGD of Pinawa. The land surface in the LGD of Pinawa is mainly level to very gently undulating with slopes less than

2 percent on average. The east portion of the LGD of Pinawa shows increasing amounts of bedrock, which contributes to greater local relief and slopes in excess of 9 percent [18]. Physiographically, the western part of the LGD is in the Lac du Bonnet Plain while the eastern portion, dominated by Precambrian rock outcrops. Both areas are part of the Canadian Shield [19].

The flat topography, coupled with the post glacial immature drainage throughout the area results in a dominance of very poorly drained conditions and development of extensive areas of organic soils. Better drained soils (6% of the area) occur adjacent to the Winnipeg River and its tributary channels and as minor inclusions in areas of greater relief adjacent to rock outcrops in the eastern part of the municipality. Imperfectly drained soils occupy 20% of the area. Drainage of local areas has been improved for development of infrastructure related to roads, and the WL site. Elevation in the municipality decreases gradually from 270 metres above sea level (m asl) in the south to 262 m asl in the north [18]. Figure 2-1 provides an aerial view of the LGD of Pinawa, showing the Seven Sisters Dam forebay in the foreground, the Winnipeg River turning northwards past the WL site and the largely forested area of the LGD of Pinawa and WL site.

The Rural Municipality (RM) of Lac du Bonnet is located to the west and north of the LGD of Pinawa. The RM of Lac du Bonnet is largely similar to the LGD of Pinawa, except for the presence of large glacial sand and till deposits in its western extent. Physiographically, the RM of Lac du Bonnet is located mainly in the Lac du Bonnet Plain while a small area on the east side is in the Bloodvein River Plain [20]. The Lac du Bonnet Plain is generally level to very gently undulating with low local relief and slopes average less than 2 percent except for two prominent upland areas; Milner Ridge and the Brightstone Sand Hills. These uplands have greater local relief with slopes up to 5 percent. Exposures of Precambrian bedrock increase to the east and the Bloodvein River Plain is dominated by rock outcrops, hummocky and ridged topography, higher relief and slopes exceeding 9 percent. Elevation of the land surface falls gradually from 241 m asl in the south to 231 m asl in the northwest corner. The two uplands rise above 290 m asl and elevations increase to 273 m asl in the bedrock terrain to the east. The low gradient of the land surface (0.8 m/km or 4 ft/mi) results in poorly developed drainage and a dominance of very poorly drained organic terrain [20].

Figure 2-1: Aerial Photograph from 37000 feet of the LDG of Pinawa (north of the Seven Sisters Dam forebay) and the Western Portion of the RM of Lac du Bonnet. A portion of the RM of Whitemouth is in the foreground. View is towards the north. Collection of the Author.

2.2.2 Topography

Figure 2-2 provides a contour map of the area surrounding the WL site. The ground surface of the WL site rises from the Winnipeg River to the level of the main site. The Winnipeg River is at approximately 257 m asl at the WL site and the river banks rise approximately 13 m to the level of WL main campus where the main floor (600 Level) of WR-1 is located at approximately 267 m asl. The majority of this rise occurs at the river banks.

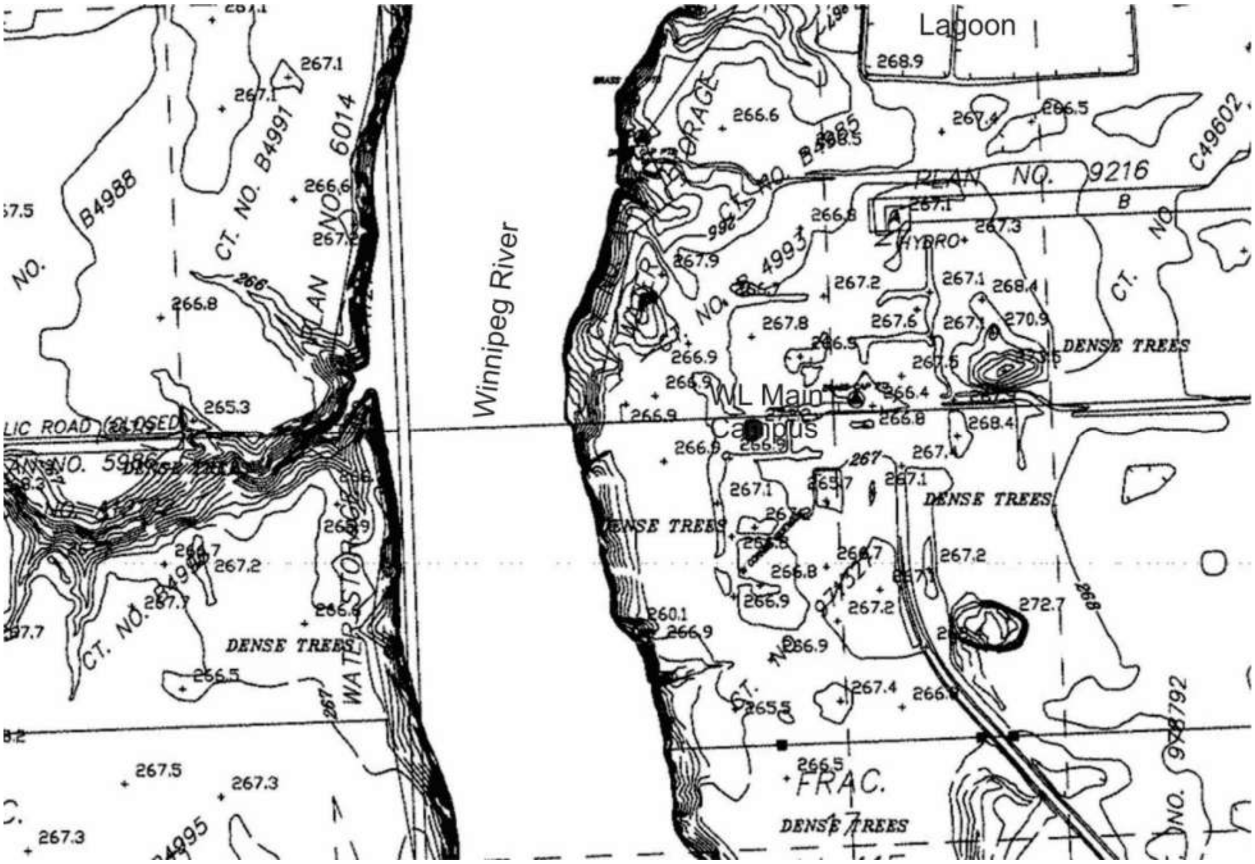


Figure 2-2: Typical Riverbank and Area Contour Map in the Area of the WL Main Campus

2.2.3 Bathymetry and River Character

The Winnipeg River flow in general is northwestward from the Lake of Woods, near Kenora, Ontario to Lake Winnipeg in Manitoba. This river is 235 kilometres (km) (146 miles (mi)) long from the Norman Dam at Kenora to its mouth at Lake Winnipeg. Its watershed is mainly in Canada (106,500 km^2 in area) and extends into northern Minnesota by approximately 29,000 km^2 [21]. The watershed stretches to the height of land about 100 km (62 mi) west of Lake Superior.

The flow of water in the river is controlled by the Lake of the Woods Control Board through a control structure at the start of the Winnipeg River. Two dams in Ontario and six hydroelectric dams in Manitoba provide further regulation and controls of the flows. The regulation of the Winnipeg River has increased the size of lakes along the route of the river, however, dams on the Winnipeg River are run-of-river systems, and have limited storage capacity [22]. Upstream from the WL site is Natalie Lake, the forebay of Seven Sisters Dam. Immediately downstream of the Seven Sisters Dam the Winnipeg River is joined by a tributary, the Whitemouth River. The two rivers meet in an area of exposed bedrock. The Winnipeg River channel turns northward past the Seven Sisters Dam. South of the Highway 211 bridge frequent rock outcrops and shallows are notable in years of lower water (Figure 2-3). Nearer the WL site north of the

Highway 211 bridge the channel becomes somewhat narrower (Figure 2-4). River depth charts [23] indicate that shelves are present downstream from the Highway 211 bridge on the east side of the river. Upon reaching a widening of the river downstream from the WL site near the town of Lac du Bonnet the river reaches depths of up to approximately 15 fathoms (~27.4 m). The river formed post glacially and cuts through overburden with its base in bedrock. The variable depths in the river near the WL site suggest a series of rapids that has been flooded by hydroelectric development. The current river character is wider than what would have been present prior to hydroelectric development based upon the flooded shelves on the east side of the river. This appears to be supported by historic records including paintings that appear to indicate settings reminiscent of the now flooded narrower central river channel (Figure 2-5).

Figure 2-3: The Winnipeg River Upstream of the Highway 211 Bridge towards Seven Sisters Dam (Collection of the Author)

Figure 2-4: The Winnipeg River Downstream of the Highway 211 Bridge (Collection of the Author)

Figure 2-5: Painting of a Camp on the Banks of the Winnipeg River, in Manitoba circa 1864 Paul Kane (1810-1871), unknown location

2.3 Quaternary Historical Geology

Table 2-2: Sources of Information

Reference Study	Regional Reference	Site/Local Reference
Quaternary Historical Geology	D.S. Fullerton, R.B. Colton, C.A Bush, Limits of Mountain and Continental Glaciation East of the Continental Divide in Northern Montana and North-Western North Dakota, U.S.A, in Quaternary Glaciations Extent and Chronology, Part II North America, J. Ehlers and P.L. Gibbard, 2004.	W.D. Robertson and J.A. Cherry, Review of the Hydrogeology of the Radioactive Waste Management Site, 1985 February.
	Simon Fraser University https://www.sfu.ca/archaeology/museum/exhibits/virtual-exhibits/glacial-and-post-glacial-archaeology-of-north-america/glaciation-of-north-america.html	
	M.T. Corkery, Geology and Landforms of Manitoba, Chapter 2, The Geography of Manitoba: Its Land and Its People, Eds. John C. Everitt, John Welsted, Christoph Stadel, 1996.	
	J.T. Teller and M.M. Fenton, Late Wisconsinan Glacial Stratigraphy and History of Southeastern Manitoba, Canadian Journal of Earth Sciences. v. 17, 1980.	
	B. Redekopp, Lake Agassiz, The Rise and Demise of the World's Greatest Lake, Heartland Associates Inc. Winnipeg, Canada.	
	J.T. Teller, Lake Agassiz Deposits in the Main Offshore Basin of Southern Manitoba; Canadian Journal of Earth Sciences, v. 13, p. 27-43, 1976.	
	L. Clayton and S.R. Moran, Chronology of Late-Wisconsinan Glaciation in Middle North America, Quaternary Science Reviews, v. 1, p. 55-82, 1982.	

Reference Study	Regional Reference	Site/Local Reference
	L.H. Thorleifson, The Eastern Outlets of Lake Agassiz, M.Sc. Thesis University of Manitoba, 1983.	

The last glacial period, termed the Wisconsinan Glaciation Period in North America, began about 80,000 years ago [24] and ended about 8,000 years ago. It is divided into the Early (80,000 to 55,000 years ago) and Late (25,000 to 10,000 years ago) glacial stages with an interglacial stage between 55,000 to 25,000 years ago [24]. During the Late Wisconsinan glacial stage, most of Canada and parts of the northern United States were covered by two massive ice sheets, the Cordilleran, which lay to the west of the Rocky Mountains, and the Laurentide to the east. An ice sheet is formed through the convergence of several glaciers, and is the largest of all ice bodies. These ice sheets are estimated to have had a maximum thickness of 2 to 4 km [25]. The Laurentide ice sheet is generally considered to be comprised of two centres of ice formation; the Labrador that formed east of Hudson Bay centered in northern Quebec and extended to eastern Manitoba; and the Keewatin that formed west of Hudson Bay in Nunavut and extended to the Rocky Mountains and south to Iowa (Figure 2-6).

Figure 2-6: North American Glaciation of the Late Wisconsinan Period, Showing Keewatin and Labradorian Ice Sheets Courtesy USGS

The pre-glacial topography of Manitoba was devoid of high mountains and deep valleys [26], regardless, glacial erosion played a role in the evolution of the landscape of Manitoba. In the north, glacial action scraped off the surface materials and previous rock deposits leaving extensive exposures of Precambrian bedrock once the ice melted [26]. Bedrock remains exposed in outcrops as well in the eastern areas of Manitoba, which include outcrops of the Lac du Bonnet Batholith, which forms the bedrock at the WL site. At the WL site, site exposures of the Lac du Bonnet Batholith are limited to exposures along the river and one outcrop near Highway 211. No outcrops are present immediately around WR-1.

The first Late Wisconsinan lobe of ice advanced into southeastern Manitoba from the northeast 22,000 to 24,000 years ago [27] as part of the (Labradorian) Laurentide advance. In a 2,000 to 3,000 year time line after the Laurentide advance, Keewatin ice advanced into the Red River Lowland from the northwest. The Keewatin lobe of the Laurentide Ice Sheet pushed eastward to about the Agassiz-Sandilands Uplands (locally called Milner Ridge to the west of the Winnipeg River from the WL site). The Keewatin ice met with the margin of the active, but somewhat constricted, edge of the Laurentide ice. Initially, a broad trough or ice-free region developed between the Keewatin and Labradorian lobes of ice about 21,000 years B.P., and much of the extensive Belair and Agassiz-Sandilands glaciofluvial ridge was deposited. Glaciofluvial deposition ended as the Keewatin ice continued eastward over the uplands to meet the Labradorian ice [27]. Deposition may have also occurred during glacial retreat and the elevated sand portion seen on the WL site may have resulted from water sorting. There are extensive beach ridges resulting from Lake Agassiz in [28] as well as other glaciofluvial structures.

Although glacial retreat is dated at about 15,000 to 16,000 years B.P., elsewhere in North America there is no evidence that southeastern Manitoba was ice free at this time [27]. Shortly after about 13,000 years B.P., following the ice retreat in the Red River Lowland, the Keewatin lobe re-advanced southward over the clay plain of Lake Agassiz as far as east-central North Dakota. By 11,000 years B.P., the last active ice was gone from southern Manitoba except, possibly, in the extreme northeastern part [27].

Lake Agassiz, the largest of the glacial lakes in Manitoba, probably came into existence about 12,000 to 13,000 years before present [29] [30]. It developed due to ice damming from the glacier to the north [28] [31]. Glaciation and glacial Lake Agassiz is the dominant process for most of the surface soil of the WL site [32]. Much of the sedimentation from Lake Agassiz in the WL site area is in the form of varved clays, sediments displaying regular alternations of thin laminations and somewhat thicker layers. The alternations represent seasonal deposition with the coarse-grained layers being deposited in summer when meltwater inflows are higher, and the fine-grained layers accumulating in slower melt and erosion conditions during the winter. The glacial lake clay is underlain by clay till and a beach-outwash deposit that outcrops east of the Waste Management Area (WMA) and is locally referred to as the upland recharge area. This unit is connected to the underlying basal sand. The beach-outwash deposit material has a high sand-gravel fraction. The appearance of the material near a borrow pit close to the WL landfill is shown in Figure 2-7 and excavated material from the borrow pit in Figure 2-8. The elevated sand fraction may result from sorting of till from glaciofluvial or glaciolacustrine action.

Figure 2-7: Woodbridge Sand Beech-Outwash Deposit Appearance Near WL Landfill, the Upland Recharge Area

Figure 2-8: Woodbridge Sand Beach-Outwash Deposit Excavated Near WL Landfill, the Upland Recharge Area

2.4 Quaternary Overburden Geology

Table 2-3: Sources of Information

Feature	Regional Reference	Site/Local Reference
Quaternary (Overburden) Geology	Agriculture and Agri-Food Canada, Municipality of Pinawa, Information Bulletin 99-25, 1999.	WLDP-26000-REPT-004, WR-1 Hydrogeological Study Report. 2018
	R.A. McPherson, Pleistocene Stratigraphy of the Winnipeg River in the Pine-Falls-Seven Sisters Area; M. Sc. thesis,	W.D. Robertson and J.A. Cherry, Review of the Hydrogeology of the Radioactive Waste

Feature	**Regional Reference**	**Site/Local Reference**
	University of Manitoba, Winnipeg, Manitoba, 61 p., 1968.	Management Site, 1985 February.
		J.E. Guthrie and G.A. Scott, Pre-operational Environmental Survey Report of the Whiteshell Nuclear Research Establishment Area, 1988.
		Shawinigan Engineering Company, Shawinigan Engineering Report 2410-2-60, Report on Proposed Site for Whiteshell Nuclear Research Establishment for Atomic Energy of Canada Limited, 1960.
		WLDP-35000-041-000-0014, KGS Group, Whiteshell Laboratories Projects Branch Comprehensive Final Report on Installation of 7 Groundwater Monitoring Wells Nests, 2016 March.
		J.A. Cherry, B.T. Beswick, and W.E. Clister, Hydrogeologic Regime of the Environmental Control Area and Vicinity, Whiteshell Nuclear Research Establishment, Manitoba, Preliminary Progress Report, 1970 November.
		J.A. Cherry, G.E. Grisak, and W.E. Clister, Hydrogeological Studies at a Subsurface Radioactive-Waste-Management Site in West-Central Canada, 1973 May.

Feature	Regional Reference	Site/Local Reference
		WLDP-03702-041-000-0008, Atomic Energy of Canada Limited, Whiteshell Laboratories Decommissioning Project, Comprehensive Study Report, Vol. 1, 2001 March.
		WLDP-03704-ENA-009, Atomic Energy of Canada Limited, Hydrogeology of the Waste Management Area, Lagoon and Landfill-Enhanced Monitoring Program, 2008 March.

2.4.1 Regional and Local

The surficial geology in the region where the WL site is situated is comprised of deposits of till and both sandy and clay-based glaciofluvial and glaciolacustrine materials (Figure 2-9). Deposits of glacial deposited material are found as till deposits, which is poorly sorted material from boulder and cobbles down to fine grained material. Till may be deposited directly by glacial action or may be re-transported by glacial outflow into glaciofluvial deposits. Predominantly sandy and/or clayey tills are observed throughout the western portions of the region, but are less widespread in the central and eastern portion of the region, where they are generally confined to bedrock depressions between bedrock outcrops. End-moraine and outwash complexes (comprising mostly sand and gravel) are evident west of the Winnipeg River. In general, the Winnipeg River divides the area into two basic subregions with regard to overburden geology: (i) calcareous tills to the west, and (ii) sandy tills and glaciofluvial deposits to the east [13]. Finer glaciolacustrine deposits are evident along the drainage depressions of the Winnipeg River and Pinawa Channel and the Lee River.

Quaternary deposits on the WL site extend to depths of 22 mbgs (metres below ground surface) in the sandy upland area (to the east of the WMA), and to depths of 17 mbgs nearer the Winnipeg River. The sandy upland may be the remains of ancient beach deposits [12]. Further east of the Winnipeg River, the overburden soils become thinner, and the Precambrian bedrock outcrops more numerous [12] with outcrops becoming more common towards the Pinawa Channel.

Extensive deposits of lacustrine clay, mud and silt, are found over the existing glacial deposits in the western portion of the region, but are less widespread in the central and eastern areas. The glaciolacustrine clays are comprised primarily of montmorillonite and illite, or possibly interlayered with montmorillonite, illite, dolomite, and quartz, with minor kaolinite and/or chlorite, and minor feldspar. Silt nodules present within the clay are comprised mostly of dolomite, with minor quartz, and clay minerals [33].

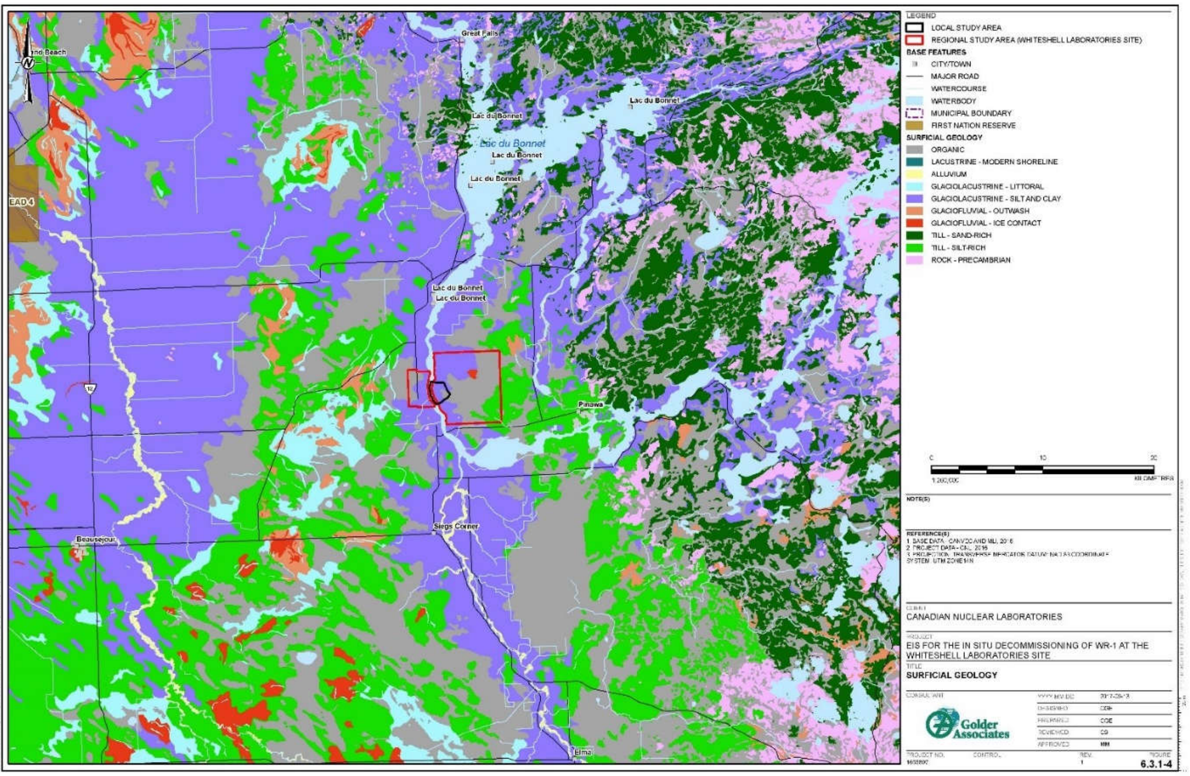


Figure 2-9: Regional Surface Geology in the WR-1 Area [1]. The red outlines indicates the WL site and the black outline indicates the WL main camps where WR-1 is located.

2.4.2 WL Site

Geologic data were collected from the results of recent drilling and core logging at the WL main campus to supplement existing site geology data. In the area surrounding the WR-1 site, 29 monitoring wells were installed at well nest (nest) locations 1 to 7 to various depths in the overburden in 2015. These wells were installed to collect WL site hydrogeological data, which has been measured on an ongoing basis at the WMA, the lagoons and the landfill. It also provided confirmation of the soil type at the WL site. The wells were arranged to provide hydrogeologic head measurements in the assumed up and downstream groundwater flow directions around WR-1.

The drilling of boreholes for the shallow bedrock (upper 10 m of bedrock) at three nest locations (nests 2, 4, and 7) and the installation of monitoring wells at these locations were completed in 2016 (16-2E, 16-4F, and 16-7E). In addition, one deeper borehole (16-8A) was installed to a depth of 30 m into the bedrock (42 m depth from ground surface), based on the observations and findings of the shallow bedrock wells at nests 2, 4, and 7. The selection of the locations for the bedrock boreholes in the 2016 program was also based on the general pattern of groundwater flow from east to west across the WR-1 area towards the Winnipeg River, and the need to further improve hydrostratigraphic information in this area.

The seven monitoring well nests, and a single monitoring well (16-8A) that encompass a total of 32 monitoring wells drilled [16]. The monitoring well nests are named numerically (i.e., monitoring well Nest 1 through monitoring well nest 7). Each monitoring well nest includes between 4 and 6 monitoring wells. Individual monitoring wells are named using the installation year, the monitoring well nest number, and a letter indicating the relative depth (with “A” assigned to the deepest monitoring interval). In the following sections, the term monitoring well nest is used to refer to the conditions observed throughout the group of monitoring wells, while individual monitoring well names are used to refer to conditions at a specific depth interval. The monitoring well names and geological units for each monitoring well nest are summarized in Table 2-4. Monitoring well nest locations are shown on Figure 2-10. The stratigraphic data collected from these boreholes [15] were supplemented through the review of the following existing reports on the WL site, [14] [32] [34] [35] [36].

Table 2-4: Monitoring Well Nest Details

Monitoring Well Nest	Monitoring Well	Hydrostratigraphic Unit
1	15-1A	Basal Sand
	15-1B	Clay Till
	15-1C	Clay
	15-1D	Clay
2	15-2A	Basal Sand
	15-2B	Clay Till
	15-2C	Clay Till
	15-2D	Clay
	16-2E	Bedrock
3	15-3A	Basal Sand
	15-3B	Clay Till
	15-3C	Clay
	15-3D	Clay
4	15-4A	Basal Sand
	15-4B	Clay Till
	15-4C	Clay Till
	15-4D	Clay
	15-4E	Clay

Monitoring Well Nest	Monitoring Well	Hydrostratigraphic Unit
	16-4F	Bedrock
5	15-5A	Basal Sand
	15-5B	Clay Till
	15-5C	Clay
	15-5D	Clay
6	15-6A	Clay Till
	15-6B	Clay Till
	15-6C	Clay Till
	15-6D	Clay
7	15-7A	Clay Till
	15-7B	Clay Till
	15-7D	Clay
	16-7E	Bedrock
8	16-8A	Bedrock

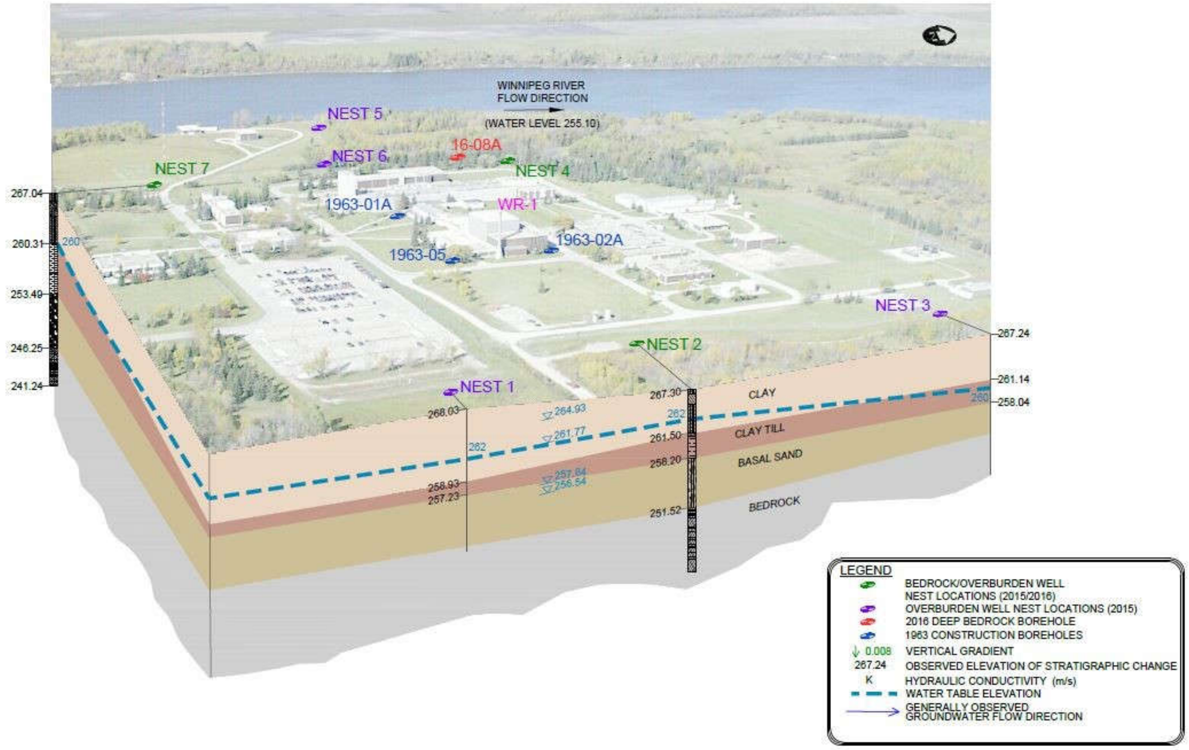


Figure 2-10: Well Nest Locations Generalized Cross Section of Overburden Geology at the WL Main Campus [16]

At the WR-1 location the soil beds are silt, clay, clay till and the basal sand unit. Eastward the basal sand unit thickens and a sand and gravel upland recharges and drives the groundwater flow to the west. Figure 2-10 shows the overburden geology of the WL main campus and WR-1 area. The silt material forms the majority of a low alluvial terrace along the Winnipeg River. An east-west cross section of the quaternary deposits present at the WL site is displayed in (Figure 2-11); and Figure 2-12 shows the surficial geology of the WL site.

The quaternary deposits from the Lac du Bonnet Batholith bedrock upwards are local defined as follows:

- **Basal Sand.** Bedrock is overlain by a silty sand till (this layer is called basal sand or basal till in some sources) throughout the majority of the WL site. The till varies from a silty coarse sand till to a clean medium to coarse sand till [34], and boulders are common above the bedrock surface. This unit is referred to as the basal sand in the area of WR-1 (as in [16]) due to the increased sand content observed. At the WMA to the northeast of WR-1, this unit has been found to vary in thickness from 1 m to 7 m [36]. Near to WR-1, this unit varies in thickness from 3.6 m to 8.3 m [37]. In other areas of the WL site this unit appears to thin towards the Winnipeg River. This unit is thinnest over the local bedrock high in the vicinity of piezometer nest 4 and borehole 16-8 in the area of WR-1 (Figure 2-13).
- **Clay Till.** The basal sand is overlain by a clay till unit containing sand and silty sand seams. The bulk porosity of this unit in the WMA was determined to be 0.23 indicating a high degree of consolidation [36]. No porosity measurements have been completed in the area of WR-1, however there is no evidence of a change in character of the unit across the site. At the WMA, this unit has been found to vary in thickness from 2 m to 5 m [36]. Near WR-1, this unit varies in thickness from 3 m to 7 m. The clay till is generally thinnest in the central portion of the main campus and thickens to the northwest and southwest towards the Winnipeg River (Figure 2-14).
- **Lacustrine Clay and Surficial Interbedded Silt and Clay (Clay).** A lacustrine clay unit overlies the clay till unit other than east of the WMA. This unit is transitional, with the lower portion more laminated with silty interbeds, and the upper portion more massive. A thin surficial interbedded silt and clay unit overlies these clays. These units have been grouped given their similar properties, and relative thinness of the surficial unit. In the WMA this unit has been found to vary in thickness from 2 m to 8 m and is the thickest in the lagoon area [36]. In the area of WR-1, this unit is relatively uniform in thickness, varying from 5.5 m to 7.3 m. This unit is inferred to be absent adjacent to the Winnipeg River due to erosion, leading to a drop in topography towards the river (Figure 2-15).

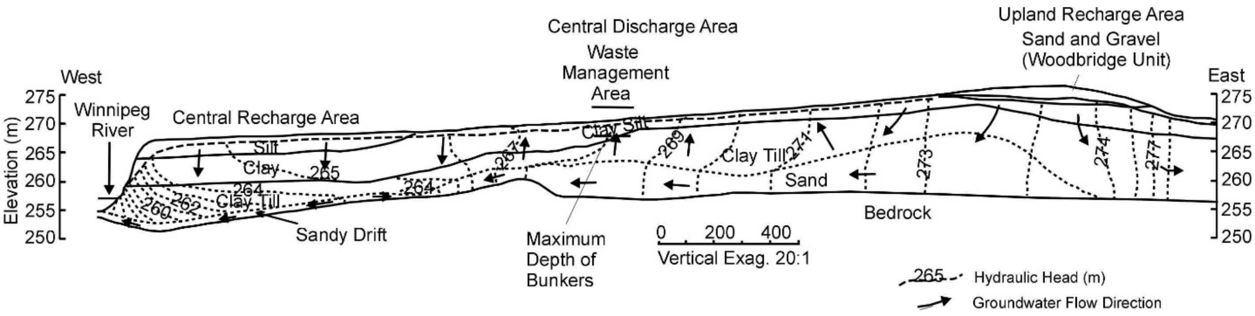


Figure 2-11: Figure Cross Section of Quaternary Deposits at the WL Site

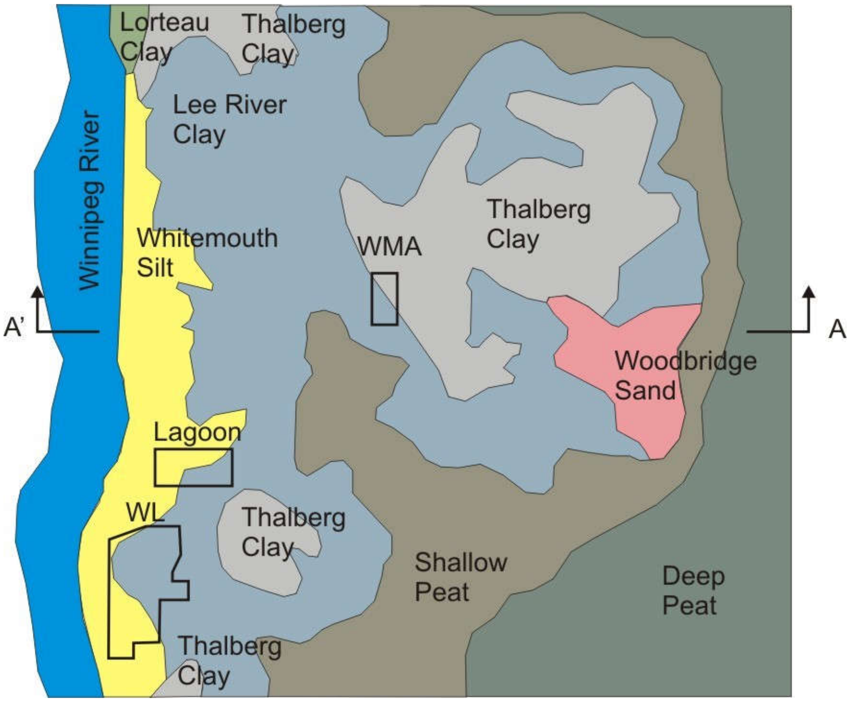


Figure 2-12: Surficial Geology Map of Whiteshell Laboratories Area

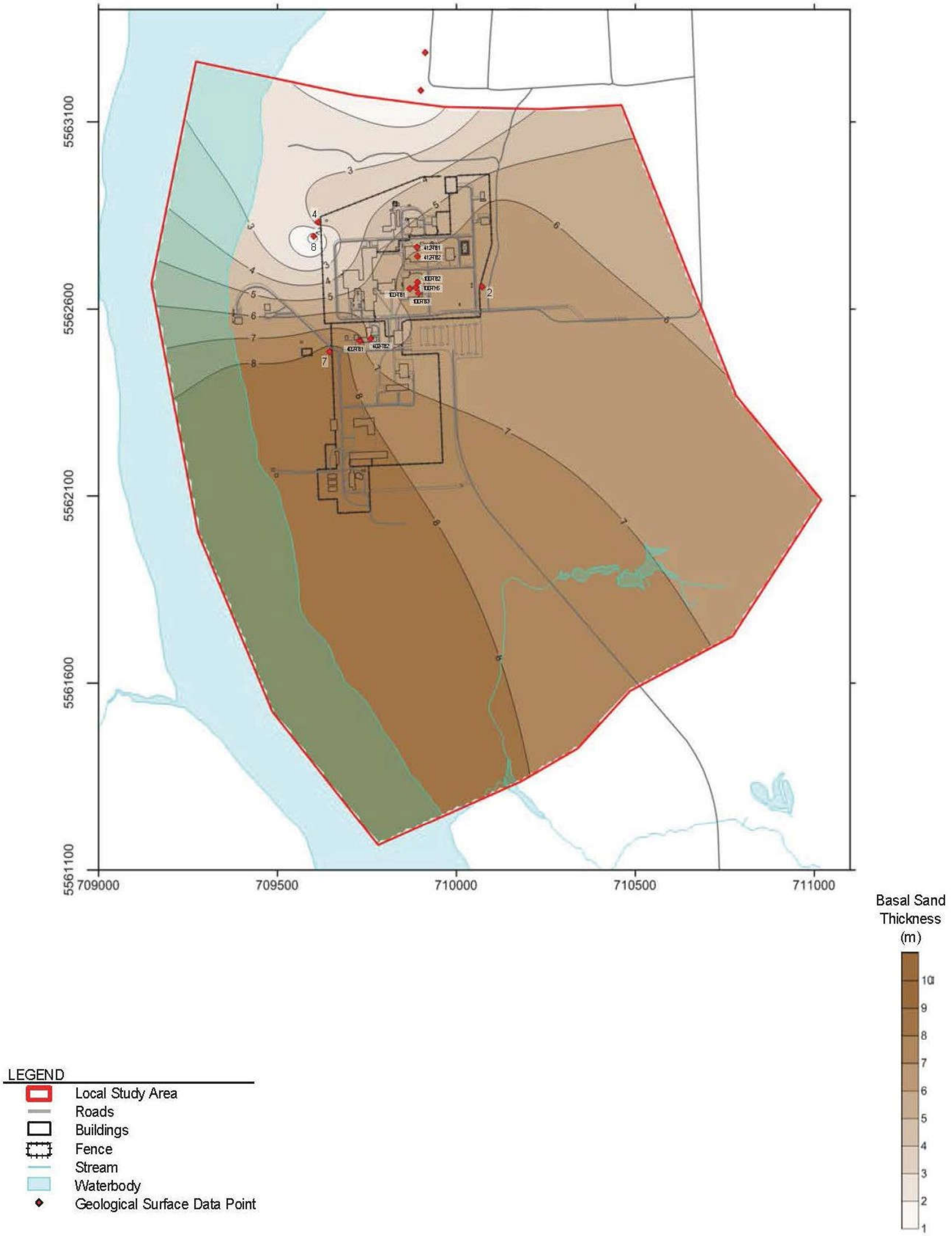


Figure 2-13: Basal Sand Isopach Map, Courtesy Golder

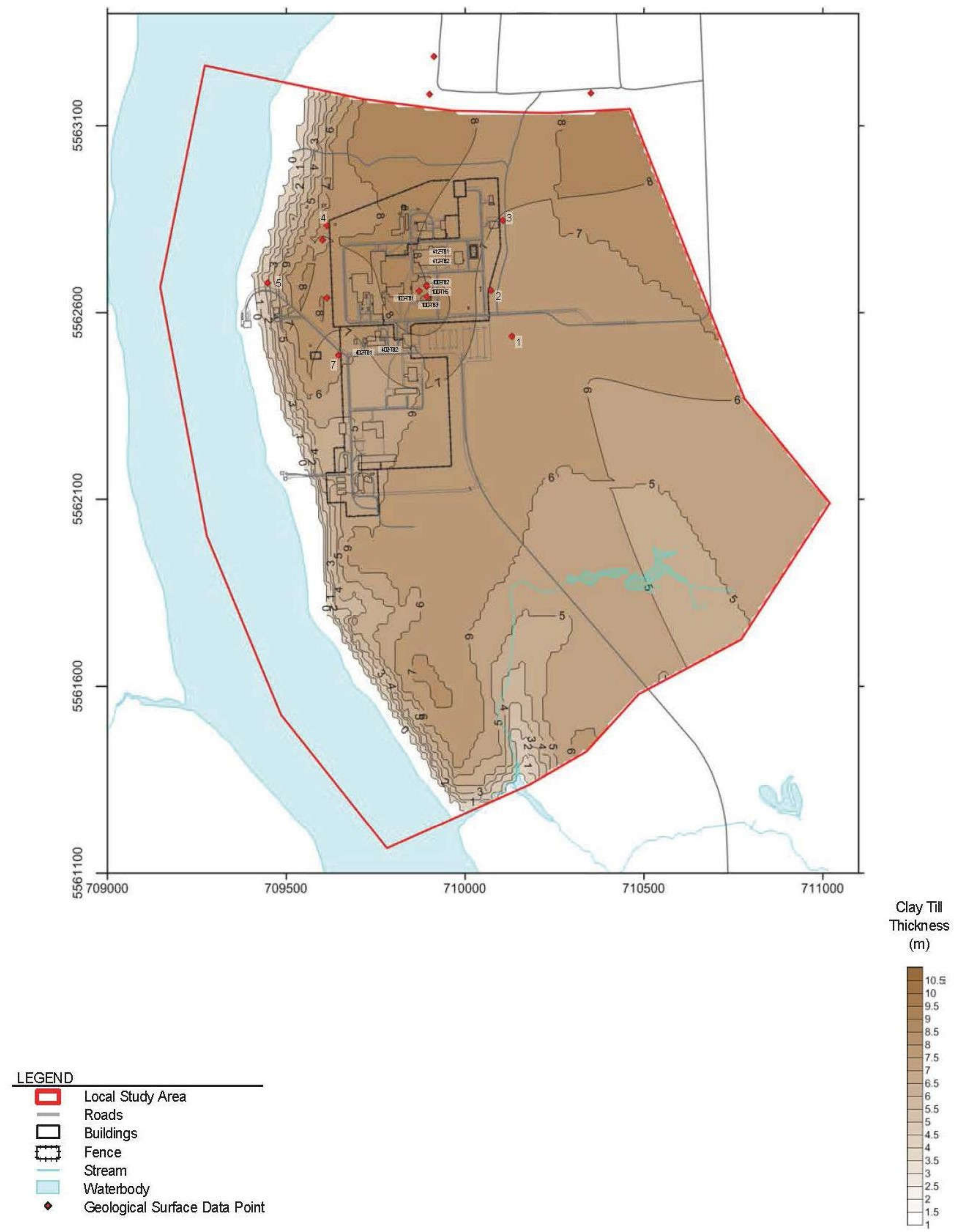


Figure 2-14: Clay Till Isopach Map, Courtesy Golder

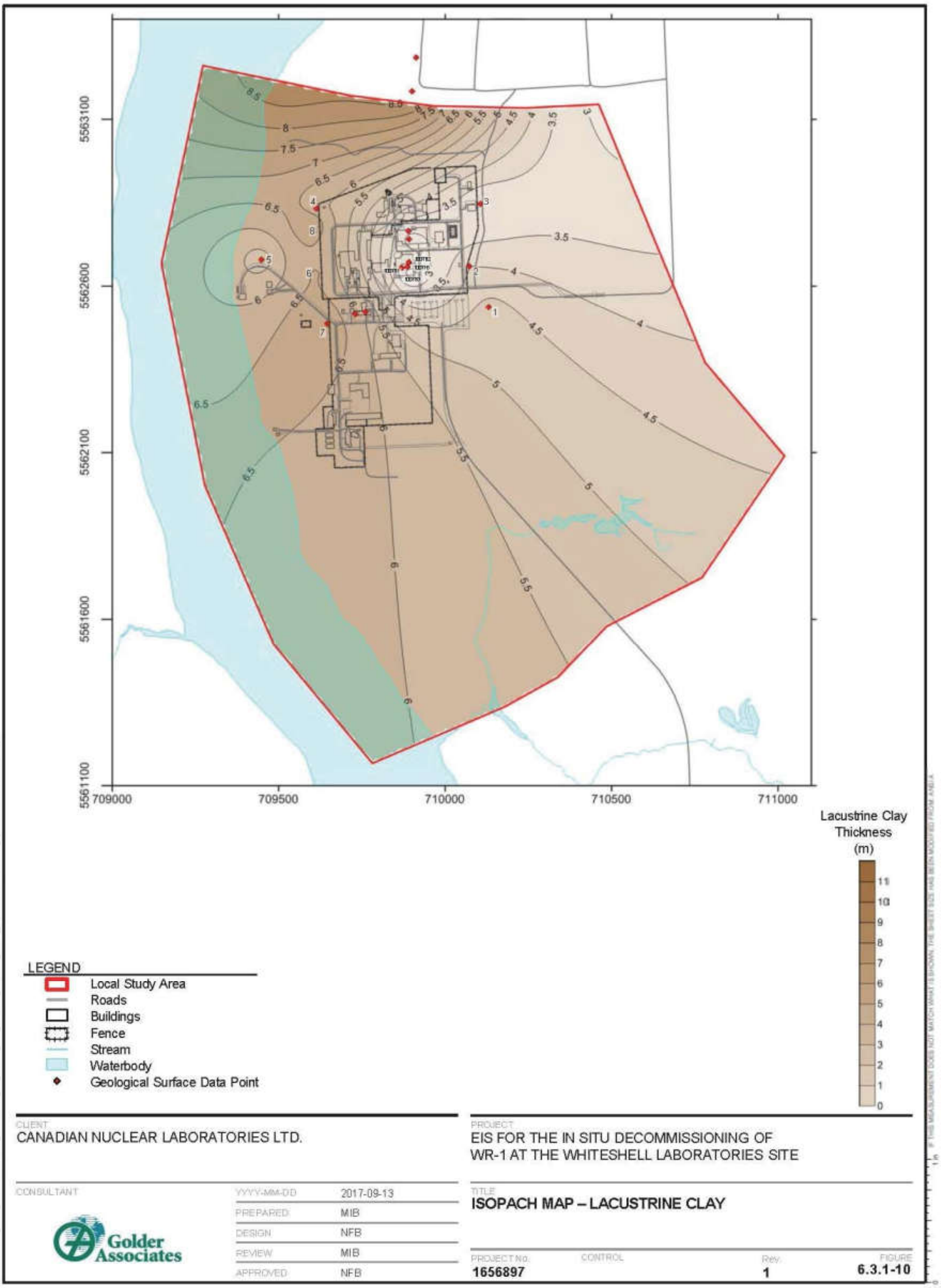


Figure 2-15: Clay Unit Isopach Map, Courtesy Golder

2.4.3 Agricultural Potential

Agriculture and Agri-Food Canada rate soils in Canada for their suitability for agriculture. Class 1 soils are most suited for agriculture and Class 7 are unsuitable. Class 5 or Class 6 soils have moderately severe to very severe limitations for agriculture due to susceptibility to drought or excessive wetness. Mineral soils in the LGD of Pinawa in general are dominantly Class 3 (23%) [18]. The organic soils covering 41% of the area have very limited capability for agriculture in their native undrained state (Figure 2-16). The organic soils are not rated for irrigation. This finding indicates the site, other than adjacent to the river, has limited agricultural value in its current condition; drainage improvements would result in increased agricultural suitability. Lack of large amounts of gravel near the surface limit the location for construction material quarrying, reducing the likelihood of site disturbance, especially with large gravel deposits to the west of the site in the Milner Ridge area.

In general, the historic surficial soil distribution within the WL site is comprised of organics in areas of poor drainage and Gleysolic (water saturated soil that may display varying degrees of mottling due to reduction of iron and other minerals in anaerobic conditions) and Chernozemic (high percentage of humus) soils in areas with improved drainage. Soils developed on outwash sands and alluvial materials are typically Luvisolic (soils developed from sedimentary rocks or in this case on clayey lacustrine deposits primarily in the Boreal Shield ecoregion).

A summary of the dominant baseline soil types and substrates within the WL site are outlined in Table 2-5.

Drainage conditions range from well drained, coarse textured soils to poorly and very poorly drained organic soils in lower elevation positions. Coarse textured soils, with higher initial total porosity, are relatively resistant to compaction compared to finer textured soils; these soils typically are, however, prone to wind erosion. Soil erosion risk is a concern for disturbed soils because the sparse vegetation cover exposes soil materials to the elements (e.g., wind and water). In areas of organic soils that are not deep, where organic surface horizons are removed and subsurface materials and exposed, the water erosion potential of the underlying material would be low if sandy, and moderate if silty. Areas containing organic materials will have a low sensitivity to wind erosion.

A layer of silt approximately 3.5 m thick was noted near the river, it was assumed that it may be a river deposit from past flooding [12]. The map showing the erosion risk in the LGD of Pinawa (Figure 2-17) [18] indicates that the gentle sloped region near the Winnipeg River has moderate erosional potential while most of the WL main campus have limited or negligible potential. Erosion is noted to be present along the river banks on the WL site (Figure 2-18) and some areas show slope failure and steep slopes.

Table 2-5: Baseline Soil Types and Substrates at the WL Site

Soil Series	Soil Subgroup	Substrate/Parent Material	Area (ha)
LSA			
$ZZ	Undifferentiated	Active Fluvial River Bed	35.0
LEV	Peaty Humic Luvic Gleysol	Moderately Calcareous Lacustrine Clay	98.6
OOK	Terric Mesisol	Shallow Organic	14.7
THG	Gleyed Solinetzic Dark Gray Chernozem	Weakly Calcareous Lacustrine Clay	28.5
WHU	Dark Gray Luvisol	Strongly Calcareous, Moderately Fine Textured Alluvial Sediments	83.3
RSA			
$ZZ	Undifferentiated	Active Fluvial River Bed	16.2
BYH	Typic Mesisol	Deep Organic	1,290.5
FYL	Peaty Rego Humic Gleysols	Weakly to Moderately Calcareous Lacustrine Clay	206.1
LEV	Peaty Humic Luvic Gleysol	Moderately Calcareous Lacustrine Clay	574.2
LTI	Solinetzic Gray Luvisol	Moderately to Strongly Calcareous Lacustrine Clay	27.3
OOK	Terric Mesisol	Shallow Organic	1,084.5
THG	Gleyed Solinetzic Dark Gray Chernozem	Weakly Calcareous Lacustrine Clay	590.8
WHU	Dark Gray Luvisol	Strongly Calcareous, Moderately Fine Textured Alluvial Sediments	491.1
WOG	Orthic Gray Luvisol	Coarse Grained Outwash	60.7

Table Information obtained from MLI 2003.

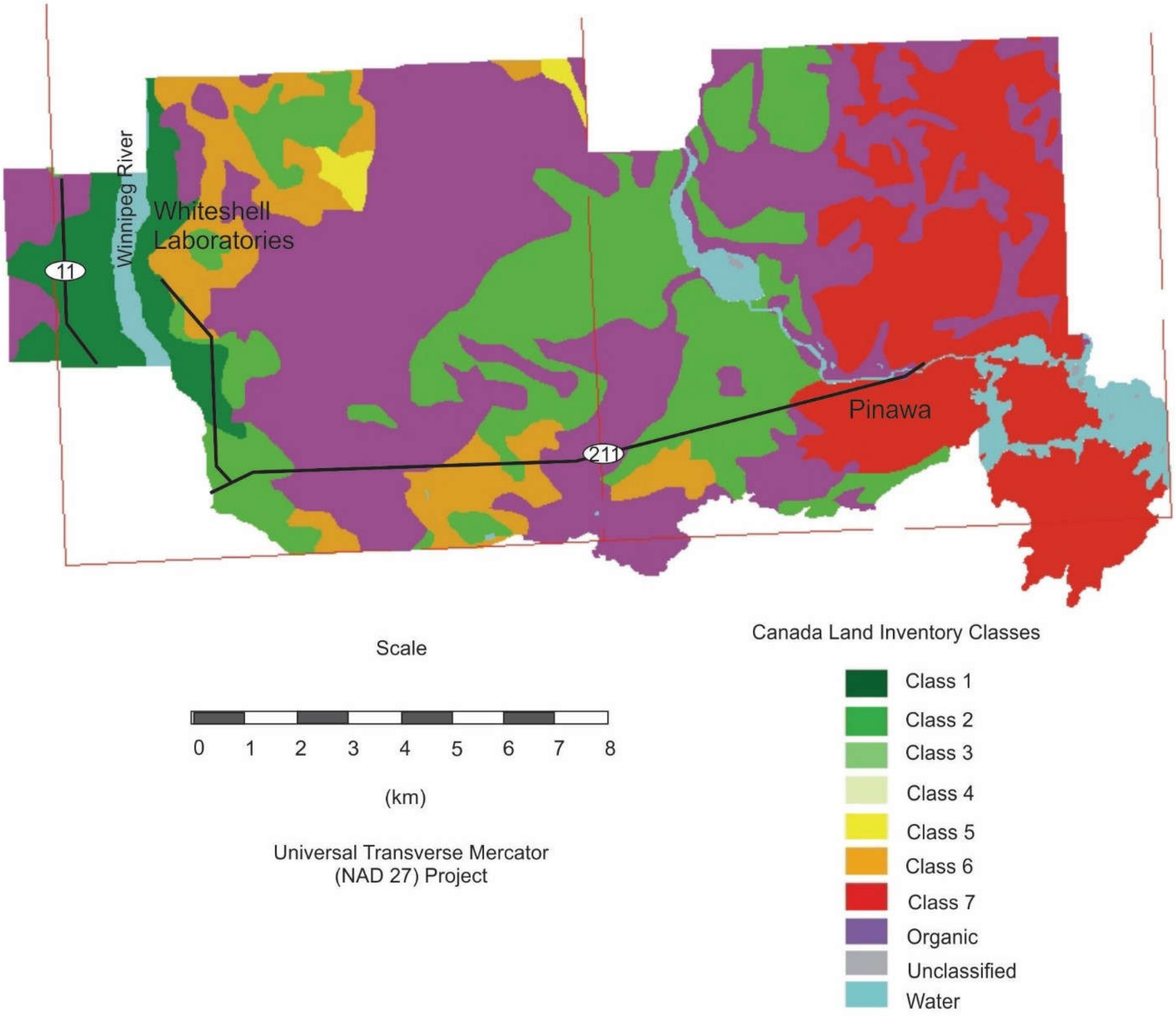


Figure 2-16: Agricultural Potential on Land Unimproved by Irrigation [18]

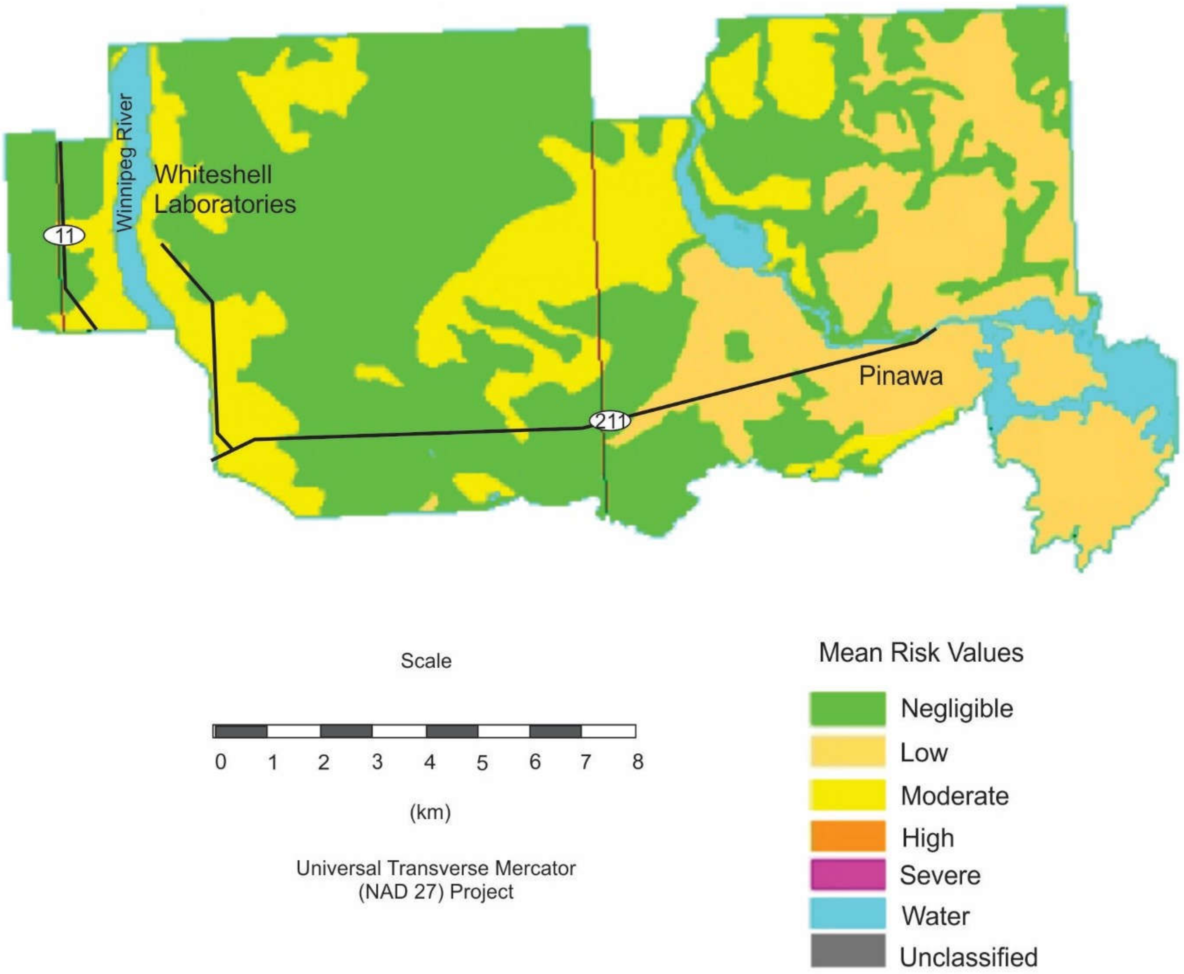


Figure 2-17: Erosion Risk in the LGD of Pinawa [18]

Figure 2-18: Example of Riverbank Erosion Noted Along the Winnipeg River Along the WL Site

2.5 Bedrock Geology

A number of terms are mentioned throughout this report describing various features and observations made during borehole investigations into the bedrock geology throughout the Lac du Bonnet batholith and WL local site. These terms are described in Table 2-6 below.

Table 2-6: Key Observations and Features

Observation/Feature	Description
Calcite Infillings	This refers to mineralization by calcite (calcium carbonate) within open fractures. The source in the Lac du Bonnet Batholith is groundwater or glacial meltwater that has dissolved calcium. See Section 2.5.2.
Cataclasite	Another name for fault breccia (fracture infill material) which consists of angular rock fragments in a fine grained matrix. See Section 2.5.2 and “Thrust Faults Cataclastes” below.

Observation/Feature	Description
Erosion surfaces	The top of the batholith represents an erosion surface on which glacial sediments were deposited. The current exposed land surface is an erosion surface as well. See Section 2.5.2.
Epeirogenic	Uplifts or depression of land over long wavelengths but displaying little folding other than wide undulations. Cratons, such as the Canadian Shield are subject to epeirogeny. See Section 2.5.2.
Fracture Infilling	Fracture infillings represent a mineral or minerals deposited by various processes. Magmatic intrusion may fill an existing fracture. Groundwater may intrude a fracture and deposit minerals. This process may occur at different temperatures (deuteric, high and low temperature hydrothermal, low temperature groundwater) as is the case in the Lac du Bonnet Batholith. Surfaces of the earliest fractures were first altered by fluids derived from magma upon its saturation by water (deuteric alteration). Once the temperature had fallen to allow solidification, convective circulation between the cooler country rocks resulted in hydrothermal alteration along fractures. Near surface fractures only represent low-temperature alteration but these processes can overprint on earlier alterations. Hydrothermal alteration caused the development of a second zone of pinking alteration on the primary alteration zone. More recent (in geological terms) alteration of hydrogeologically active fractures has caused bleaching of the rock. Intensive water movement results in solution cavities and low-temperature mineral assemblages. At the URL site all mesoscopic fractures appeared to act as pathways for groundwater recharge to the main fracture zones at the URL. Chlorite filled fractures were noted to show strong signs of water-rock interaction, represented by chlorite breakdown and the formation of goethite/hematite residue. See Section 2.5.2.
Fracture Intensity	A measure of the number of fractures over a unit distance. See Section 2.5.4.
Fracture Zone	A zone of rock showing fractures and alteration. The fracture zones are known to occur in areas that were structurally controlled by

Observation/Feature	**Description**
	earlier alteration. The zones were formed by tectonic activity early after solidification of the batholith. See Section 2.5.4.
Fault Zones	A crack in the rock mass along where movement has occurred. See Section 2.5.2.
Open fracture	A fracture that is either water bearing (in testing from hydrogeological pumping tests), or shows signs of early hydrothermal alteration such as bleaching. See Section 2.5.2 and Section 2.5.4.
Pegmatite dykes	Intrusion of magmatic melts that intrude into an existing rock and form large (typically greater than 2.5 cm) interlocking crystals. The large crystals indicate that there was room for the fractures to form and elevated temperatures when the batholith was still in early stages of cooling so the crystals have an elevated temperature and slow cooling rate allowing large crystals to form. See Section 2.5.4.
Quartz Veins	Infilling of a fracture by SiO_2 (quartz). Quartz is one of the last minerals to crystalize when magmatic melts are solidifying. See Section 2.5.4.
Rubble Zone	The central core of a fracture zone where the rock has been broken into fragments. See Section 4.4.
Synorogenic	Refers to a process or event (e.g., recrystallization of metamorphic rock, or the intrusion of batholiths) which occurs at the same time as deformation See Section 2.5.1.
Thrust Faults	A low dip (to horizontal) fault where the hanging wall block has moved upwards relative to the footwall block. Within the Lac du Bonnet Batholith these are the main structural discontinuities. See Section 2.5.2, Section 2.7 and Section 4.5.

Observation/Feature	Description
Thrust Faults Cataclastes	See Fracture Zone as well. A cohesive granular fault rock. Fault breccia contains cohesive coarser fragments and fault gouge contains non-cohesive material. See Section 2.5.2.

2.5.1 Regional Geologic and Tectonic Setting

Table 2-7: Sources of Information

Feature	Regional Reference Study
Regional Bedrock Geology	G.P. Beakhouse, C.E. Blackburn, F.W. Breaks, J. Ayer, D. Stone, and G.M. Stott, Western Superior Province, Geologic Survey of Canada, Open File 3138, 1995.
	D.L. Ciceri, The Winnipeg River/Western Wabigoon Subprovince Boundary, Superior Province, Northwestern Ontario: Structural and Metamorphic Gradients in the Tustin-Bridges Vermilion Bay Greenstone Belt, University of Toronto, M.Sc. Thesis.
	G.P. Beakhouse, Winnipeg River Subprovince, in Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p. 279-301, 1991.
	J.A. Percival, Geology and Metallogeny of the Superior Province, Canada, in W.D. Goodfellow, ed., Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods: Geological Association of Canada, Mineral Deposits Division, Special Publication, 2017.
	J.A. Percival, and R.M. Easton, Geology of the Canadian Shield in Ontario: an update; Ontario Geological Survey, Open File Report 6196, Geological Survey of Canada, Open File 5511, Ontario Power Generation, Report 06819-REP-01200-10158-R00, 65, 2007.
	H.R. Williams, G.M. Stott, P.C. Thurston, R.K. Sutcliffe, G. Bennett, R.M. Easton, and D.K. Armstrong, Tectonic Evolution of Ontario:

Feature	Regional Reference Study
	Summary and Synthesis; in Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p. 1255-1334, 1991.
	J.A. Percival, M. Sanborn-Barrie, T. Skulski, G.M. Stott, H. Helmstaedt, and D.J. White, Tectonic Evolution of the Western Superior Province from NATMAP and Lithoprobe Studies, Canadian Journal of Earth Sciences, v. 43, p. 1085-1117, 2006.
	K.L. Buchan, and R.E. Ernst, Diabase Dyke Swarms and Related Units in Canada and Adjacent Regions, Geological Survey of Canada, Map No. 2022A, scale 1:5 000 000, 2004.
	I.A. Osmani, Proterozoic Mafic Dike Swarms in the Superior Province of Ontario, Chapter 17, Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, Eds. P.C. Thurston, H.R. Williams, R.H. Sutcliffe and G.M. Stott, 1991.
	C.C. Davison, A. Brown, R.A. Everitt, M. Gascoyne, E.T. Kozak, G.S. Lodha, C.D. Martin, N.M. Soonawala, D.R. Stevenson, G.A. Thorne, and S.H. Whitaker, The Disposal of Canada’s Nuclear Fuel Waste: Site Screening and Site Evaluation Technology, AECL-10713, COG-93-3.
	K.D. Card, and A. Ciesielski, DNAG #1, Subdivisions of the Superior Province of the Canadian Shield, Geoscience Canada, 13: 5-13, 1986.
	J.A. Percival, J.B. Whalen, K.Y. Tomlinson, V.J. McNicoll, and G.M. Stott, Geology and Tectonostratigraphic Assemblages, North-Central Wabigoon Subprovince, Ontario; Geological Survey of Canada, Open File 4270, Ontario Geological Survey, Preliminary Map P.3447, scale 1:250 000, 2002.
	J.A. Percival, V. McNicoll, J.L. Brown, and J.B. Whalen, Convergent Margin Tectonics, Central Wabigoon Subprovince, Superior Province, Canada; Precambrian Research, v. 132, p. 213-244, 2004.
	J.A. Percival, and H. Helmstaedt, 2004, Insights on Archean Continent–Ocean Assembly, Western Superior Province, from New Structural, Geochemical and Geochronological Observations: Introduction and Summary; Precambrian Research, v. 132, p. 209-212, 2004.

Feature	Regional Reference Study
	G.R. Edwards, and R.H. Sutcliffe, Archean Granitoid Terranes of the Western Superior Province, Ontario; Geological Association of Canada–Mineralogical Association of Canada, Program with Abstracts, v. 5, p. 50, 1980.
	P.C. Thurston, and D.W. Davis, The Wabigoon Diapiric Axis as a Basement Complex; in Summary of Field Work and Other Activities, Ontario Geological Survey, Miscellaneous Paper 126, p. 138-141, 1985.
	F.W. Breaks, English River Subprovince, in Geology of Ontario, P.C. Thurston, H.R. Williams, R.H. Sutcliffe and G.M. Stott (ed.), Ontario Geological Survey, Special Volume 4, Part 1, p. 239–277, 1991.
	Nicholas L. Swanson-Hysell, Jahandar Ramezani, Luke M. Fairchild, Ian R. Rose, Failed Rifting and Fast Drifting: Midcontinent Rift Development, Laurentia's Rapid Motion and the Driver of Grenvillian Orogenesis, Geological Society of America Bulletin, Volume 131, Number 5-6, 2019.

The WL site is situated on overburden deposits, located over the western portion of the Lac du Bonnet Batholith. This batholith is located on the western margin of the Superior Province (Figure 2-19), which is the largest Archean craton in the world [38] [39] and is on the north edge of the Winnipeg River subprovince [40]. The Superior Province forms the core of the North American continent and is surrounded by provinces of Paleoproterozoic age on the west, north, and east, and Mesoproterozoic age (Grenville Province) on the southeast [41] [42].

Percival and Easton [42] summarized the overall geological history of the Superior Province. The Superior Province records about one billion years of geological history, from 3.6 to 2.6 billion years ago. Five microcontinental fragments evolved independently between 3.6 and 2.75 billion years ago, prior to a series of five discrete accretionary events between 2.72 and 2.68 billion years ago that assembled the continental and intervening oceanic crustal domains into a coherent Superior craton. These subprovinces generally decrease in age southward in the Superior province, consistent with a progressively southward moving accretionary complex [43].

The Northern Superior superterrane recorded 3.6 to 2.75 billion years ago aged events prior to a collision about 2.72 billion years ago with the 3.0 billion years ago aged North Caribou superterrane [42]. Following rifting at 2.98 billion years ago, the Uchi margin of the North Caribou superterrane evolved in an upper plate setting before collision 2.72 to 2.70 billion years ago with the Winnipeg River terrane (<3.4 billion years ago), which trapped synorogenic English

River turbidites in the collision zone. The Winnipeg River terrane was reworked in magmatic and tectonic events 2.75 to 2.68 billion years ago, including the central Superior orogeny (2.71-2.70 billion years ago) that marks accretion of the juvenile western Wabigoon terrane [42]. In the south, the Wawa–Abitibi terrane evolved in a mainly oceanic setting until Shebandowanian collision with the composite Superior superterrane at 2.695 billion years ago. Synorogenic Quetico turbidites were trapped in the collision zone. The final accretionary event involved addition of the Minnesota River Valley Terrane (MRVT) from the south, and deposition and metamorphism of synorogenic turbidites of the Pontiac terrane during the Minnesotan orogeny (ca. 2.68 billion years ago) [44] (Figure 2-20).

Tectonic stability has prevailed in large parts of the Superior Province since approximately 2.6 billion years ago. Proterozoic and younger activity is limited to rifting of the margins of the Superior Province, emplacement of numerous mafic dyke swarms [45] [46], compressional reactivation, and large-scale rotation at approximately 1.9 billion years ago, and failed rifting at approximately 1.1 billion years ago. This failed rifting lead to the formation of the North American mid-continental rift zone. Midcontinent Rift system forms a more than 2500 km arcuate swath extending from the Lake Superior region, where rift rocks are exposed, far to the southwest into the Great Plains under Phanerozoic sedimentary cover [47]. With the exception of the northwestern and northeastern Superior margins that were pervasively deformed and metamorphosed at 1.9 to 1.8 billion years ago the craton has escaped ductile deformation [41]. Deep erosion, largely in Precambrian time, has exposed the roots of the orogens that were welded together to form the Shield [48].

Card and Ciesielski [49] subdivided the western Superior Province into four domain types. These are: volcanoplutonic, metasedimentary, plutonic and high grade gneiss (metamorphic rock formed at depth with high temperature and high pressure) domains as listed in Beakhouse et al. [38].

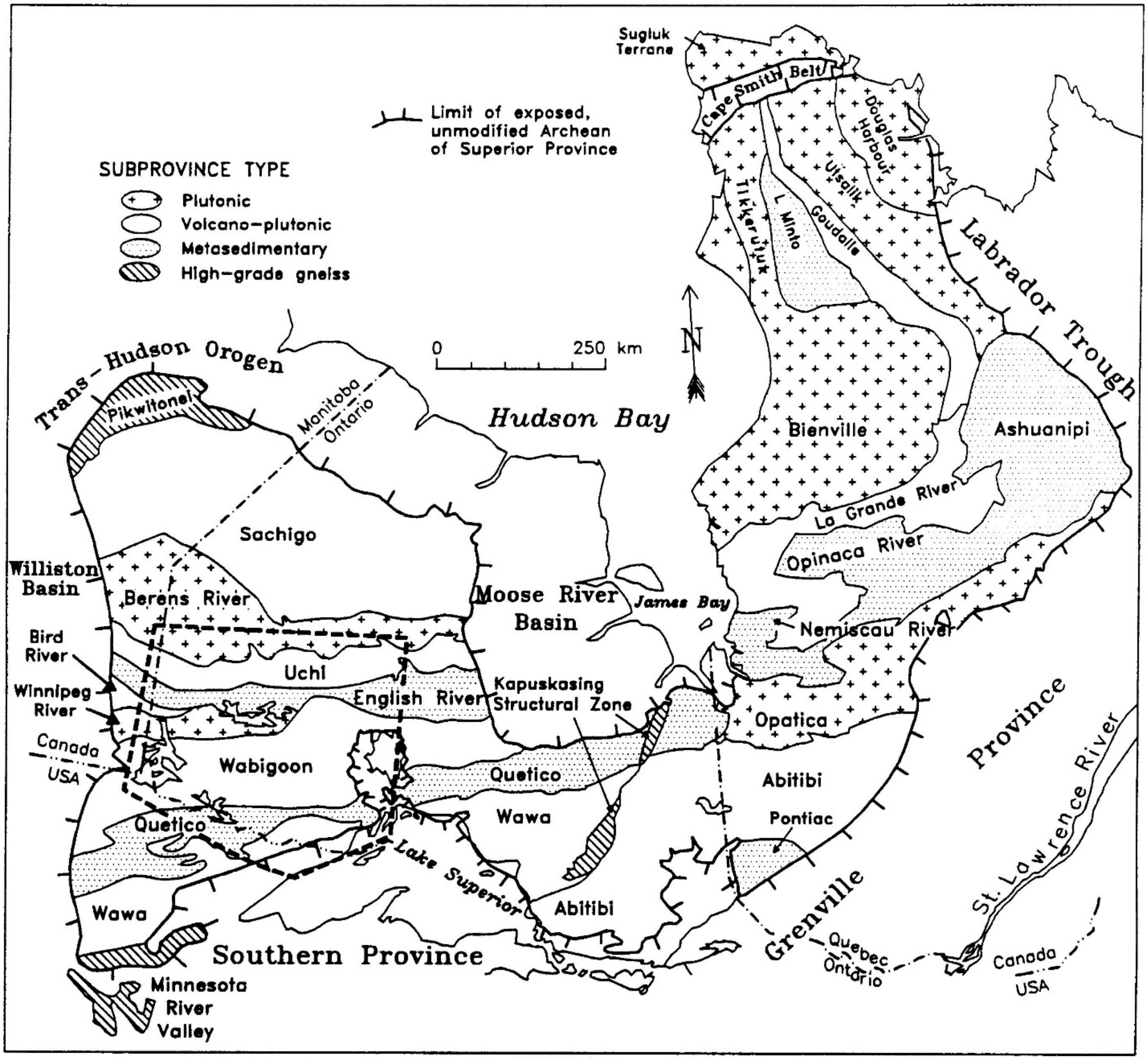


Figure 2-19: Superior Province of the Canadian Shield, Winnipeg River Sub-Province is at the West End of the Superior Province

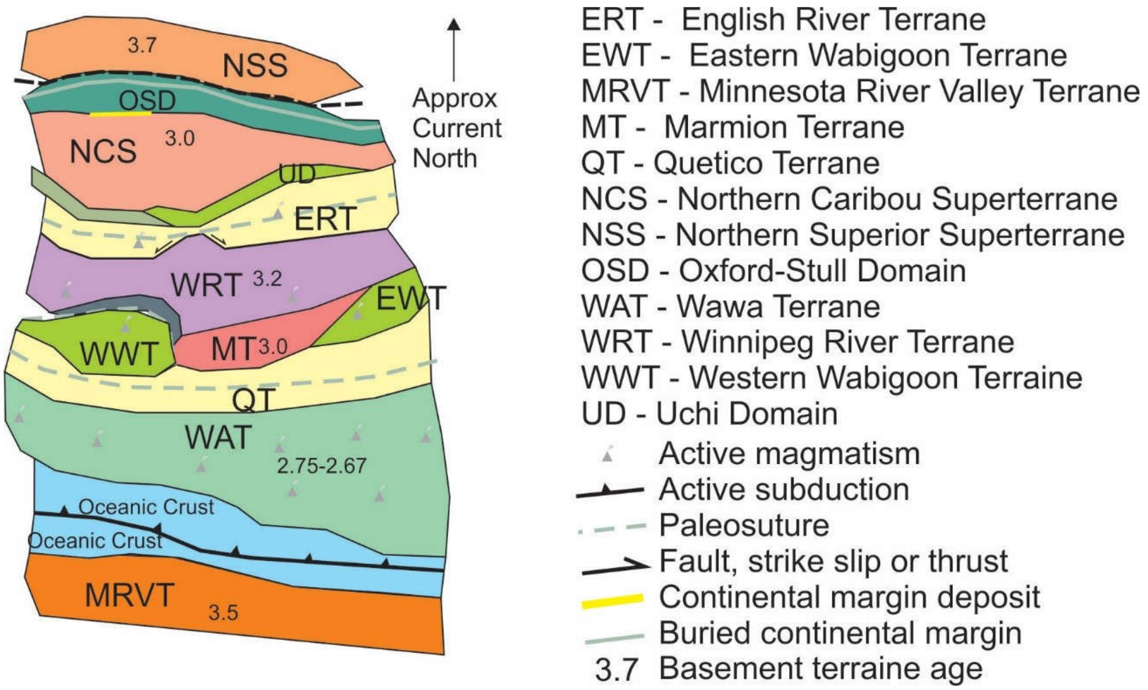


Figure 2-20: Idealized Assemblage of Superior Province Terranes as of 2.68 Billion Years Ago Showing the Impending Superior Minnesota River Valley Terrane Accretion and Orogeny adapted from [44]

The Winnipeg River terrane collectively describes the plutonic domain exposed north and east of the western Wabigoon volcanic domain. It consists of two main elements [42]: 1) the Winnipeg River Subprovince proper is a plutonic domain up to 70 km wide and with an exposed strike length of 400 kilometres [40]. It is composed of Mesoarchean metaplutonic rocks variably intruded by Neoarchean plutons; and 2) further to the east a largely Neoarchean plutonic domain, formerly referred to as the central Wabigoon granitoid complex [50] [51] [52] and Wabigoon diapiric axis [53] [54]. The subprovince extends an unknown distance beneath Paleozoic rocks of the Williston Basin in the west. To the east, the subprovince probably continues eastwards to the Whitewater Lake area [55]. The subprovince is composed of diverse plutonic rocks and a volumetrically minor amount of supracrustal rock [40].

The Lac du Bonnet Batholith, an intrusive magmatic structure, lies within the Winnipeg River Subprovince (Figure 2-21). North of the Lac du Bonnet Batholith are volcanoplutonic domains of the Bird River subprovince (part of the English River Terrane) [42], which are dominantly comprised of volcanic supracrustal sequences (greenstone belts) intruded by syn-volcanic to post-tectonic granitoid plutons [38]. Also to the north are metasedimentary domains of the English River Terrane. These rocks are predominantly clastic metasedimentary. The rocks are considered to represent wacke, siltstone and shale derived from adjacent volcanoplutonic domains and deposited in extensive basins by turbidity currents [55]. Mineral assemblages suggest low metamorphic grades near the margins of these domains but that are mainly characterized by upper amphibolite to granulite grade metamorphism and widespread partial melting of the metasedimentary gneiss. Granitoid rocks include granites and granodioite derived from partial melting of the metasedimentary host rocks as well as sheet-like intrusions and elliptical plutons and batholiths [38]. The boundary of the English River and Winnipeg River Terranes separates dominantly metasedimentary rocks of the English River terrane from mainly metaplutonic rocks of the Winnipeg River terrane to the south. Metamorphic grade is generally high and metamorphic isograds transect the lithological boundary [42].

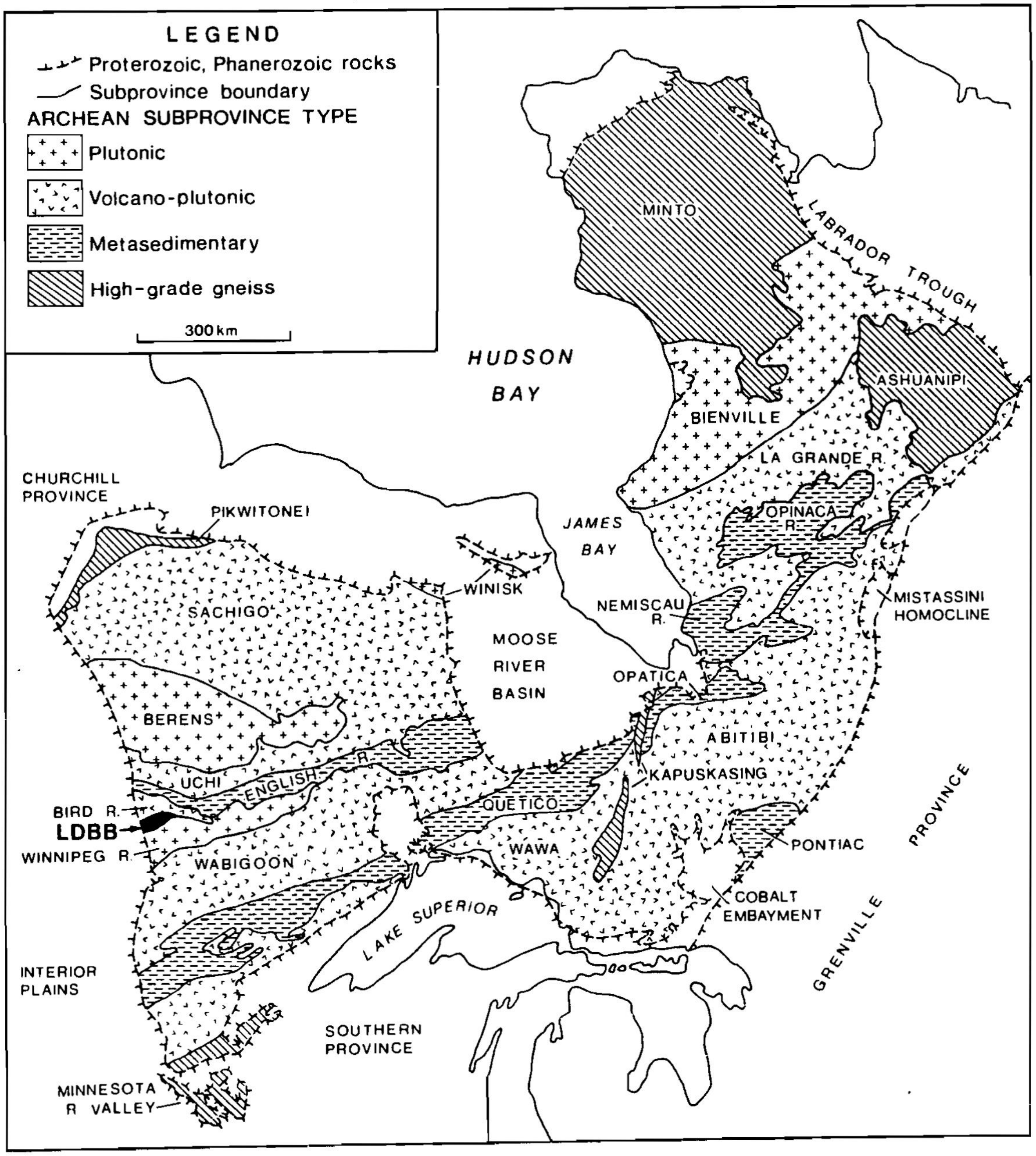


Figure 2-21: Location of Lac du Bonnet Batholith

2.5.2 Local Lac du Bonnet Batholith Lithology

Table 2-8: Sources of Information

Feature	Local/Regional Reference Study	WL Site Reference Study
Local Bedrock Geology **(URL, WL broader area including WMA, Lac Du Bonnet area)**	R.A. Everitt, A. Brown, C.C. Davison, M. Gascoyne, and C.D. Martin, Regional and local setting of the Underground Research Laboratory, In Proceedings of the Symposium on Unique Underground Structures, Denver, Colorado, pp. 64-1 to 64-23, 1990.	WLDP-26000-REPT-004, WR-1 Hydrogeological Study Report. 2018 November.
	W.D. McRitchie, The Petrology and Environment of the Acidic Plutonic Rocks of the Wanipigow - Winnipeg Rivers Region, Southeastern Manitoba, in Geology and Geophysics of the Rice Lake Region, Southeastern Manitoba (Project Pioneer), edited by W. D. McRitchie and W. Weber, Manitoba Mines Branch, Publication 71-1, pp. 7-61, 1971.	J.E. Guthrie and G.A. Scott, Pre-operational Environmental Survey Report of the Whiteshell Nuclear Research Establishment Area, 1988.
	G.P. Beakhouse, A Subdivision of the Western English River Subprovince, Canadian Journal of Earth Sciences 14: 1481-1489, in Everitt et al., 1996.	
	A. Brown, N.M. Soonawala, R.A. Everitt, and D.C. Kamineni, Geology and Geophysics of the Underground Research Laboratory Site, Lac du Bonnet Batholith, Manitoba, Canadian Journal of Earth Sciences 26: 404-425, 1989.	
	R.A. Everitt, J. McMurry, A. Brown, and C. Davison, Geology of the Lac du Bonnet Batholith, Inside and Out: AECL's Underground Research Laboratory, Southeastern Manitoba	

Feature	Local/Regional Reference Study	WL Site Reference Study
	Field Trip Guidebook B5, Geological Association of Canada/Mineralogy Association of Canada Annual Meeting, Winnipeg, Manitoba, 1996 May 27-29.	
	T.E. Krogh, G.L. Davis, I. Ermanovics, and N.B.W. Harris, U-Pb Isotopic Ages of Zircons from the Berens Block and English River Gneiss Belt, Proceedings of 1976 Geotraverse Conference, University of Toronto, 12-1, 46.	
	D.C. Kamineni, D. Stone, and Z.E. Peterman, Early Proterozoic Deformation in the Western Superior Province, Canadian Shield, Geological Society of America Bulletin, 102: 1623-1634, 1990.	
	J.A. Percival, W. Bleeker, F.A. Cook, T. Rivers, G. Ross, and C.R. van Staal, Panlithoprobe Workshop IV: Intra-Orogen Correlations and Comparative Orogenic Anatomy, Geoscience Canada, 31: 23-39, 2004.	
	P. Cerny, B.J. Fryer, F.J. Longstaffe, and H.Y. Tammemagi, The Archean Lac du Bonnet Batholith, Manitoba: Igneous History, Metamorphic Effects, and Fluid Overprinting, Geochimica et Cosmochimica Acta, 51: 421-438, 1987.	
	G.F. D. McCrank, A Geological Survey of the Lac du Bonnet Batholith, Manitoba, AECL-7816, 1985.	
	T.J. Katsube, and J.P. Hume, Geotechnical Studies at Whiteshell Research Area (RA-3), Mining	

Feature	Local/Regional Reference Study	WL Site Reference Study
	Research Laboratories Divisional Report, CANMET-MRL-87-52 TR, 1987.	
	R.A. Everitt, and A. Brown, Geological Mapping of AECL Research's Underground Research Laboratory - A Cross Section of Thrust Faults and Associated Fractures in the Roof Zone of an Archean Bathotith, Proceedings of Fractured and Jointed Rock Masses, A Regional Conference of the International Society for Rock Mechanics, June 14, 1992, Granlibakken, California Vol. 1, p. 1-1 1, 1996.	
	R.S. Read, and C. D. Martin, AECL-11311, COG-95-171, Technical Summary of AECL's Mine-by Experiment Phase 1: Excavation Response, 1996.	
	S.S. Lim, C.D. Martin, and U., Akesson, In-situ Stress and Microcracking in Granite Cores with Depth, Engineering Geology s 147–148: 1–13, 2012 October.	
	Bezys, R.K., Matile, G.L.D. and Keller, G.R. 2001: Investigations of Precambrian Monadnocks (NTS 62I/1 and 62I/8); in Report of Activities 2001, Manitoba Industry, Trade and Mines, Manitoba Geological Survey, p. 133-137, 2001.	
	Gascoyne, M., A. Brown, R.B. Ejeckam, R.A. Everitt, Dating fractures and Fracture Movement in the Lac du Bonnet Batholith AECL-11725, COG-96-634-1, 1997.	

The surface exposure of the Lac du Bonnet Batholith (Figure 2-22) extends from a tapered eastern margin, westward approximately 85 km. West of the Winnipeg River, the batholith is largely concealed by glaciolacustrine, glaciofluvial and glacial sediments and by Paleozoic carbonate rocks; however, geophysical data indicate that the granitic rocks extend westward at least another 20 km [56]. The existence of monadnocks associated with the Lac du Bonnet Batholith is known to the north of Beausejour and provide further evidence of the extent of the batholith west of the WL site [57]. To the north, the batholith is in sharp contact with the narrow belt of metavolcanic rocks of the Bird River Greenstone Belt, and to the south it is in gradational contact with gneisses and migmatites of the Winnipeg River Subprovince [57] (Figure 2-23).

The batholith is associated temporally and spatially with several other felsic intrusive bodies of roughly the same exposed size and age in the Winnipeg River Subprovince including the Betula Lake and Medika plutons to the south east [59]. The relatively sparsely fractured characteristics of large portions of these bodies, and of the Lac du Bonnet Batholith, are attributed at least in part to their intrusion at or near the end of regional deformation [17] [60], and to prolonged cooling, which delayed the onset of brittle deformation. The slow cooling rate was in part due to the size of the intrusive bodies and their proximity to each other, and to the distance separating the intrusions regionally from later tectonic events in the Superior Province at the end of the Kenoran Orogeny [59]. The batholith intruded at a depth of 10-12 km, based on a comparison of isobaric minima in the normative quartz-albite-alkali feldspar system [57].

Age dating using U-Pb, and Rb-Sr from several studies are summarized in Everitt et al. [17], which indicates a U-Pb date of 2665 ± 20 Ma [61] in [17], and a whole rock Rb-Sr averaging 2.568 ± 0.23 billion years ago Kamineni et al. [62] in Everitt et al. [17]. This equates to a late Kenoran Orogeny timeline of 2.72 and 2.68 billion years ago [63], and reflects the re-melting of older crustal rocks. Figure 2-24 indicates the intrusion of the Lac du Bonnet Batholith relative to the timeline of the Canadian Shield.

A Late Proterozoic (Proterozoic era is from 2.5 billion years to 542 million years ago) or Early Phanerozoic erosional surface close to the currently exposed surface of Lac du Bonnet Batholith is evidenced by the deposition of Ordovician (post 505 Ma) sediment. The margin of the Ordovician rock is less than 40 km west of the site. Those sediments directly and unconformably overlay the batholith under the more recent glacial and glacio-lacustrine deposits. The dip of the batholith is roughly 2.5 m per km based on two boreholes northeast of Beausejour and seismic reflection surveys. Using the dip, and projecting the depth of the batholith from the contact with the Ordovician sediments eastward, indicates that the elevation of the batholith in the WL area would be approximately 100 m above the present surface of the batholith [64]. This thickness of batholith (~100 m), plus any sediments laid down and subsequently eroded [65], represent the erosion at the WL site since that time.

Age of fractures and fracture fillings are best understood through the development of fractures and fracture systems through the geological history of the batholith. Thrust faulting in the batholith occurred during the Late Archean-Early Proterozoic in response to tectonism related to orogenic belt to the south [17], these thrust faults have been generally referred to fracture zones when encountered during drilling work and excavations at the Underground Research Laboratory (URL) and in the WN series holes at the WL site north of the Waste Management Area. McCrank [66] noted fracture-filling materials include dykes of granite, pegmatite and aplite (early fractures), and hydrothermal fillings of epidote, chlorite and calcite. Epidote vein filling of fractures occurred when the present surface of the batholith was close to the surface approximately 2 billion years ago with an average erosion rate of (4 km per 100 Ma). Following the period of erosion to approximately 2 billion years ago, it is likely that the western Superior Province underwent several periods of subsidence, with platform and marginal basin sedimentation prior to Hudsonian Orogeny around 1.7 billion years ago [64]. Epidotized[1] cataclastic rocks from thrust fault zones in the batholith have ages of 2350 ± 60 Ma based on Rubidium-Strontium (Rb-Sr) dating. Epidote is a common mineral formed during low grades of metamorphism and hydrothermal activity. Neo-mineralization microcline and whole-rock samples from the same fault zones have ages of 2298 ± 48 Ma and 2206 ± 86 Ma respectively [64]. The location of these faults is influenced both in location and orientation by earlier structural fabrics that developed in the rock mass early in the intrusion and crystallization of the batholith. The age dating and mineralization infers that the batholith cooling rate processed slowly from the stage of granite crystallization to that of epidote infilling associated with thrust fault cataclastes with an estimated cooling rate of 66°C per 100 Ma. The overlap of biotite and fault zone ages implicitly shows that the deformation occurred prior to regional thermal stabilization of the Lac du Bonnet Batholith [64].

At the URL, boreholes and excavations show two notable infilling populations of fractures, partially by calcite down to 200 m depth and chlorite filled and chlorite sericite filled fractures that occur to at least 400 m depth. The composition of the deeper fractures may be related more to host rock composition. Argon dating on limited samples of illite from one thrust fault in the batholith at the URL, suggest either alteration or perhaps renewed movement at 832 ± 1 Ma and 510 ± 1Ma which was probably related to epeirogenic movement (generalized craton uplift) and the formation of new erosion surfaces [64].

There are no absolute dates between Early Proterozoic faults pre-dating the epidotal alteration (2350 ± 60 million years ago), and fracture infillings associated with Pleistocene (2.5 million years ago to 11 thousand years ago) glaciations, however dates in [64] indicate dates of 404 ± 64 thousand years ago and 475 ± 33 thousand years ago. Illite (clay) from Fracture Zone 2 (approximately 400 m deep) at the URL gave an age of formation prior to 832 ± 1 million years ago and an overprinted age post 510 ± 1 million years ago.

Uranium dating of calcite contain older but still largely Pleistocene calcite infillings in major fracture zones, whereas near surface fractures contain mainly younger (<350 thousand years ago) calcites. Ages commonly range from 20 thousand years ago to 55 thousand years ago but are more recent than 350 thousand years ago. This demonstrates the long term presence of

---

[1] Epidote is a secondary mineral, in granites it is related to hydrothermal alteration of various minerals (feldspars, micas, pyroxenes, amphiboles, garnets, and others). It is silicate based mineral, commonly occurring with a yellowish-green or pistachio-green colour but does occur as grey, brown or nearly black.

water with elevated calcium levels slowly depositing calcium that lead to formation of calcium in pre-existing fractures.

The near surface mesoscopic fractures follow an orthogonal pattern in the upper tens of metres of the batholith implying a general extension of the ground. Many of the larger extension fractures also show evidence of normal movement, disrupting earlier low-temperature infillings such as calcite to form pathways for groundwater. The amount of water flow in these fractures will vary based of the amount of previous infilling, the degree of disruption of that infilling and local connectivity and local fracture frequency at a particular location on the batholith. As stated in [64], all types of mesoscopic fractures studied appear to act as pathways for groundwater recharge to the main fracture zones at the URL site. It is not unreasonable to assume this is the case for fractures elsewhere within the batholith.

Chlorite filled fractures in some areas of study at the URL show strong evidence of water-rock interaction, represented by chlorite breakdown and formation of goethite/hematite residue. Calcite filling was noted to be stable in the bicarbonate dominated groundwater at shallow depths in the batholith. More geologically recent activity may relate to glacial deposition, with some glacial chattermarks having been filled by calcite, probably due to subglacial pressures [64].

This dating of fracture infilling indicates that the relatively simple fracture systems developed over the long geologic history, both in fracture types, locations, and the fracture infilling, which occurred at various periods from various processes in the long history of the batholith.

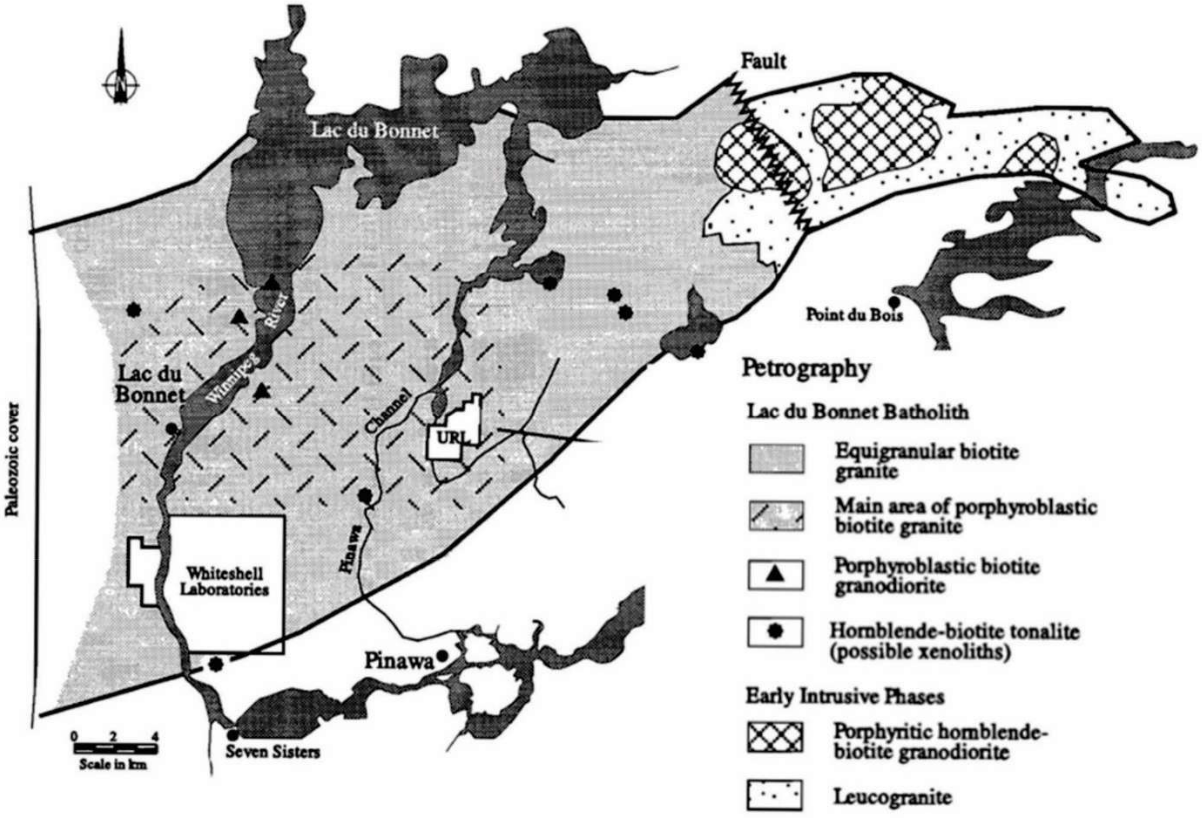
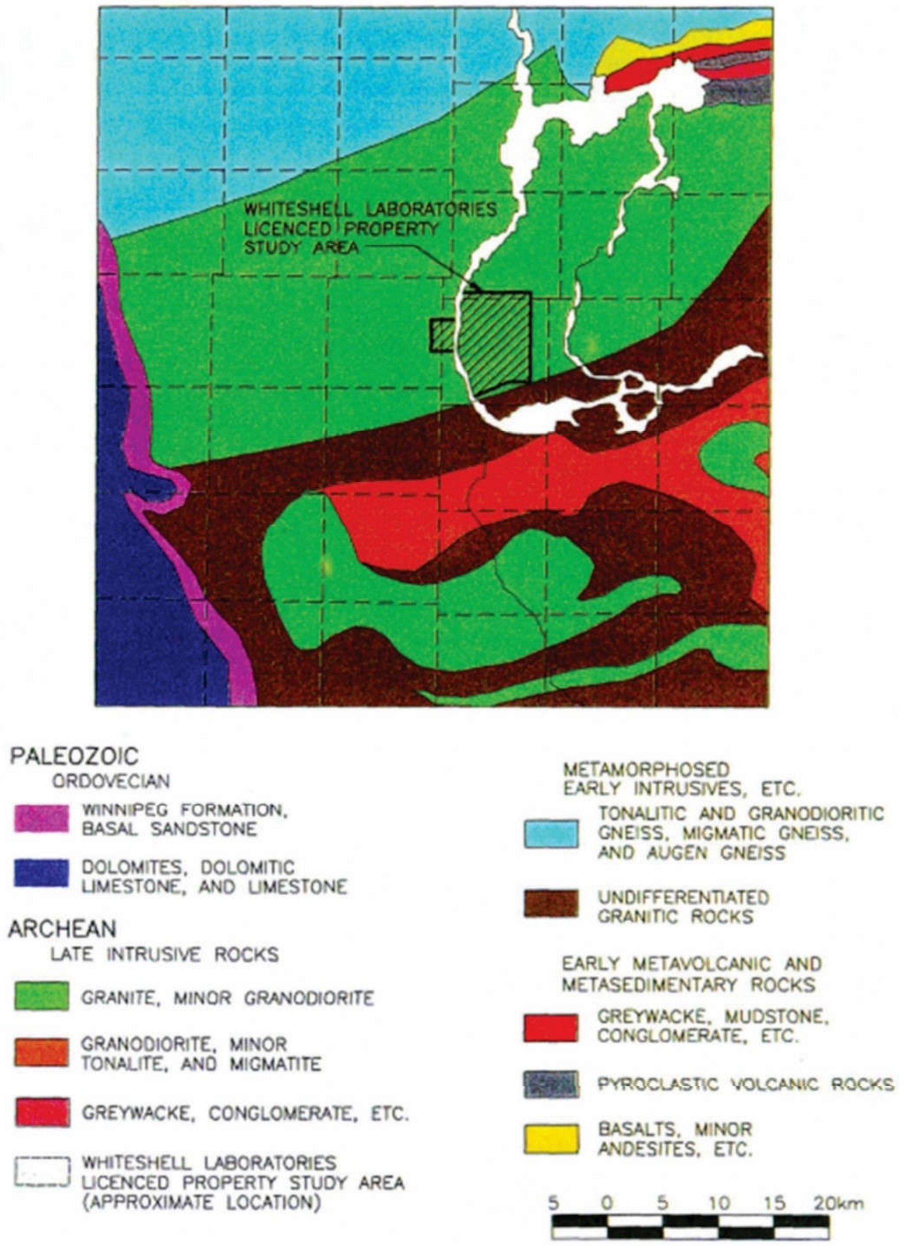


Figure 2-22: Lac du Bonnet Batholith Geology [16]



NOTE:

Modified from the Geological Map of Manitoba, 1:1,000,000 in Guthrie and Scott, 1988

Figure 2-23: Regional Geology Near Whiteshell Laboratories [13]

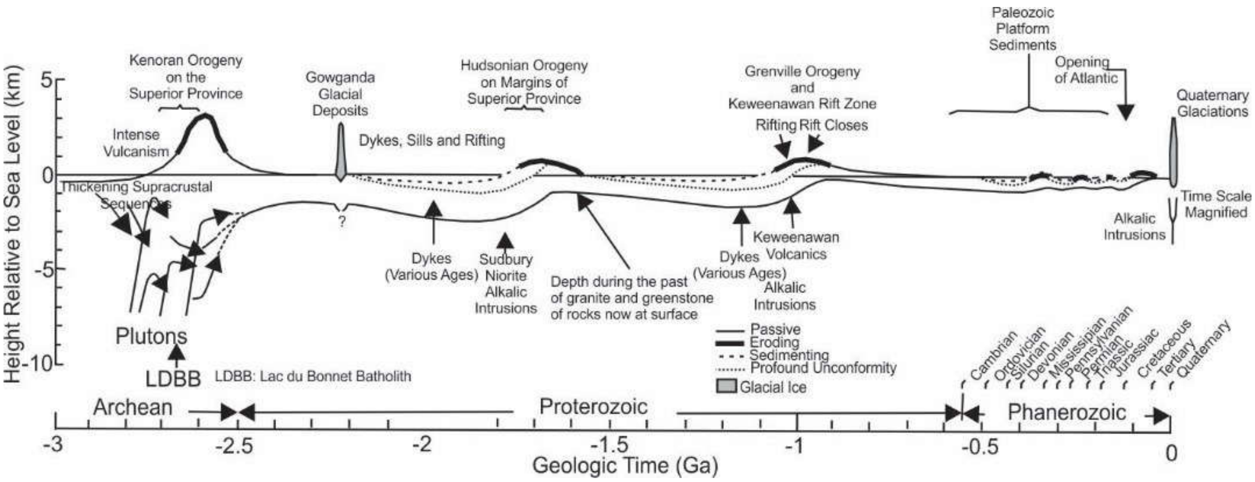


Figure 2-24: Geological Timeline of the Canadian Shield Indicating the Intrusion Time of the Lac du Bonnet Batholith. Modified from [48].

Cerny et al. [67] identified five phases of the Lac du Bonnet Batholith based on of mineralogy, texture, intrusive relationships, and geochemistry. In order of decreasing relative age:

1. gneissic hornblende-biotite tonalite (possibly xenoliths);
2. gneissic porphyritic hornblende-biotite granodiorite;
3. gneissic to undeformed leucogranite;
4. biotite granite (the main phase of the batholith); and
5. late-tectonic biotite granodiorite dykes.

The oldest phase occurs as widespread but relatively minor occurrences in other rock types, as xenolithic inclusions [66]. Most surface exposures of the batholith consist of late-tectonic biotite-bearing granite. Porphyritic biotite granite, described as porphyroblastic by Cerny et al. [67], is dominant in the central portion of the batholith and accounts for about one-fourth of the exposures.

An alternative division of the batholith saw it divided into eight units during surface mapping [66] as described in [68].

1. Predominantly pink, massive, porphyritic granite to granodiorite subdivided into biotite rich (>5% biotite) and biotite-poor phases;
2. Pink hornblende granite to granodiorite;
3. Grey granite to granodiorite, mineralogically and texturally similar to Unit 1 but containing few fractures;
4. Xenolith-bearing pink granite to granodiorite; xenoliths are grey tonalite and amphibiolite;
5. Pink, fine- and coarse-grained granite;
6. Pink, gneissic gradational to Unit 1;
7. Light brown porphyritic hornblende-biotite granite; and
8. Pink foliated biotite granite.

The granite of Unit 1 [69] makes up the majority of the batholith with the other units occurring as marginal phases or segregations in the batholith. Unit 4 [69] was thought to represent the roof zone of the batholith. Units 7 and 8 are restricted to the extreme eastern end of the batholith and may relate to older intrusive bodies. Unit 6 is limited to the margins as a synkinematic phase that is gradational to Unit 1 [66].

Extensive samples were taken of the granite and mineralogy investigate from boreholes at the Whiteshell site (WN Series) and URL approximately 15 km to the northeast of the WL site (Figure 2-22), the quartz-feldspar mineralogy is summarized in Figure 2-25.

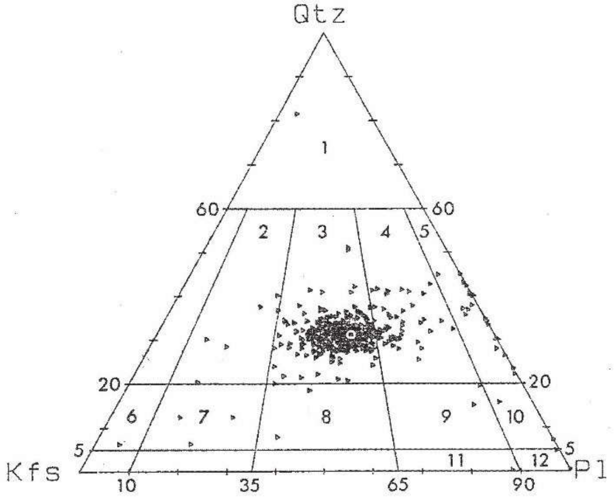


Figure 2-25: Modal Composition of 432 Core samples from WM and URL Series Boreholes. This average mode (Quartz (Qtz), Plagioclaise (Pl) and K-Feldspar (Kfs) normalized to 100%) is quartz 31.2% ±6%, plaigoclaise 39.8% ±10.5%, microcline 29.0% ±10.7% [68].

The presently exposed topographic surface of the batholith is thought to be close to the original roof zone of the intrusion [69]. Pink, hematite-bearing granite predominates to depths of about 200 m, below which the dominant phase is grey magnetite-bearing granite, similar to the pink granite except for a lower Fe_2O: FeO ratio. None of the grey granite is encountered in the shallow drilling conducted near the WR-1 site. Grey granite outcrop occurrences are known to exist near the old Pinawa Dam site and at the URL site.

Where pink granite is found below 200 m in boreholes and excavations at the URL, the colour change consistently is associated with alteration in and around fractures. The distribution of alteration around fractures and variation of degree of alteration (pinking) around fracture zones encountered at the URL suggest the colour change resulted from one or more hydrothermal or deuteric alteration episodes along the pervasive network of open fractures in the upper 200 m of the batholith [60]. These alterations of the primary plagioglase feldspar and biotite resulted in the hydrothermal formation of chlorite and epidote, with reddening of the rock related to dispostion of iron oxides with mineral cleaves, grain boundaries and microcracks. Reddening occurs mostly about fractures and is superimposed across lithologic contacts. Low temperature alteration overprints the higher temperature forms, with illite replacing epidote and biotite with iron oxides removed leading to a bleached appearance [64]. Figure 2-26 shows a segment of the core recovered from the WL site. The rock shows pinking-red alteration, and localized bleaching of the rock by later stages of alteration. A rubblized section of the core occurs where the rock was broken by the drill along fractures and rotated in the core barrel breaking it into broken pieces of core.

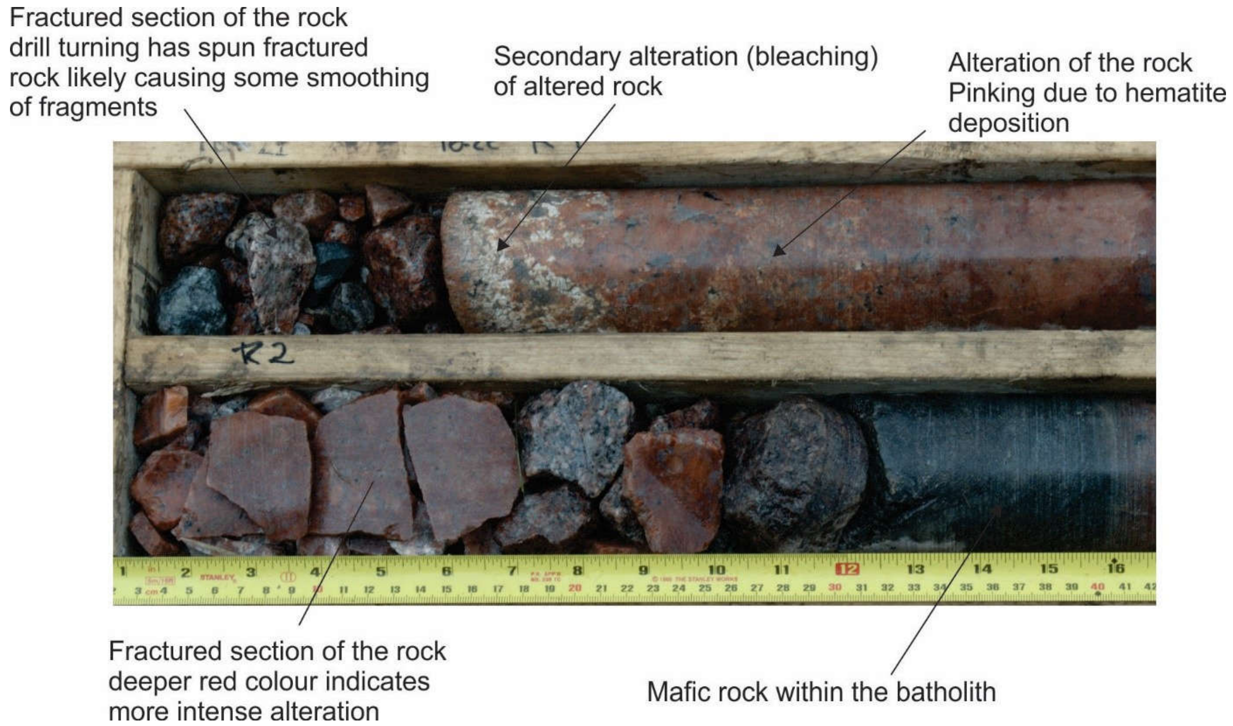


Figure 2-26: Core Sample from WL Site Showing Alteration of the Rock Along Fractures

The subvertical fracture sets are interpreted as extensional intrablock fracturing initiated by geometric flexing and general expansion of the thrust plates, probably in the early Proterozoic. Reactivation and extension of some fractures must have occurred during Paleozoic transgression, during subsequent removal of the Paleozoic cover, and during continental glaciation, as indicated by the fracture infillings [59] (as described above in this section).

In the central portions of fracture zones identified at the URL, alteration of granite can extend beyond pink into a heavily altered red colour around open fractures. The block diagram indicates near surface vertical joints are present and decrease with depth (Figure 2-27). Subhorizontal fracture zones act as hydraulic pathways and show evidence of localized alteration.

The decreasing frequency, extent and complexity of subvertical fracturing with depth from surface are seen as a consequence of both the stacking of the thrust plates, and of the distance from surface. The greatest and most varied "flexing" and fracturing would be experienced by the uppermost blocks.

At greater depths (below Fracture Zone 2 at the URL, where strains are higher due to lack of stress relief from fracturing, cracking encountered was related to due excavation related stress relief [70] [71]. Deep drilling found few narrow fracture zones at depth [59].

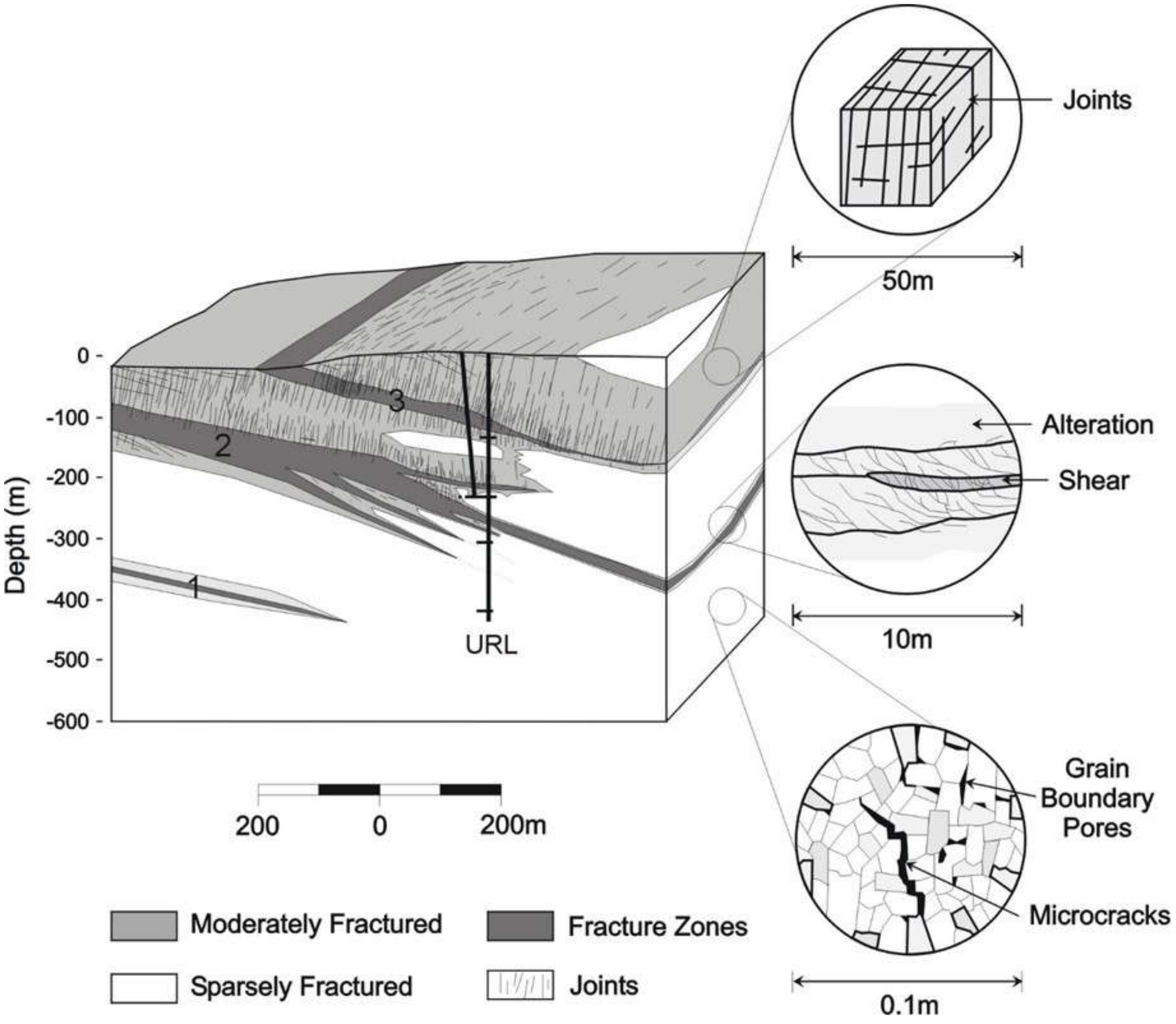


Figure 2-27: Cross Section of Underground Research Laboratory Geology [59]

Borehole observations at WN 1 and WN 2 (Figure 2-28) to the north of the WMA show that at these locations the bedrock is predominately a medium to coarse grained pink granite (typical of the upper surface of the Lac du Bonnet Batholith) to a depth of approximately 300 m, where it transitions to a pink granite to granodiorite (Figure 2-29). At both locations a zone of mixed granodiorite, granite and pegmatite with xenoliths of tonalite was noted between depths of approximately 50 m to 100 m (Figure 2-29).

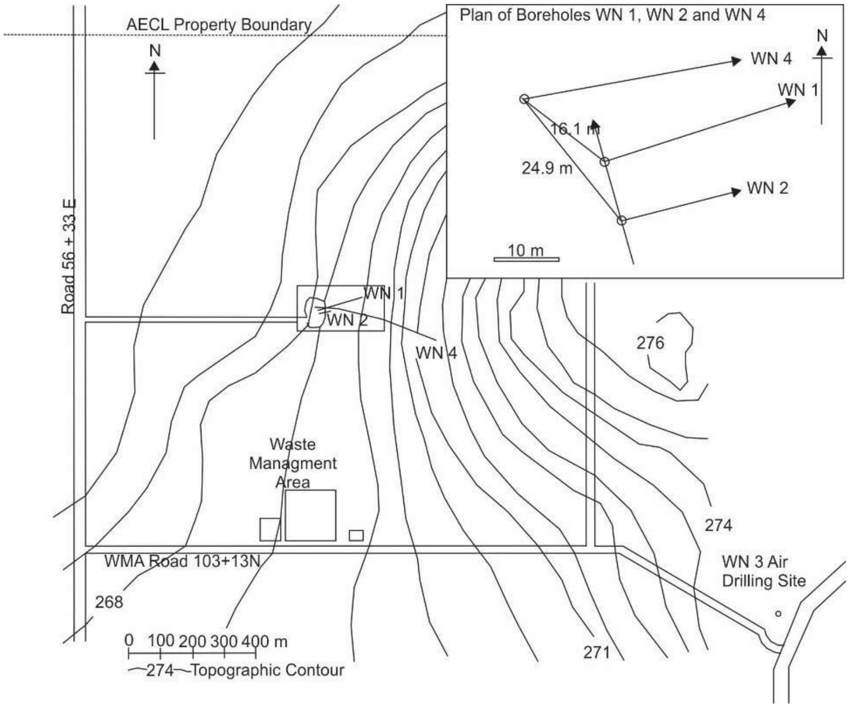


Figure 2-28: Location of WN Series Boreholes North of the WL WMA

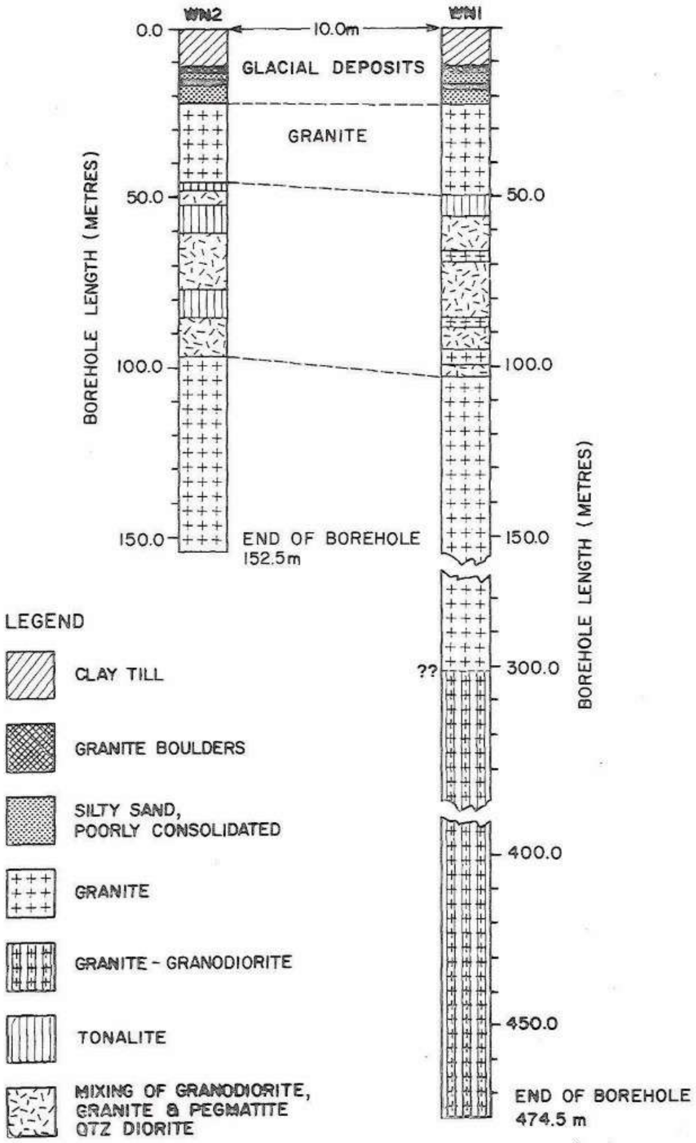


Figure 2-29: WN1 and 2 Core Logs

2.5.3 WR-1 Site Lithology

Table 2-9: Sources of Information

Feature	WL Site Reference Study
WL Site Bedrock Geology	WLDP-26000-REPT-004, WR-1 Hydrogeological Study Report. 2018 November.
	Shawinigan Engineering Company, Shawinigan Engineering Report 2410-2-60, Report on Proposed Site for Whiteshell Nuclear Research Establishment for Atomic Energy of Canada Limited, 1960.

Recent boreholes drilled in the vicinity of WR-1 [16] extended several metres into the underlying bedrock. The core logs indicated that the shallow bedrock near WR-1 is dominated by pink to red-pink granite with mafic granolithic dykes and possibly layered xenolithic structures. Pegmatitic (larger grain size) granite was also encountered. Areas of the pink granite include altered red granite similar to more heavily altered and oxidized fractures similar to those found in fracture zones at the URL (Figure 2-27). Where localized bleaching of fracture fillings occurs, it indicates some of the fractures encountered were water bearing and have undergone extensive secondary alteration in geological history. The fracture zones at the URL are still water bearing features. These fractures maintain a preferential flow path through the rock mass.

Borehole 16-2E (nest 2) is to the east of WR-1 (Figure 2-30). The borehole encountered bedrock at approximately 16 m depth below surface, the rock type is a pink coloured syenogranite, monzogranite to tonalite with a granodioite dyke present from approximately 17 m depth below surface 20.5 m depth below surface and a second dyke from approximately 22 m depth below surface to the end of the borehole at 24 m depth below surface. The upper surface of the rock appears heavily weathered at the unconformity of the rock and overlying sediments.

Borehole 16-4F (nest 4) is to the northwest of WR-1 (Figure 2-30). The borehole encountered bedrock at 16.9 m depth below surface, and the rock type is largely a coarse grained mafic dyke (identified as diorite) to the bottom of the borehole at approximately 26 m depth below surface. There are approximately 26 fractures, in the 10 m of core, many of the core breaks and fractures are steeply oriented indicating the presence or past presence of sub-vertical fracturing in the dyke. The difference in rock type is an indication of the local variability found elsewhere in the batholith.

Borehole 16-7E (nest 7) is to the southwest of WR-1 (Figure 2-30). The borehole encountered bedrock at 20.8 m depth below surface. The rock is heavily weathered red-pink granite with red clay and gravel, or drilled turned fracture rock, present in fractures. There are heavily fractured zones encountered at 21.1 m, at 22.7 m, and 23.1 m depth below surface. It is unknown from current drilling if these represent splays of a larger potential fracture zone, or are separate fractures but their relatively close vertical distances suggests that they may be interrelated. Below that the granite hosts many healed fractures to the bottom of the borehole at 25.8 m depth below surface. The composition of the fractures reflects similarities to the fracture zones encountered at the URL in terms of appearance and colouration/alteration.

Borehole 16-8A is to the northwest of WR-1 (Figure 2-30). The borehole encountered bedrock at 12.2 m depth below surface with alkali feldspar granite, red, porphyritic structure, deformation of structures, and vertical fractures. The upper few metres of the borehole present vertical fractures and fractures with sand sized particles and clay. At approximately 29 m depth below surface the rock is syenogranite, red, medium-grained, with phanertic texture, deformation of structures, microvertical fractures throughout, the presence of vertical fractures decreases and quartz content increases. Borehole bottom is at 42.6 m depth below surface. The fracturing and degree of red to pink granite present further suggests a fracture network.

Early exploratory boreholes drilled on the site [12] (Figure 2-30) further confirm that the surface of the bedrock at the soil-rock interface is irregular as is suggested by the varying depths rock is encountered in the more recent boreholes, with the rock shallowest at borehole 16-8A and deepest at Borehole 16-7E. Borehole 16-4F is near Borehole 16-8A with marked differences in geology. The variability of the rock contact depth could influence local deposition of Quaternary glacial deposits leading to local flow rate variations. The irregular surface of the bedrock is in keeping with what is seen elsewhere on the Lac du Bonnet batholith. It can be expected that the rock surface has joint sets as well as is the case elsewhere on the Lac du Bonnet batholith and Canadian Shield in general. This jointing is evidenced in a river side outcrop near the WL site north of the Highway 211 bridge (Figure 2-31) as well as in a larger outcrop near the intersection of Ara Mooradian Way and Highway 211 (Figure 2-32), where both closed joints (Figure 2-33) and open joints (Figure 2-34) are noticeable.

This larger outcrop, which is as high as 5 to 7 m above the surrounding overburden (Figure 2-35), shows the typical pink colouration of most outcrops of the Lac du Bonnet Batholith (Figure 2-36). A similar large outcrop to the west of the Winnipeg River near the WL site hosts the Cold Spring Granite quarry.

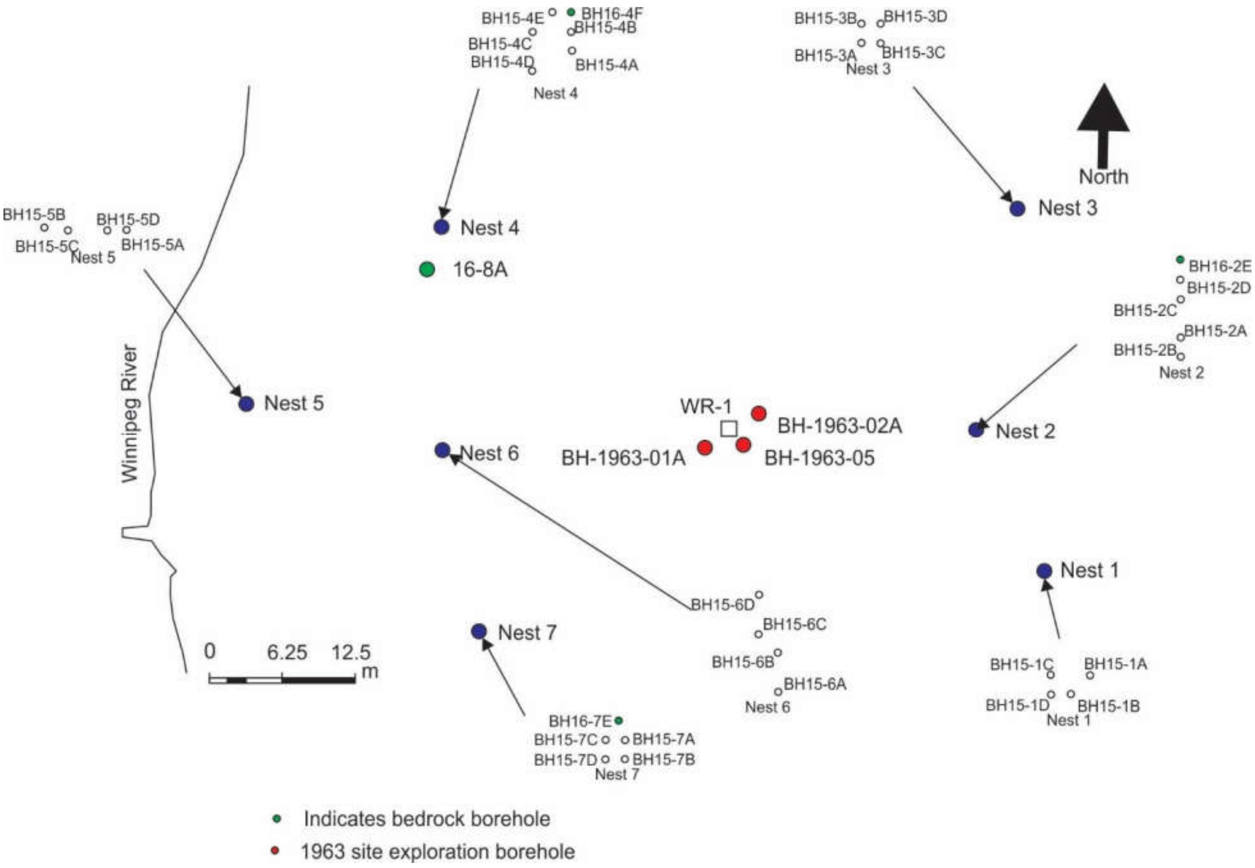


Figure 2-30: Site Map Showing Borehole Locations on the WL Main Campus

Figure 2-31: River Outcrop Near the WL Site

Figure 2-32: Aerial View of Outcrop Near Highway 211 on the WL Site

Figure 2-33: Jointing on Outcrop near Highway 211 on the WL Site

Figure 2-34: Open Jointing on Outcrop near Highway 211 on the WL Site. Vegetation has populated the joints where soil has accumulated.

Figure 2-35: Elevation View of West Side of Outcrop near Highway 211 on the WL Site

Figure 2-36: Pink Colouration of the Lac du Bonnet Batholith on the Outcrop near Highway 211 on the WL Site

2.5.4 Local and WR-1 Site Structural Geology

Table 2-10: Sources of Information

Feature	Local Reference	Site Reference
Bedrock Fracture Frequency and Orientation	R.A. Everitt, J. McMurry, A. Brown, and C. Davison, Geology of the Lac du Bonnet Batholith, Inside and Out: AECL's Underground Research Laboratory, Southeastern Manitoba Field Trip Guidebook B5, Geological Association of Canada/Mineralogy Association of Canada Annual Meeting, Winnipeg, Manitoba, 1996 May 27-29.	P. Pehme, S. Chapman, and B. Parker, G360 Institute for Groundwater Research, Technical Memo: Summary of Geophysical Data Processing, Temporary Transducer Deployment Design and Implementation in Borehole 16-8A CNL Whiteshell Laboratories Facility, near Pinawa, Manitoba, Canada, 2017 June 20.
	G.F. D. McCrank, A Geological Survey of the Lac du Bonnet Batholith, Manitoba, AECL-7816, 1985.	
	C.C. Davison, Physical Hydrogeology Measurements Conducted in Boreholes WN-1, WN-2 and WN-4 to Assess the Local Hydraulic Conductivity and Hydraulic Potential of a Granitic Rock Mass, Atomic Energy of Canada Limited Technical Record, TR-26, 1980.	
	R.A. Everitt, and A. Brown, Subsurface Geology of the Underground Research Laboratory: An overview of Recent Developments. In Proceedings of the 20th Information Meeting of the Canadian Nuclear Fuel Waste Management Program, Winnipeg, Manitoba, 1985, Atomic Energy of Canada Limited Technical Record, TR-375, 1986.	

Feature	Local Reference	Site Reference
	D.R. Stevenson, E.T. Kozak, C.C. Davison, M. Gascoyne, and R.A. Broadfoot, Hydrogeologic Characteristics of Domains of Sparsely Fractured Rock in the Granitic Lac du Bonnet Batholith, Southeastern Manitoba, Canada, AECL-11558, COG-96-117, 1996.	

Locally, fractures in the Lac du Bonnet Batholith have a polymodal azimuth distribution. They occur in four preferred orientations: north-northeast, east, southeast and south-southeast (Figure 2-37). This represents the near surface, expansion-related, orthogonal fracture network described earlier. The most common set trends north-northeast (010° to 040°) and accounts for 28% of the sample population. The southeast set of fractures is oriented from 120° to 140° and accounts for 19% of the sample population. The east and south-southeast sets are less common, and account for 12% and 13% of the sample population, respectively; they comprise fractures oriented from 080° to 100° and 160° to 180°, respectively. The distinction between sets, based on orientation, is within an uncertainty of ±15° azimuth [66].

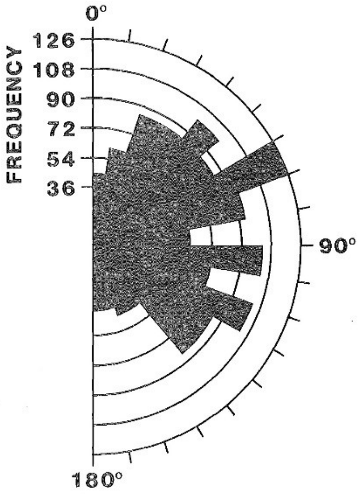


Figure 2-37: Rose Diagram of Fracture Orientations on the Lac du Bonnet Batholith

Everitt et al. [59] noted that subvertical fractures are grouped into those striking north northeast (015°-020°), those striking east southeast (110°-130°), and those striking south southeast (160°-170°). Locally significant groups strike south (180°) and northeast (035°). The first two groups show many characteristics of extension fractures, such as irregularity and lens-shaped infilling. Unequivocal right hand strike-slip movement is visible on fractures striking south southeast; left-hand strike slip movement occurs on fractures striking northeast. These observations suggest a north northeast-trending compressive stress axis at the time of fracturing, similar to the stress field during the formation of later pegmatite dykes and quartz veins [59]. In general, subvertical fractures are partially or completely filled with a combination of chlorite, iron oxides, carbonates, and clay minerals.

Observations of outcrops on the Lac du Bonnet Batholith indicates that fracture intensity (based on 7517 mapped fractures, infilled or open) averaged for the entire batholith is 1.5 fractures per metre [66]. The intensity is based on average fracture spacing and number of fractures per metre. Data on fracture spacing was not nearly as complete nor as uniformly distributed throughout the mapped areas as the fracture intensity data. Spacing values show the rock to be less intensely fractured than fracture intensity values. The average spacing value, based on limited data, is 3.5 m between fractures with a standard deviation of 3.4 m. The fracture spacing values range from 0.8 m to 22.8 m. Fracture spacing decreases in a negative exponential manner (Figure 2-38) [66].

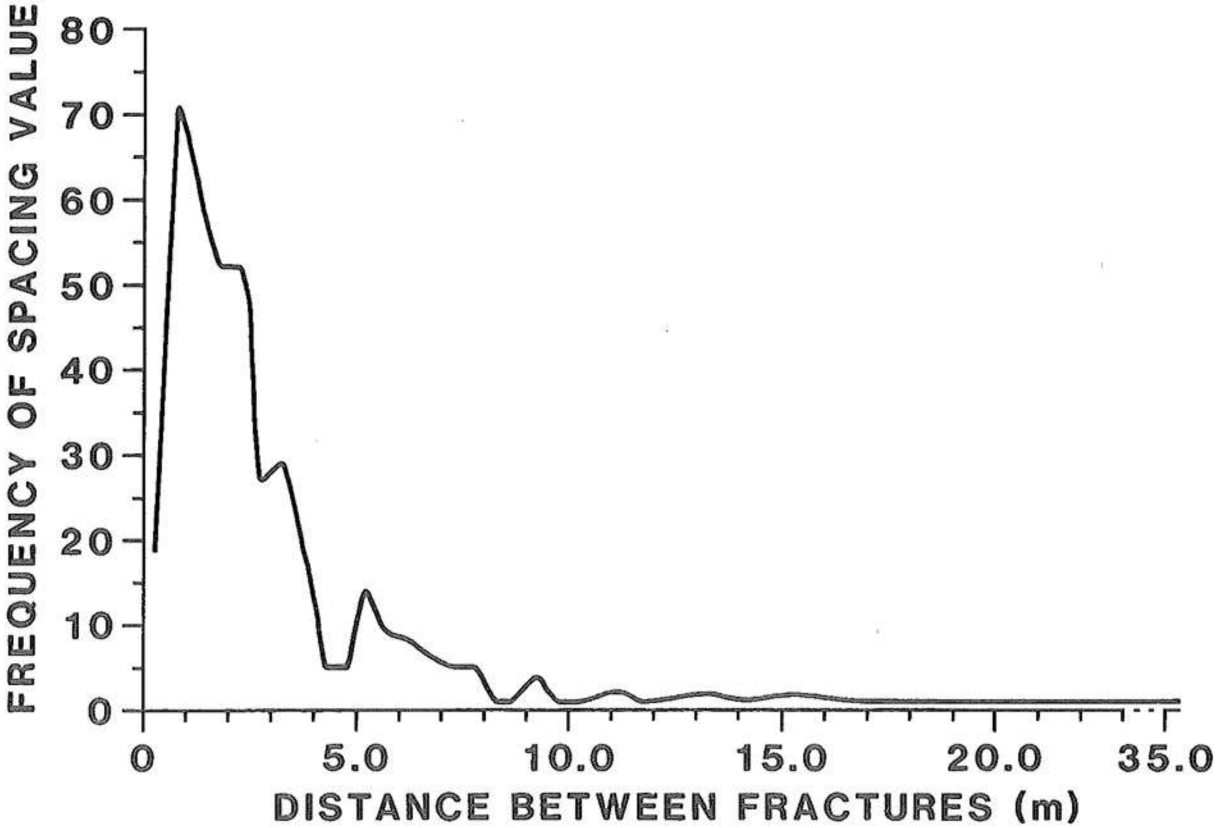


Figure 2-38: Fracture Spacing Frequency Value versus Distance between Fractures

At the WL site, a set of boreholes (WN series boreholes) [72] were drilled in the late 1970s to the north of the Waste Management Area provided similar fracture results to what was seen at the URL. This indicates that the fracture zones are not specific to a region of the batholith.

At the WN boreholes, fracture zones were noted between 20 m and 150 m and between 395 m and 400 m. Figure 2-39 shows the fractures encountered in borehole WN1 and WN2, which have dips that range anywhere from subvertical to subhorizontal. More fractures were encountered in WN2 than in WN1 in the upper 150 m. Below 150 m there were very few fractures found and only one open fracture noted in WN1. All of the fractures in the interval 150 m to 375 m in WN1 have dip angles ranging from 10° to 50°, and no subvertical fractures were intersected in this zone [72]. The decreasing number and frequency of fractures with depth is similar to what was found in investigations into the rock mass at the URL.

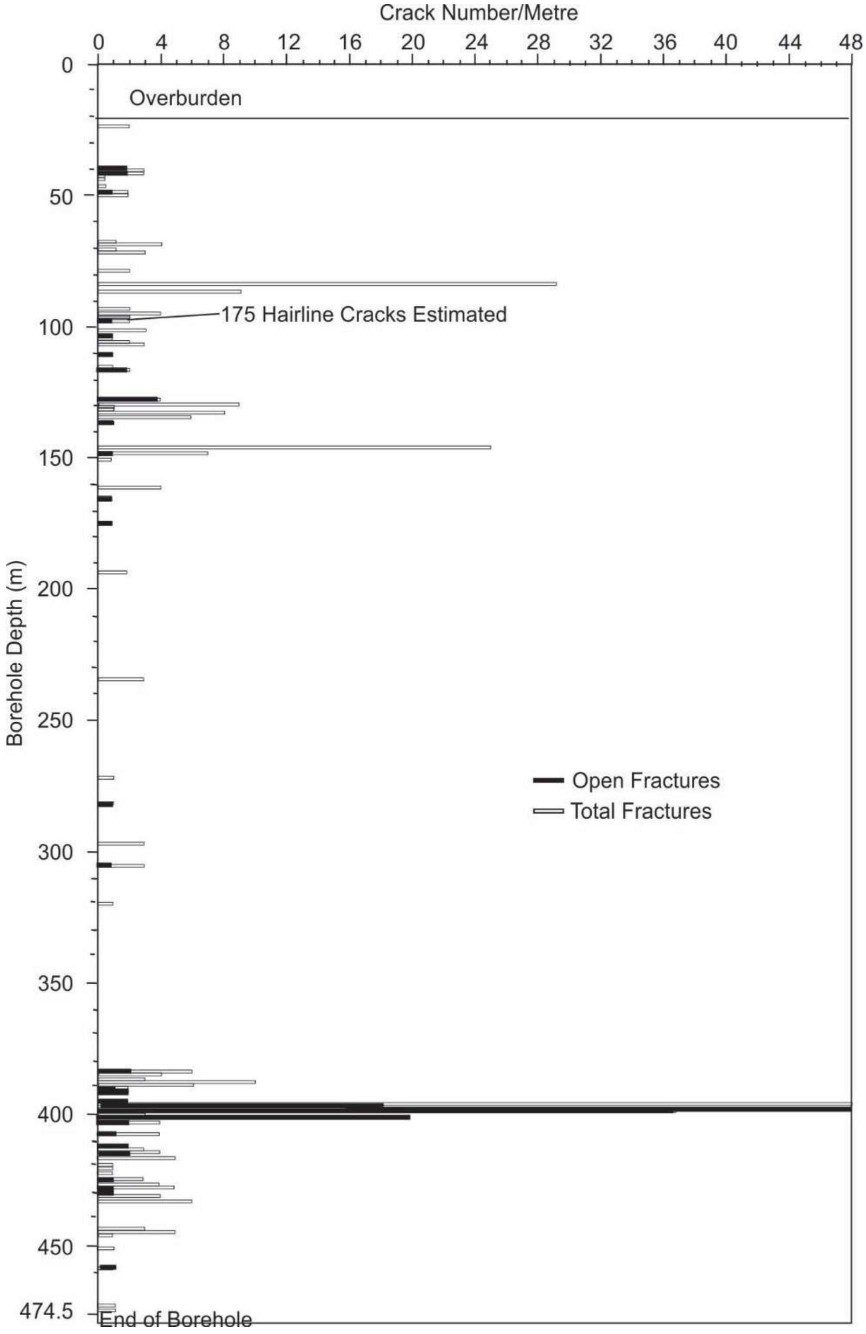


Figure 2-39: Fractures Encountered in Borehole WN1

Davison [72] speculated that all of the fractures below 375 m in WN-1 may be entirely related to the intensely fracture zone which was intersected by WN-1 between 395 m and 405 m. WN-4 was drilled approximately 20 m away from WN-1 (Figure 2-28) and it encountered a corresponding zone of extremely intense fracturing between 377 m and 403 m. This interval contained numerous fractures of various orientations and many of these fractures were considered to be open by the fracture logging techniques. Sub-vertical fractures are rare below a depth of about 200 m, below which they are limited to the margins of low-dipping thrust faults and splays, or to unusual rock types such as dykes [59]. Fracture zones conform to gross mineralogical or structural layering within the rock [73]. The similarities between the WN drill area and URL portions of the Lac du Bonnet Batholith suggest that similar fracture patterns exist in at least the main portion of the batholith.

The pattern of decreasing fractures with depth at the URL location also suggests that the frequency of fractures at the WL site should be accompanied by an overall trend of decreasing fractures with depth occurring even at depth. The dip of the fractures at the WN site was not described, however, assuming a similar average dip to the URL fracture zones of approximately 25° to the east would suggest a sub-overburden exposure east of Winnipeg River. That area is heavily vegetated with no rock surface exposures.

Between 1985 and 1993 a series of boreholes were drilled at various locations across the Lac du Bonnet batholith and in the adjacent gneissic belt to the south [74]. The general pattern of the batholith was the upper part of the rock mass being a pink porphyritic granite hosting moderately fractured rock and fracture zones with thin interspersed domains of slightly fractured rock. The upper pink granite domains are underlain by small domains of sparsely fractured, pinkish grey, greenish grey or grey granite and very large domains of massive, sparsely fractured, grey granite [74].

Given the data available from the WL site for bedrock geology but with the above observations and the general uniformity of the Lac du Bonnet Batholith in terms of fracture frequency in outcrops, there is no indication to expect a difference in intensity or spacing of fractures in the rock underlying the WL site than observed elsewhere on the batholith, nor a large difference in the chemical alteration of fracture zones between the WL site and the URL fracture zones [59]. Boreholes 16-7 and 16-8A suggest a potential fracture zone may exist at the WL main campus based on the presence of red (altered) granite similar to fracture zones at the URL, however, the extent of fracturing is not available. Borehole logging of fractures in Borehole 16-7 [75] indicates the predominant dip direction is northwards. Hydraulic conductivity of the potential fracture zone is unknown, however, assuming conditions elsewhere on the batholith for fracture spacing and fracture zones are maintained, increased hydraulic conductivity in the fracture zone would be expected relative to the surrounding rock mass. At the URL, fracture zones acted as elevated hydraulic conduits without changing overall rock mass permeability.

2.5.5 Lineament Study of the Lac du Bonnet Batholith

Table 2-11: Sources of Information

Feature	Regional Reference	Site/Local Reference
Lineaments, **Faults,** **Magnetic Anomalies,**	D.C. Kamineni, D. Stone, and Z.E. Peterman, Early Proterozoic Deformation in the Western Superior Province, Canadian Shield,	R.A. Everitt, J. McMurry, A. Brown, and C. Davison, Geology of the Lac du Bonnet Batholith, Inside and Out: AECL's Underground Research Laboratory, Southeastern Manitoba

Feature	Regional Reference	Site/Local Reference
	Geological Society of America Bulletin, 102: 1623-1634, 1990.	Field Trip Guidebook B5, Geological Association of Canada/Mineralogy Association of Canada Annual Meeting, Winnipeg, Manitoba, 1996 May 27-29.
	D.L. Trueman, Stratigraphic, Structural and Metamorphic Petrology of the Archean Greenstone Belt at Bird River, Manitoba, Ph.D. thesis, University of Manitoba, Winnipeg, Canada, 1980.	G.F. D. McCrank, A Geological Survey of the Lac du Bonnet Batholith, Manitoba, AECL-7816, 1985.
	H.P. Gilbert, Stratigraphic Investigations in the Bird River Greenstone Belt Manitoba, part of NTS521.5, 6 in Report of Activities 2008 Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, p. 121-138.	H.Y. Tammemagi, P.S. Kerford, J.C. Requelma, and C.A. Temple, A Geological Reconnaissance Study of the Lac du Bonnet Batholith, AECL-6439, 1980.
	D.C. Kamineni, A. Brown, Z. Peterman, and D. Stone, Radiometric Ages, Cooling Rates and Deformation of Two Granitic Plutons in the Superior Province, Canadian Shield, Geological Society of America, Abstracts with Program 22(7): A244, 1990.	
	D. Stone, D.C. Kamineni, A. Brown, R. and Everitt, A Comparison of Fracture Styles in Two Granite Bodies of the Superior Province, Canadian Journal of Earth Sciences, 26: 387-403, 1989.	

Two series of lineament studies were performed in the 1980s on the Lac du Bonnet batholith and on surrounding rock masses. Tammemagi et al. [76] indicated in an initial aerial photo lineament study that no major lineaments were observed in the Lac du Bonnet Batholith, but qualified the statement with a notation that the parallel trends of the Winnipeg River and the Pinawa Channel (Lee River) as they cross the batholith may be more than a coincidence, suggesting a structural control of the river alignments. McCrank [66] performed investigations in fractures and lineaments on and around the Lac du Bonnet Batholith (Figure 2-40 and Figure 2-41) and concurred that although magnetic anomalies do not exactly coincide with the river, courses suggest that there is likely a structural correlation.

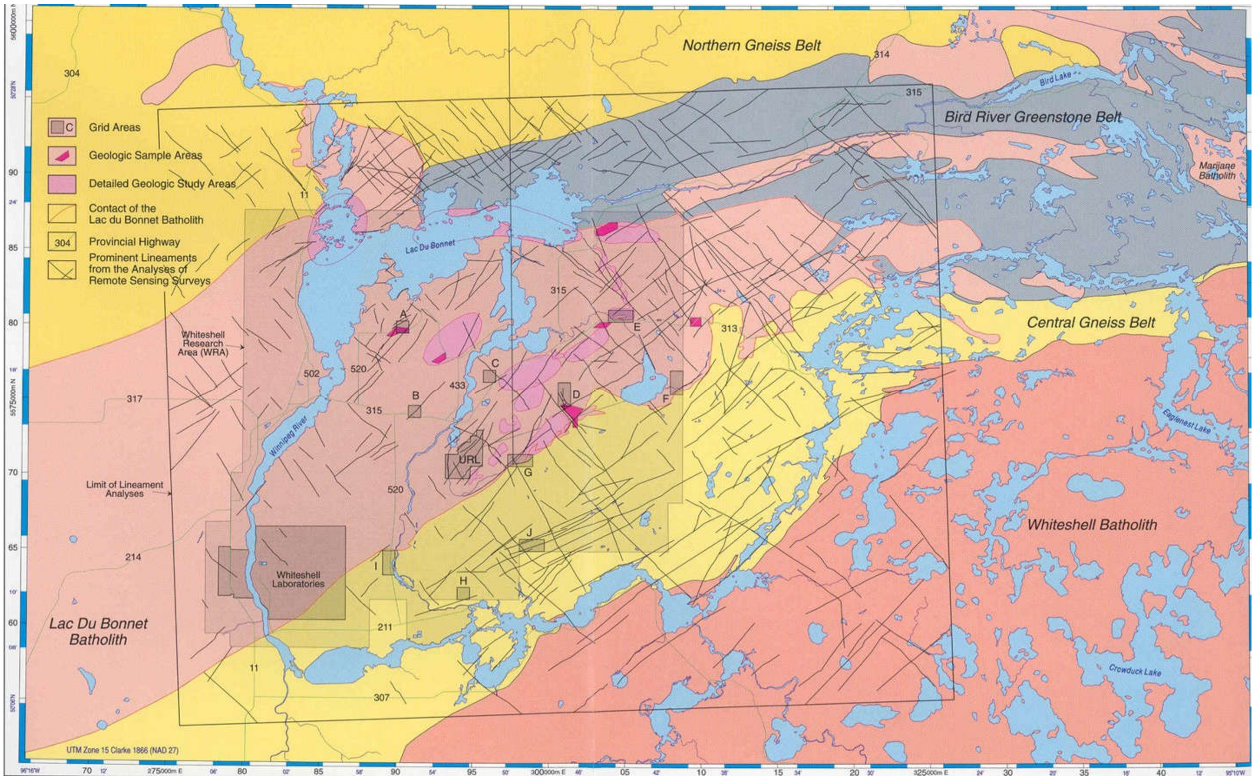


Figure 2-40: Lineament Study Area for Lac du Bonnet Batholith [66]

McCrank [66] discussed the probability that large-scale faults are probably present, though there is little outcrop evidence for their occurrence within the Lac du Bonnet Batholith. Regional large scale faulting is indicated by the one-half kilometre, apparently right lateral displacement of the batholith contact with the Bird River Greenstone Belt along a large northwest-oriented lineament [77]. Another large fault was defined by Trueman [77] and Cerny et al. [78] to the northeast in the Bird River Greenstone Belt. The occurrence of faulting is well known in the Bird River greenstone belt [79].

As described in previous sections of the report, as a consequence of its large volume and its regional setting, the Lac du Bonnet Batholith cooled slowly and responded to deformation in a ductile manner during much of its history of crystallization and cooling [80] [81]. With the exception of some strike-slip faults at the batholith margin, large scale brittle deformation appears to have been limited mainly to metre-scale displacements on chloritic thrust faults (such as the fracture zones encountered at the URL), most of which are concealed by overburden in linear valleys and have low to intermediate east-southeast, east-northeast, or west-north-west dips [62]. It is possible that the fracture zones identified in the WN series holes and the boreholes near the west side of WR-1 more speculatively are of similar nature based on their similar fracture characteristics to the fracture zones found at the URL.

A comparison of the faults identified by McCrank [66] with similarly oriented lineaments, which were identified on Landsat imagery, aerial photographs and aeromagnetic total field and vertical gradiometer field maps [66], indicates the possibility that related faults may be present throughout the batholith and in the surrounding area. These possible faults trend east-northeast and northwest. A third possible fault direction, north-northeast, is indicated by elongate magnetic anomalies, associated areas of high fracture frequency, and by the presence of fracture-filling materials such as epidote, chlorite and calcite [66] (Figure 2-41). These aerial photograph lineaments indicate that the fault may extend to the west along the north shore of Lac du Bonnet and parallel to the northern contact of the batholith. McArthur Falls, a probable fault scarp, is located along this lineament.

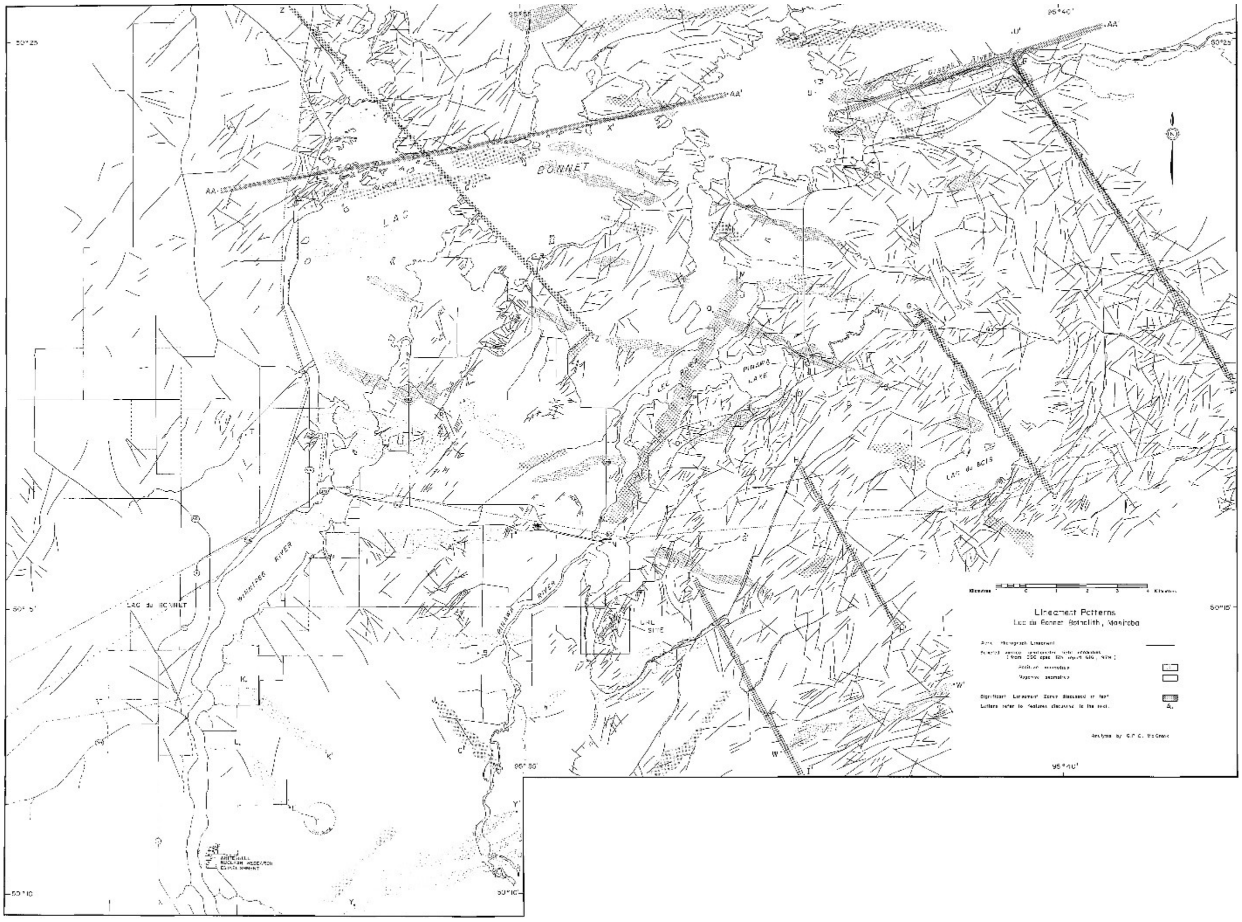


Figure 2-41: Lineaments, Anomalies and Fractures in the Lac du Bonnet Batholith [66]

Except for those features no direct evidence of large-scale faulting was discovered by T.J. Katsube and J.P. Hume [68], but the report did note a similarly oriented lineament, south of the map area in Figure 2-41, which appears to coincide with the most southerly channel of the Winnipeg River and may be a fault scarp, which could be the cause of Seven Sisters Falls. Similarly oriented lineaments faintly visible on the image may be faults responsible for Great Falls, Silver Falls and Pine Falls. There is no evidence that any of these potential lineaments intersects the WL site. This is further suggested by recorded evidence of historic river elevation changes (falls) prior to damming the river as the hydro dams were located at locations were a natural river elevation change occurred.

Faulting is known in the eastern end of the batholith limited primarily to a northwest-striking fault in the eastern part of the intrusion [77] that offsets the northern contact of the batholith and forms a contact between the early leucogranite and the main phase biotite granite [59].

2.6 Economic Geology

Economic geology in the area of the WL site was assessed by consulting regional knowledge of the area, the Manitoba Government website [82], Manitoba Government Publications [83], and various available papers [84]. Mines, quarries and claims can be located using the Province of Manitoba, Growth Enterprise and Trade website [82]. A summary map is provided in Figure 2-42 below.

Industrial materials extraction includes peat quarries (the nearest approximately 20 km to the southwest of the WL site along Highway 44 – Map item (1)), and extensive gravel quarries along Highway 44 and in the Milner Ridge area (which is part of the Sandilands uplands – Map Item (2)) [84]. Dimensional stone has been excavated from the Lac du Bonnet batholith from a quarry (Cold Spring Quarries) that operates west of the WL site across the Winnipeg River (Map Item 3). Other quarries are located at sites further south and east of the WL site (Map Item (4)) [82] [84].

Locally, east of the WMA, on the WL site, excavation of material from the outcropping of basal sand underlying the site is done for site operations (Figure 2-8). This excavation occurs near to the site landfill towards the eastern edge of the site.

The Bird River Subprovince (Bird River greenstone belt) in contact with the north side of the Lac du Bonnet Batholith, hosts several mineral deposits. Deposits include: base metal mineralization of both magmatic and stratigraphic associations; platinum group metals; chromium and rare metals (e.g., tantalum, lithium, cesium and others) [79]. The Bernic Lake pegmatite group, which includes the Tanco mine for rare metals (tantalum, lithium and cesium), is in this area. These pegmatites are collectively part of the Cat Lake – Winnipeg River pegmatite district (Map Item (5)) [85].

Copper and nickel were produced until the mid-1970s at the Maskwa-Dumbarton mine (Map Item (6)) [79]. Near Shatford Lake at the eastern end of the Lac du Bonnet batholith are deposits of garnet bearing rock and an iron formation (Map Item (7)) [79].

Further north in the Rice Lake greenstone belt (Map Item (8)) [86] are economic deposits of gold, including the Bissett mines, and known deposits of massive sulfides hosting iron, copper, zinc and precious metals.

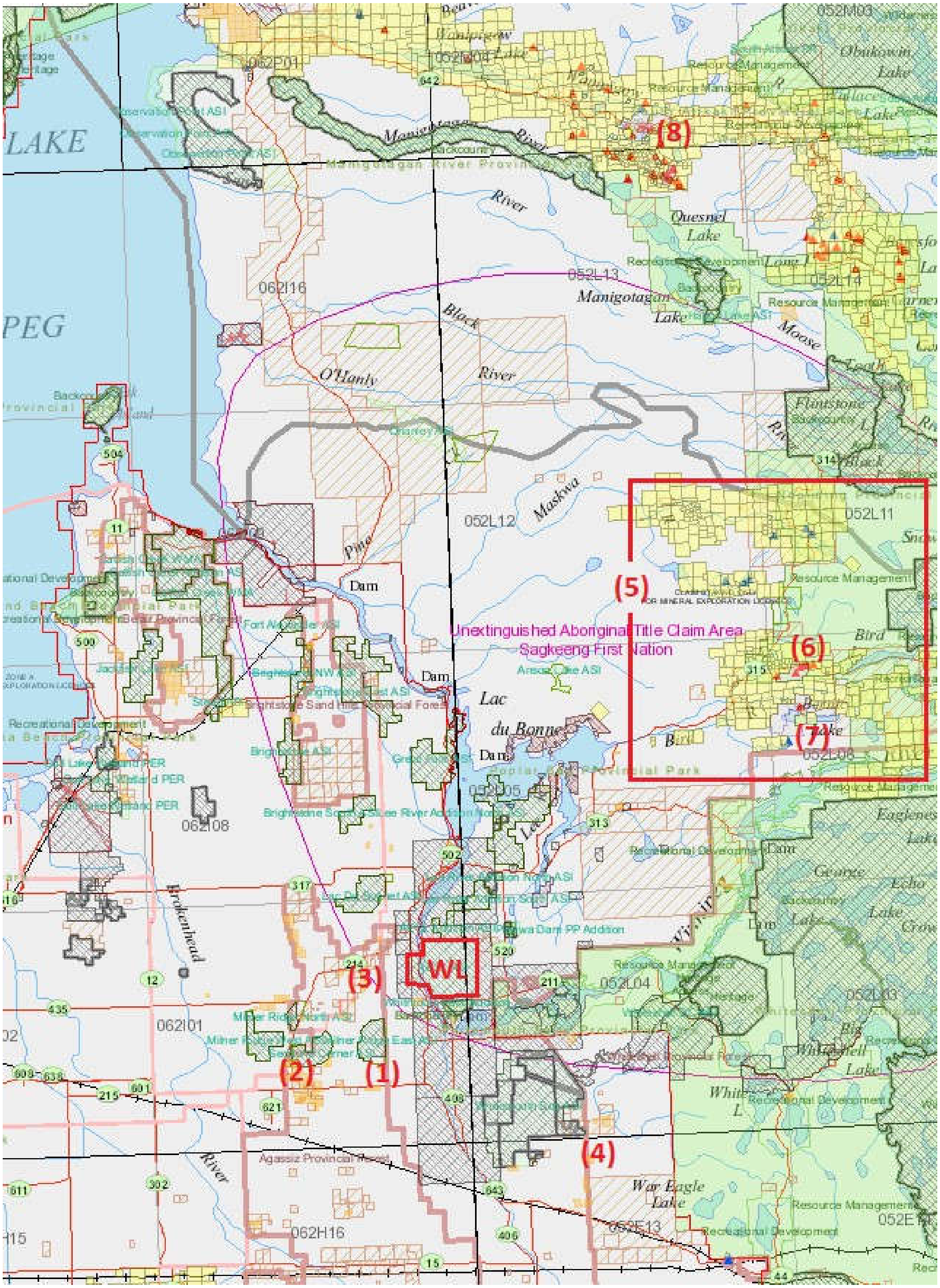


Figure 2-42: Economic Geological Sites in Eastern Manitoba

2.7 Descriptive Geological Model

The above information on physiography and geomorphology, quaternary geology and history, bedrock geology and economic geology are used to interpret and develop a descriptive geological model for the WL site and surrounding area. The descriptive geological model of the WL site includes the following key elements and information:

- The WL site is located on quaternary glacial deposits in southeastern Manitoba. An access road, Ara Mooradian Way, parallels the east shore of the Winnipeg River north from Provincial Road 211. The WL main campus is at the north end of Ara Mooradian Way. Provincial Highway 11 is on the west side of the Winnipeg River approximately 1 km from the river near the WL site. The WL main campus buildings sit on glacial lacustrine lake clay from glacial Lake Agassiz, which formed at the end of the last glacial period (Wisconsinan glaciation). Underlying the glacial lake clay is clay till, which is in turn underlain by a basal sand unit, which sits unconformably atop the Lac du Bonnet batholith Precambrian rock of the Canadian Shield. The WR-1 building lower levels cut through the overburden layers and the base of the building rests on the bedrock. Surface soil types vary across the WL site. The overburden depth is up to 22 m thickness in the sandy upland area near the east side of the WL site, but is roughly 17 m thick at the main campus. The buried bedrock surface has a variable depth. The site is relatively flat but drops approximately 7 m from the ground level at WR-1 to the Winnipeg River. This drop occurs almost entirely at the river bank approximately 500 m from WR-1.
- The bedrock in the local and regional area of the WL site is Precambrian Canadian Shield, specifically the entire site is underlain by the Lac du Bonnet batholith located in the Winnipeg River Subprovince of the Winnipeg River Terrane, part of the Superior Province. The Winnipeg River Subprovince is composed of Mesoarchean metaplutonic rocks variably intruded by Neoarchean plutons. Batholiths and plutons are intrusive magmatic rock formations. The Lac du Bonnet batholith includes five main phases: gneissic hornblende-biotite tonalite (possibly xenoliths), gneissic porphyritic hornblende-biotite granodiorite, gneissic to undeformed leucogranite, biotite granite (the main phase of the batholith), and late-tectonic biotite granodiorite dykes. Outcrops are rare in the vicinity of WR-1 but exposures are present along the river and more extensive outcrops of the Lac du Bonnet batholith occur to the east of site and the rock mass was extensively studied as part of the CNFWMP.
- The relatively sparsely fractured characteristics of large portions of the Lac du Bonnet batholith is attributed at least in part its intrusion at or near the end of regional deformation and to prolonged cooling, which delayed the onset of brittle deformation. This was in part due to the size of the batholith and its proximity to similarly emplaced intrusive bodies. The Lac du Bonnet batholith was emplaced approximately 2.65 billion years ago and it remained distant from later tectonic events in the Superior Province at the end of the Kenoran Orogeny, but the subhorizontal thrust faults (fracture zones) are believed to have been formed as part of the tectonic stresses from that orogeny. At the

site of the URL approximately 20 km from the WL site, extensive studies of the rock mass revealed the presence of shallow dipping (25-30°) short displacement thrust faults, which are termed fracture zones. Alteration of the granite to deeper pink and red along with notable more intense subparallel fractures are characteristic of these zones. Boreholes on the north of the WL site identified more of these fracture zones as did boreholes drilled at various locations across the batholith. Shallow drilling on the WL main campus has shown the presence of fractures and similar rock alteration. Faulting is known in the eastern end of the batholith, which is remote from the WL site.

- Lineament studies were performed in the 1980s for the Lac du Bonnet batholith as was surface mapping of exposed outcrops. Lineaments oriented in a northwest direction are noted to be present on the WL site; due to the amount of overburden it was not possible to discern other lineaments in the bedrock near WR-1. From rock outcrop mapping the most common fracture set trends north-northeast (010° to 040°) and accounts for 28% of the sample population. The southeast set of fractures is oriented from 120° to 140° and accounts for 19% of the sample population. The east and south-southeast sets are less common, and account for 12% and 13% of the sample population, respectively; they comprise fractures oriented from 080° to 100° and 160° to 180°, respectively. With the exception of some strike-slip faults noted in the eastern end of the batholith, brittle deformation appears to have been limited mainly to metre-scale displacements on chloritic thrust faults (such as the Fracture Zone 2 at the URL), most of which are concealed by overburden in linear valleys and have low to intermediate east-southeast, east-northeast, or west-northwest dips. Evidences of fracture zones were found in drilling at the WL site. It is unknown if a preferentially oriented fracture is present that would influence groundwater travel time.
- Drilling near the WR-1 location on the WL site indicates similar overburden to what is known elsewhere on the WL site, near the lagoon and WMA with glacial lake clay, clay till and basal sand overlying the Lac du Bonnet batholith. The basal sand is an aquifer that runs under the site from the eastern upland to the river with greater amounts of silt and clay near WR-1. The rock in the vicinity of WR-1 varies from a coarse grained mafic dyke, to a heavily altered granite reminiscent of fracture zones encountered elsewhere in the batholith, with decreasing fractures with depth and increasing quartz content. None of the boreholes in the vicinity of WR-1 extended beyond 29 m depth and the features noted are the previous erosional surface of the batholith before deposition of the glacial sediments.
- Economic geological resources in the vicinity of the WL site includes aggregate pits, dimensional stone quarries and somewhat more remote mining for rare metals. An aggregate pit for use in site operations is present on the east side of landfill site.
- Primary uncertainties in the geological model are the potential for the presence of a fracture zone towards the Winnipeg River, an understanding of structural controls on the river trace, and the impact of bedrock topography on basal sand-bedrock transport. Some of this uncertainty may be reduced through further determination of fracture orientation and dips in the existing cores obtained from WL site and consideration of that potential in numerical modelling.

3. Hydrogeology

Table 3-1: Sources of Information

Feature	Regional Reference	Local Reference	WR-1 Site Reference
Hydrogeology	R.N. Betcher, M. Gascoyne, and D. Brown, Uranium in Groundwaters of Southeastern Manitoba, Canada, Canadian Journal of Earth Sciences, Volume 25, pages 2089-2103, 1988.	W.D. Robertson and J.A. Cherry, Review of the Hydrogeology of the Radioactive Waste Management Site, 1985 February.	WLDP-26000-REPT-004, WR-1 Hydrogeological Study Report. 2018 November.
	R. Betcher, G. Grove, C. Pupp, Groundwaters in Manitoba: Hydrogeology, Quality Concerns, Management, National Hydrology Research Institute Environment Canada, Contribution No. CS-93017, 1995 March.	WLDP-03704-ENA-009, Atomic Energy of Canada Limited, Hydrogeology of the Waste Management Area, Lagoon and Landfill-Enhanced Monitoring Program, 2008 March.	WLDP-03704-041-000, Environmental Assessment Follow Up Program – 2015 Hydrogeological Assessment for Annual Safety Report.
			WLDP-03704-041-000, Environmental Assessment Follow Up Program – 2016 Hydrogeological Assessment for Annual Safety Report.
			WLDP-03704-041-000, Environmental Assessment Follow Up Program – 2017 Hydrogeological Assessment for Annual Safety Report.

Feature	Regional Reference	Local Reference	WR-1 Site Reference
			WLDP-03704-041-000, Environmental Assessment Follow Up Program – 2014 Groundwater Assessment Report.

3.1 Summary of WL Local Site Hydrogeology

Observed groundwater elevations indicate that the horizontal groundwater flow is predominately from the northeast to the southwest across the WL site, and reflected in each stratigraphic unit. The results confirm previous observations and hypotheses: the WR-1 building is situated in an overburden recharge area, with groundwater flow westward towards the Winnipeg River. The more permeable basal sand deposits and shallow fractured bedrock have similar hydraulic characteristics, which indicates likely connectivity between the two units, and together these units represent the predominant subsurface hydraulic pathway for groundwater across the WL property [16]. Connection between the basal sand and bedrock is also indicated by results from extensive groundwater measurements at the WMA [7] [8] [9].

The majority of past hydrogeological efforts focussed on the WMA [32] or on the landfill and lagoon areas [10] [36].

Groundwater flow in the WL area, and in the vicinity of WR-1, is predominantly in an east to west direction, originating from a recharge area associated with the topographic high at the WL landfill in the east portion of the site, and flowing west towards the Winnipeg River. The recharge and discharge locations along the groundwater flow path of this flow system are controlled by climate, topography, and other hydraulic factors such as the variations in the permeability and/or thickness of the hydrostratigraphic units. Figure 2-11 provides a cross section of the groundwater flow section from the eastern upland recharge area through the WMA and lagoon towards the Winnipeg River [10] [32].

Water levels along the Winnipeg River are controlled by Manitoba Hydro dams at elevations of 275 m to the east, 273 m to the south, and 254 m to the west and north. The river is assumed to provide stable hydrological conditions on these boundaries of the WL property. The potential regional influences on the hydrogeology include precipitation, Winnipeg River levels, and the Seven Sisters Dam forebay levels in Natalie Lake [10].

3.2 Summary of WR-1 Site Hydrogeology

Hydrogeological information for the WL Main Campus site around WR-1 is described in [16] but is briefly summarized in this section.

The water table at the WL main campus is shallow and moderately replicates the surface topography, but is influenced by draw down from collection in building sumps. Horizontal groundwater gradients observed are consistent across the site and horizontal groundwater flow is anticipated to be dominated by the more permeable basal sand unit immediately above the bedrock, and the fractured bedrock zones [16]. Deep boreholes north of the WMA indicate there are fracture zones on the WL site and indications in the shallow bedrock holes near WR-1 suggest that there may be a fracture zone based on similarities of rock type in other fracture zones on the batholith. The impact of potential fracture zones on water movement at the basal sand-rock interface is one of the key uncertainties identified, however it is assumed that the basal till - rock interface is the primary pathway.

Groundwater conditions at the WL main campus were evaluated in 2015 and 2016, and updated with 2017 and 2018 monitoring data. The groundwater elevations indicated that the groundwater levels in the monitoring wells have stabilized in the fall of 2016 and experienced subsequent seasonal fluctuation in the 2017/18 period, as per the WR-1 Hydrogeological Study Report [16]. Site-wide groundwater levels indicate a general direction of horizontal groundwater flow through the basal sand unit and shallow bedrock south-westwards towards the Winnipeg River; however there are indications of a localized flow reversal to the east around WR-1 building during drier years, likely resulting from the operation of WR-1 sumps at the bedrock/basal till interface. This condition was modelled in the Groundwater Flow and Solute Transport Modelling Report [37] which simulated the groundwater elevations based on the hydrostratigraphic soil information and actual volume of water collected by WR-1 sump system. The simulated groundwater elevations were close to the actual measured groundwater elevations indicating that the hydrogeological model was calibrated to the site conditions and validated the assumption that the basal till/upper bedrock interface is the primary groundwater pathway. General vertical trend is a downward vertical gradient across the site and through the hydrostratigraphic layers. There is a slight upward gradient from the shallow bedrock to the basal sand layer in the vicinity of WR-1; however, this is assumed to be influenced by the operation of WR-1 sump system depressurizing the basal till layer directly above the shallow bedrock. The 2019 Hydrogeological Assessment supplemented the 2016-2018 data and confirmed that the predominant groundwater movement across the WR-1 site is from east to west, with the exception of sump pump drawdown flow reversal at the WR-1 building [11].

Single well pump tests were conducted in the new main campus wells to obtain estimates of the hydraulic conductivity. The average value obtained for the glaciolacustrine clay at the main campus was 1.88×10^{-7} m/s, values were calculated to range from 2.32×10^{-6} m/s to 1.80×10^{-10} m/s. Higher values are associated with sand lenses and layers encountered in some of the boreholes. The average value for clay till unit was calculated to be 1.69×10^{-8} m/s ranges from 5.76×10^{-8} to 8.61×10^{-11} m/s. The hydraulic conductivity values of the basal sand unit in the area surrounding the WR-1 site ranged from 1.0×10^{-7} m/s to 2.7×10^{-9} m/s, averaging 7.25×10^{-8} m/s and were not as high as estimates in the vicinity of WMA and lagoon (10^{-5} to 10^{-7} m/s). It is inferred that the basal sand unit contains more fine-grained silt and clay materials in the vicinity of WR-1 than at the lagoon or WMA areas.

It is assumed that the backfill surrounding WR-1 (Figure 3-1) provides a preferential hydraulic connection between ground surface and the basal sand and bedrock units. The flow model of the site assumes that the basal sand unit acts as a pathway for lateral groundwater flow and contaminant migration from WR-1. Fractures in the shallow bedrock also likely enhance groundwater flow and solute transport, which may also likely act as a hydraulic connection between the vicinity of WR-1 and the Winnipeg River. Deep migration in the bedrock is not expected to be an active pathway because of the characteristics of the basal sand and shallow bedrock units [16].

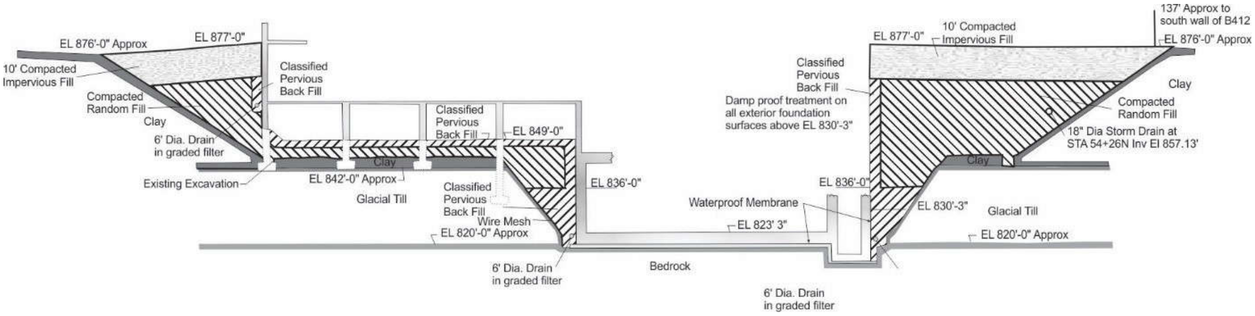


Figure 3-1: Cross Section of WR-1 Foundation Showing Expected Arrangement of Backfill

3.2.1 Groundwater Chemistry

The wells installed on the WL main campus were sampled for groundwater chemistry [16]. Initial sampling showed sulphate levels ranging from 180 to 2500 mg/L; this is similar to values from groundwater well testing performed at the WMA from 2007 to 2017 (Figure 3-2). The values of sulphate reach levels that are known to promote sulphate attack on concrete (Table 3-2). The calcium (63 to 461 mg/L), magnesium (88 to 323 mg/L), and pH (7.11 to 8.67) are also similar to the chemistry seen in groundwater wells at the WMA [8] [9] [10].

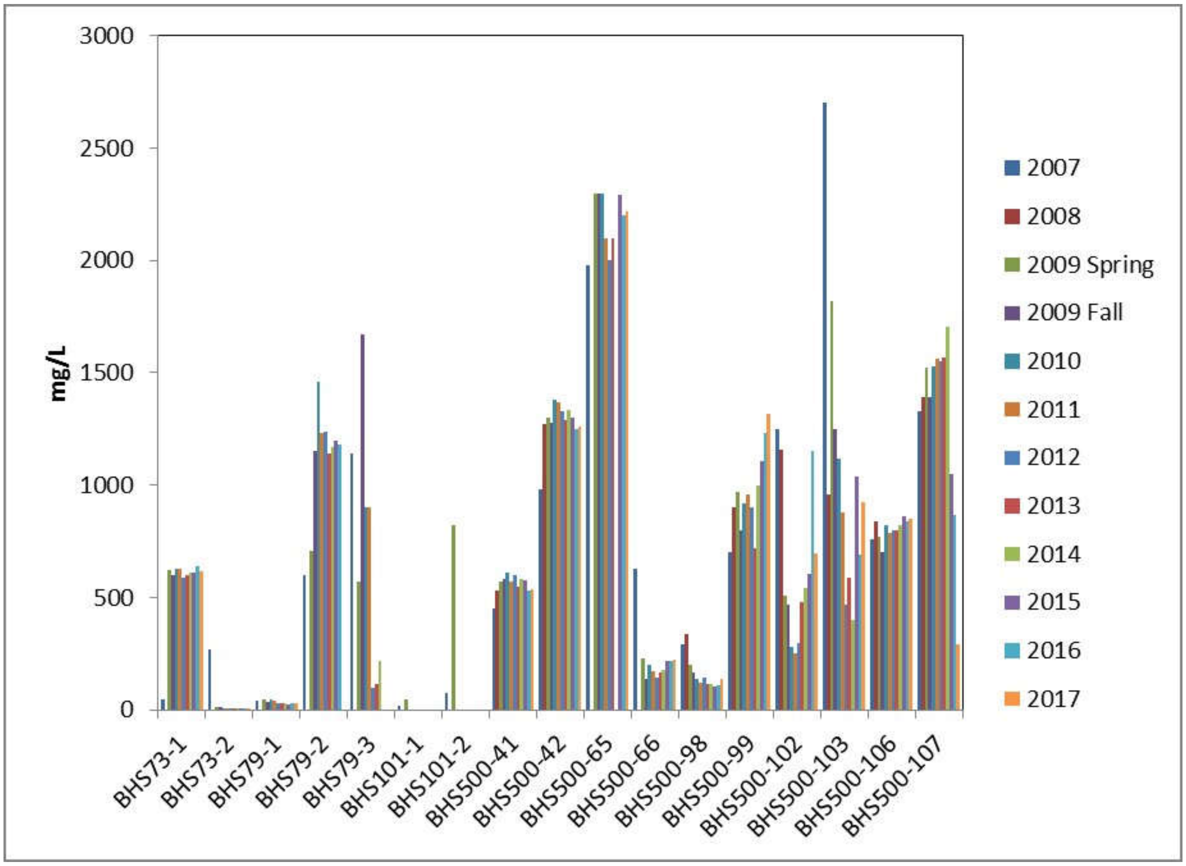


Figure 3-2: 2007 to 2017 Groundwater Sulphate Results from WMA Borehole Site Wells

Table 3-2: Groundwater Sulphate Levels and Recommended Concrete Parameters

Class of exposure	Degree of exposure	Water soluble sulphate in soil (SO_4) by %	Sulphate (SO_4) in groundwater mg/L	Minimum specified 28-day compressive strength (MPa)	Maximum water to cement ratio
S-1	Very severe	Over 2.0	Over 10,000	35	0.40
S-2	Severe	0.2 - 2.0	1500 - 10,000	32	0.45
S-3	Moderate	0.1 – 0.2	150 - 1500	30	0.50

There is no notable radiological component in the initial water samples taken on the WL main campus [16]. Only one well, 16-6F located to the northwest of WR-1 as part of nest 4, showed a slightly elevated alpha reading of 41 ppb. Slightly elevated alpha readings are to be expected as local well waters within the Canadian Shield contain naturally occurring uranium (>100 ppb) and therefore elevated alpha readings are not unexpected [87] [88]; however, in general as at the WMA [9] most uranium values are low.

3.3 Descriptive Hydrogeological Model

The information gathered from WL main campus groundwater wells, existing knowledge of groundwater flows in the WL site, and regional hydrographic conditions has provided input to develop a descriptive hydrogeological model for the WL site, which includes the following information:

- The groundwater flow at the WL site is influenced by regional, site wide, and local systems. Regional systems are dominated by river levels in the Winnipeg River and lakes created and influenced by hydro dams. This influence suggests that the fracture network of the batholith plays a role in the groundwater head levels rock that in turn influences the head gradients in the overlying sediments.
- Site wide systems are based on flow in the quaternary sediments overlaying the bedrock. A topographic high to the east of the WMA (i.e., high hydraulic gradient) appears to dominate the flow direction across the WMA, lagoons and perhaps the WL main campus. Flow is in general westwards from that point towards the Winnipeg River.
- Preliminary measurements on the WL main campus indicates flow direction dominantly is towards the Winnipeg River. The backfill materials around WR-1 are expected to form a conduit to the Basal Sand unit which would be the primary flow path towards the river. Fractures in the rock mass are expected to locally influence flow and flow direction but the overall trend towards the river is expected to dominate.
- The available geological and hydrogeological data for the WL site indicate that hydrogeology of the WL main campus can be described with reference to four units: clay, clay till, basal sand and the upper fractured bedrock.
- WR-1 is nearly entirely within the quaternary overburden sediments and its base rests on the bedrock; the lowest point, the sump area, was cut into the bedrock. The sediments are about 57 ft (17 m) thick at WR-1. The hydraulic conductivity of the Basal Sand unit averaged 7.25×10^{-8} m/s in initial testing at the WL main campus, which is lower than what has been noted elsewhere on the site in the vicinity of WMA and lagoon (10^{-5} to 10^{-7} m/s).
- The basal sand is the oldest quaternary unit deposit and has been assumed to be the primary transport path along the bedrock interface with the upper bedrock rock and basal sand having similar characteristics at the WMA. Site-wide groundwater conditions through the WR-1 site (evaluated in 2015, 2016, 2017, 2018 and 2019) indicate horizontal groundwater flow through the basal sand unit and shallow bedrock westwards towards the Winnipeg River [11]. The basal sand is considered a sand till but was noted to have an increased clay fraction from borehole logging at the WL main campus. Porosity and specific storage were not available from the initial sampling results on the WL main campus.
- The clay till is the second oldest quaternary unit deposit and the permeability was found on average to be lower in average hydraulic conductivity at 1.69×10^{-8} m/s than the overlying clay unit with an average hydraulic conductivity of 1.88×10^{-7} m/s. The

hydraulic conductivity of the clay unit is in part due to the presence of sand lenses encountered by some of the boreholes.

- The initial results of the groundwater testing at the WL main campus showed total dissolved solids (TDS) of 600 to 2500 mg/L. The groundwater type from the initial results showing both bicarbonate-sulphate from anion analysis and the cation analysis showed a predominately calcium-magnesium water type. Gross beta and gross alpha activity in overburden groundwater are low but exceeds Health Canada drinking water quality guidelines or screening levels of 0.5 Bq/L for gross alpha and 1.0 Bq/L for gross Beta due to presence of naturally occurring uranium and daughter isotopes in the groundwater.
- Some elevated sulphate readings have been noted in WL main campus wells as is the case elsewhere on the WL site. Elevated sulphate can lead to sulphate attack on concrete.
- Observed groundwater elevations indicate that the horizontal groundwater flow is predominately from the northeast to the southwest across the WL property, and reflected in each stratigraphic unit. The results confirm previous observations and hypotheses: the WR-1 building is situated in an overburden recharge area, with groundwater flow westward towards the Winnipeg River.
- Despite dry conditions and the heterogeneity of the basal sand unit with large boulders, cobbles, sand, silt, and clay layers intersected in most of the recently drilled boreholes, overall results from 2015, 2016, 2018 and 2019 indicate horizontal groundwater flow through the basal sand unit and shallow bedrock westwards towards the Winnipeg River. The results are still influenced locally (at Nest 2) by the drawdown cones of the structures, especially WR-1 sumps. The hydrogeochemistry is based on a single set of samples for the WL main campus that does compare favourably to the WMA.

4. Geomechanical Framework

Table 4-1: Sources of Information

Feature	Regional/General Reference	Local Reference	WR-1 Site Reference
Overburden Mechanical Properties	R.A. McPherson, Pleistocene Stratigraphy of the Winnipeg River in the Pine-Falls-Seven Sisters Area; M. Sc. thesis, University of Manitoba, Winnipeg, Manitoba, 61 p., 1968.	W.D. Robertson and J.A. Cherry, Review of the Hydrogeology of the Radioactive Waste Management Site, 1985 February.	Shawinigan Engineering Company, Shawinigan Engineering Report 2410-2-60, Report on Proposed Site for Whiteshell Nuclear Research

Feature	Regional/General Reference	Local Reference	WR-1 Site Reference
			Establishment for Atomic Energy of Canada Limited, 1960.
			WLDP-35000-041-000-0014, KGS Group, Whiteshell Laboratories Projects Branch Comprehensive Final Report on Installation of 7 Groundwater Monitoring Wells Nests, 2016 March.
Bedrock Mechanical Properties	A. Annor, The Effects of Pressure and Temperature on the Permeability and Porosity of Selected Crystalline Rock Samples, Mining Research Laboratories Divisional Report MRL 86-8(INT), 1986.	R. Jackson, Anisotropic Properties Study of Lac du Bonnet Granite Specimens: Report #7 MRL 92 060(TR), 1992.	
	D.U. Deere, A.J. Hendron, F.D. Patten, and E.J. Cording, Design of Surface and Near Surface Construction in Rock, in Failure and Breakage of Rock, proc. 8th U.S. Symp. Rock Mech., (ed. C. Fairhurst), pp. 237-302, New York: Soc. Min. Engrs, Am. Inst. Min. Metal, 1967.	J.S.O. Lau, Biaxial Tests of Some Overcored Samples from AECL'S Underground Research Laboratory, Lac du Bonnet, Manitoba, Mining Research Laboratories Divisional Report MRL 89-55(TR), 1989.	
	D.U. Deere, and D.W. Deere, The Rock Quality Designation	R. Jackson, Dilatational Velocity,	

Feature	Regional/General Reference	Local Reference	WR-1 Site Reference
	(RQD) Index in Practice, in: Rock Classification Systems for Engineering Purposes, (ed. L. Kirkaldie), ASTM Special Publication No. 984, pp. 91-101, Philadelphia, Am. Soc. Test. Mat, 1988.	Young's Modulus, Poisson's Ratio and Uniaxial Compressive Strength for URL-2 and URL-5 Samples, Mining Research Laboratories Divisional Report 82-60(TR), 1992.	
		A. Annor, G. Larocque, and P. Chernis, Uniaxial Compression Tests, Brazilian Tensile Tests and Dilatational Velocity Measurements on Rock Specimens from Pinawa and Chalk River.	
Rock Discontinuities	D.C. Kamineni, D. Stone, and Z.E. Peterman, Early Proterozoic Deformation in the Western Superior Province, Canadian Shield, Geological Society of America Bulletin, 102: 1623-1634, 1990.	C.C. Davison, Physical Hydrogeology Measurements Conducted in Boreholes WN-1, WN-2 and WN-4 to Assess the Local Hydraulic Conductivity and Hydraulic Potential of a Granitic Rock Mass, Atomic Energy of Canada Limited Technical Record, TR-26, 1980.	
	G.F. D. McCrank, A Geological Survey of the Lac du Bonnet Batholith, Manitoba, AECL-7816, 1985.		
	D.C. Kamineni, A. Brown, Z. Peterman, and D. Stone, Radiometric Ages, Cooling Rates and Deformation of Two Granitic Plutons in the Superior Province, Canadian		

Feature	Regional/General Reference	Local Reference	WR-1 Site Reference
	Shield, Geological Society of America, Abstracts with Program 22(7): A244, 1990. D. Stone, D.C. Kamineni, A. Brown, R. and Everitt, A Comparison of Fracture Styles in Two Granite Bodies of the Superior Province, Canadian Journal of Earth Sciences, 26: 387-403, 1989.		
Seismicity	The National Building Code of Canada 2015, National Research Council of Canada. Earthquakes Canada, http://www.earthquakescanada.nrcan.gc.ca//index-en.php		WLDP-26000-021-000, Memo, J. Van Meter to J. Miller, Whiteshell Seismic Hazard.
Liquefaction Potential	R.W. Boulanger, and I.M. Idriss, Evaluating the Potential for Liquefaction or Cyclic Failure of Silts and Clays, Department of Civil and Environmental Engineering, College of Engineering, University of California at Davis Report UCD/CGM-04/01, 2004. State of New York Department of Transportation, Geotechnical Engineering Bureau, Geotechnical Design Procedure: Liquefaction Potential of Cohesionless Soils, GDP-9, 2015. Ohio EPA, Geotechnical and Stability Analyses for Ohio Waste Containment Facilities		WLDP-26000-041-000. KGS Group. Cone Penetration Testing Investigation for Whiteshell Main Campus – Final. 2019 December

Feature	Regional/General Reference	Local Reference	WR-1 Site Reference
	Chapter 5, Liquefaction Potential Evaluation and Analysis, Geotechnical Resource Group (GeoRG) Ohio Environmental Protection Agency Columbus, Ohio 43216-1049.		

4.1 Introduction

The geomechanical framework for the WL site is based on historical site investigation and site characterization work completed at the URL site, and local site characterization work completed in support of the WL construction. As described in preceding sections, specifically Section 2.5, the bedrock geological and lithostructural framework for the WL site is similar to the URL site; therefore, it is reasonable and appropriate to incorporate URL site geomechanical data into the WL site geomechanical framework.

4.2 Overburden Geotechnical Properties

As described in Section 2.4 the regional surficial geology in the area of the WL site comprises deposits of till and both sandy and clay based, glaciofluvial and glaciolacustrine materials. In order of deposition, the bedrock is overlain by basal sand, in turn overlain by clay till and glacial lake clay topped with local organic deposits.

Investigations for the development of the WL site described the clay and clay till with different structural properties, with the clay being highly plastic and the clay till a lower stiffer layer. It was noted that these layers have properties very similar to those reported under the Seven Sisters Dam dikes and elsewhere in Manitoba [12].

In the upper (clay) layer the liquid limit averaged 100%, and the plastic limit 35%. As with similar glaciolacustrine clays in Manitoba, this clay will shrink on drying and will swell when exposed to moisture and is susceptible to frost heave. The plasticity of the soil provides an indication of how much clay will shrink or swell. The higher the plasticity, the greater is the shrink-swell potential (0-15%: low expansion potential, 15-25%: medium expansion potential, 25% and above: high expansion potential) placing the glaciolacustrine clay in the high potential for swelling.

The bearing value of the upper clay is low and Shawinigan Engineering [12] indicated it is suitable only to support very light structures where movement due to changes in moisture content in the soil is unimportant. This soil is very impermeable, particularly in the vertical direction. Due to its varved nature (Figure 4-1), the vertical permeability will be variable, but very low. It was noted that the unit tends to be more permeable near surface due in parts to roots and natural fractures in the clay [32]. In one test hole near the south end of the site a sand layer approximately 0.6 m thick with a slight artesian head was found at approximately 7.5 m depth [12] indicating the potential for localized variability in this naturally occurring deposit.

The underlying clay till layer (Figure 4-2) contains more sand and silt particles than the upper clay. The liquid limit of this soil averaged 29% and the plastic limit averaged 16.6%, and was recommended as sufficiently stiff to support building piles [12], as was done for larger buildings on the WL site. The clay till has a density of 2.0 g/cm^3 and a porosity of 0.23, which indicates a high level of consolidation [32].

Recent testing of the soil from boreholes at the WL site (Figure 4-3) [15] showed the upper silty clay to be greater than 90% silt and clay sized particles, with moisture contents ranging from 25 to 35%. The silty clay also had greater than 90% silt and clay sized particles with an increased clay fraction and moisture contents ranging from 15% to 60%. The clay till had up to 10% gravel sized particles, up to 30% sand and the remainder of the particles in the silt and clay range and moisture contents of 15 to 20%. The basal sand (till) displayed up to 20% gravel, 40% sand and remaining particles sizes from the boreholes in the silt and clay fractions, with moisture contents of 8 to 20%. In general, clay particles are smaller than 0.002 mm, silt particles range from 0.002 to 0.05 mm and sand 0.05 to 5 mm.

At the lagoons to the north of the WL main campus, two soil samples from borehole drilling were analysed for soil grain size (Table 4-2). The sample from 1.8 m depth is a silty clay with 23.6% silt and 75.8% clay content. The other sample from 6.1 m depth of the same borehole is a till with 3.9% gravel and a similar sand, silt and clay content [36].

Results from the WMA show (Table 4-3) the glaciolacustrine clay has a maximum of 89% clay content. Silt layers are also common in this unit and samples submitted for grain size analyses show 15.4 to 59.2% silt content [36]. The clay till unit can also have a significant amount of silt. Particle size analyses of clay till samples show the clay till unit to have a near even distribution of approximately 30% sand, silt and clay (± 5%), and the remaining fraction consisting of gravel or boulders. Two of the clay till samples also had gravel fractions of 13% and 19%.

The basal sand unit, which underlies the clay till, has a variable composition. Cobbles and boulders occur throughout the basal sand unit. The basal sand unit also has bands of clay and silt (a few cm to about 0.5 m thick), and at a few borehole locations, similar bands of clay till were encountered. To illustrate the variable silt/sand content of the basal zone, the silt content for one sample was 69.5%, whereas, the sand content was 51% for another [36].

Figure 4-1: Example of the Varved Nature of the Glaciolacustrine Clay. Erosional exposure along the Winnipeg River near the WL Site, fissuring due to slumping of the clay (Collection of the Author).

Figure 4-2: Example of Weathered Clay Till Erosional Exposure along the Winnipeg River near the WL Site. Some gravel-sized grains are visible (Collection of the Author).

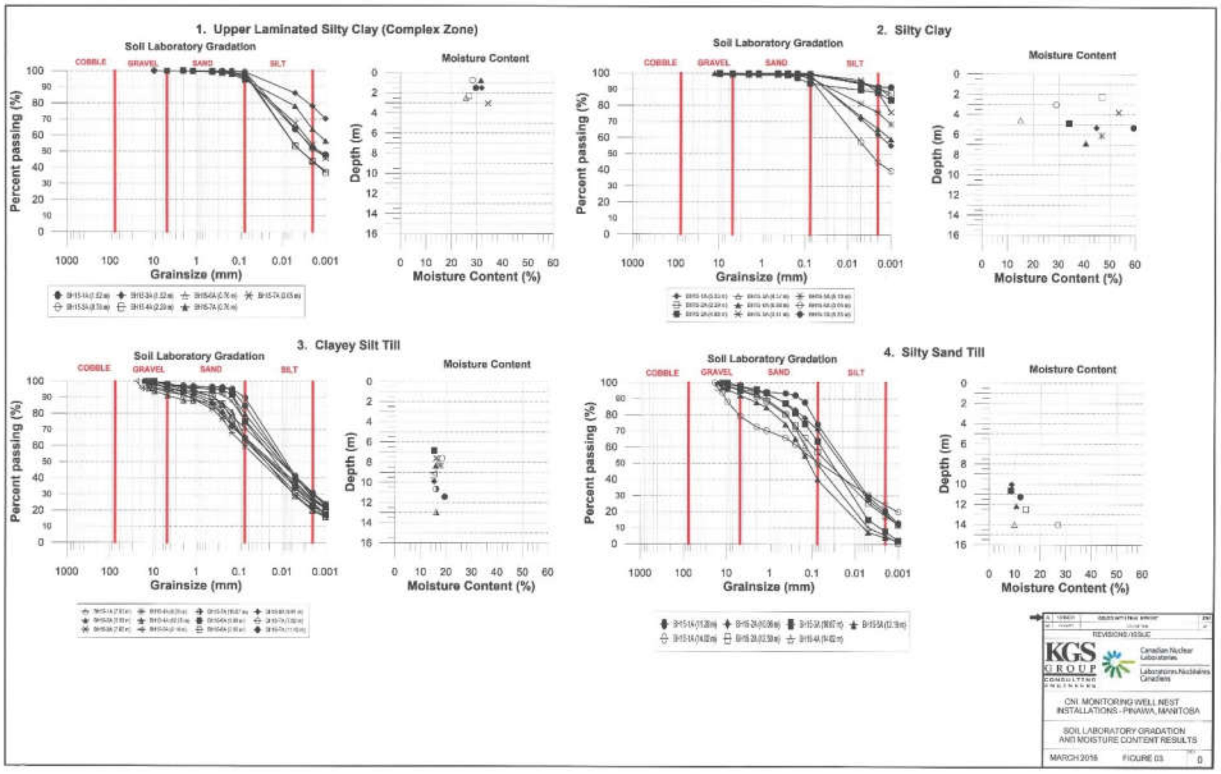


Figure 4-3: Particle Size and Moisture Content from WL Site Well Nest Boreholes [15]

Table 4-2: Soil Grain Size – Lagoon [36]

Location	Sample	Depth (m)	Grain size Distribution (%) Gr	Sa	Si	Cl	Stratigraphic Unit
BHS500-24	AS	1.8	0.0	0.6	23.6	75.8	silty clay
	DB 11	6.1	3.9	30.5	35.9	29.7	silty clay
BHS500-21	DB 1	0.96	0.0	10.6	42.7	46.7	clay silt
	DB 5	3.81	0.0	1.3	10.7	88.0	clay silt
	DB 13	9.9	5.2	29.9	36.5	28.5	till

AS = Auger Sample
DB = Drill Bit
SS = Split Spoon

Gr – Gravel, Sa – Sand, Si – Silt, Cl - Clay

Table 4-3: Soil Grain Size – Waste Management Area [36]

Location	Sample	Depth (m)	Grain size Distribution (%) Gr	Sa	Si	Cl	Stratigraphic Unit
BHS500-31	DB 2	1.5	0.0	2.3	59.2	38.5	silt clay
	DB 6	4.6	2.9	31.9	35.3	29.9	clay till
	AS 8	6.1	2.0	29.9	36.4	31.7	clay till
BHS500-33	AS 3	2.3	0.0	0.6	9.6	89.9	clay
	AS 7	5.3	1.0	45.8	34.3	18.8	clay till
	DB 14	8.4	0.0	30.9	62.3	6.7	till
BHS500-37	DB 2	1.5	0.0	2.1	15.4	82.2	silt clay
	AS 5	3.8	2.4	31.6	37.4	28.6	clay till
	AS 9	6.9	1.4	43.4	26.5	28.8	till
BHS500-39	SS 3	2.0	0.2	13.9	23.8	62.1	clay
	SS 8	4.8	19.2	27.3	28.7	24.7	clay till
	SS 12	7.3	13.0	29.3	30.6	27.1	sandy drift
	SS 17	10.4	0.2	50.6	43.6	5.6	sandy drift
	SS 21	12.8	0.0	3.8	69.5	26.6	sandy drift

AS = Auger Sample
DB = Drill Bit
SS = Split Spoon

Gr – Gravel, Sa – Sand, Si – Silt, Cl - Clay

Field testing of the upper clay unit was conducted for construction of the Shielded Modular Above-Ground Storage (SMAGS) building at the WMA, 2.3 km northeast of WR-1. Based on field Torvane testing, the undrained shear strength of the upper clay was estimated to range from 30 kPa to 75 kPa with an overall average of 46.3 kPa. The moisture content in this layer ranged from 27.1% to 53.1% with an overall average of 35.9% [15]. Two (2) unconfined compression tests were completed on Shelby tube samples extracted from test holes for the SMAGS building. Based on the testing, the clay had undrained shear strengths of 36.1 kPa and 24.5 kPa [89]. Unconfined compression test results tend to under estimate the strengths of expansive clays within the weathered upper crust because the weathering results in a fissured/fractured and “nuggety” structure where unconfined cylindrical samples of the clay fail along the pre-existing fissures and fractures. Torvane test results provide a field measure of the undrained shear strengths in the upper weathered zones [90]. While there will be variation in individual samples and localized variation in any natural deposits, the SMAGS test results give an indication of the expected soil strength results for the upper clay for the site in general.

The WL site away from the river is essentially flat (Section 2.2.2) with limited erosional potential and moderate erosional potential along the river (Section 2.4.3), given the flat terrain slope stability is unlikely to be an issue in the near term for WR-1 as long as the Winnipeg River is controlled by the run-of-river hydro dams.

The glacial lake clay is in general considered nonhomogeneous, anisotropic, active, overconsolidated and fissured [91]. The glacial lake clay and clay till are cohesive soils. Table 4-3 and Figure 4-3 indicate the high clay and silt contents, which are cohesive. Examples of the appearance of the clay and clay till cores are shown in Figure 4-4 and Figure 4-5 respectively. Till can vary widely in composition. The basal till found near WR-1 has an elevated clay-silt fraction (Table 4-3) and has a silty-sand-gravelly appearance in recovered cores (Figure 4-6 and Figure 4-7). It should be noted that larger gravel may not be recovered in cores due to the limit of the core barrel size.

Figure 4-4: Example of Clay Core from Glaciolacustrine Clay Deposit Near WR-1

Figure 4-5: Example of Clay Till Core Near WR-1

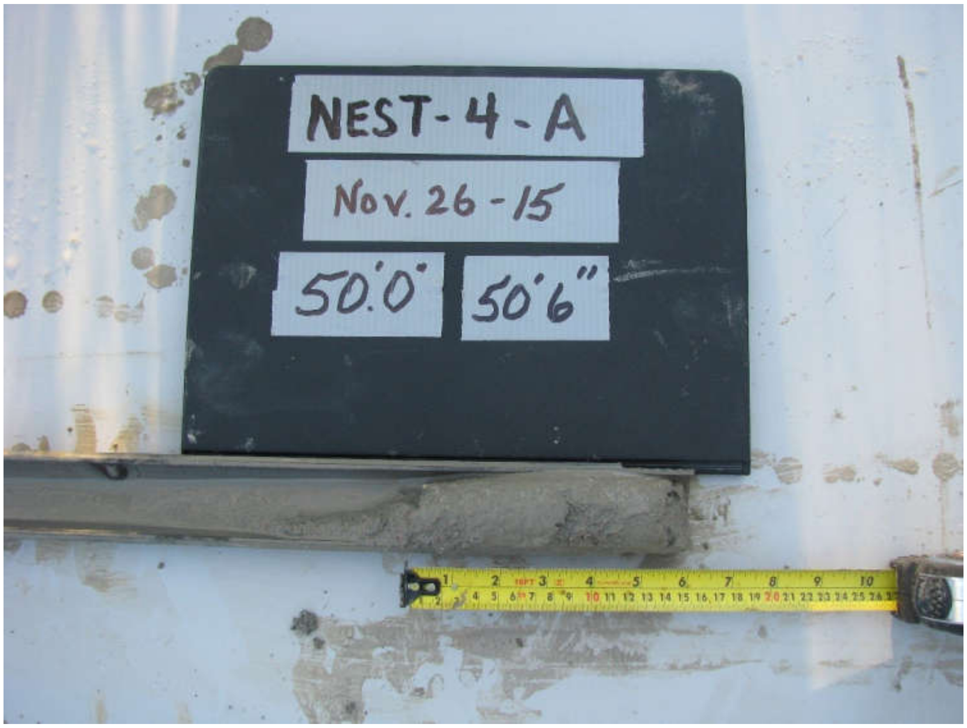


Figure 4-6: Example of Basal Till Core Near WR-1. Note larger grain-sized particles would not be able to be captured in the core barrel.

Figure 4-7: Example of Basal Till Core near South End of Main Campus. Note larger grained-sized particles would not be able to be captured in the core barrel.

4.3 Intact Rock Properties

The rock of the Lac du Bonnet batholith has been extensively studied for rock properties, e.g., [92] [93] [94] [95] [96] [97]. This includes testing from the WL site, the URL site and research areas elsewhere on the Lac du Bonnet batholith [68]. Key intact rock properties, including bulk density, Uniaxial Compressive Strength (UCS), elastic modulus and Poisson's ratio have been investigated and reported for the Lac du Bonnet batholith. A set of intact rock properties of the Lac du Bonnet batholith are provided in Table 4-4.

Table 4-4: Statistical Summary of Uniaxial Strength, Deformation and Acoustic Wave Velocity for Lac du Bonnet Granitic Samples [92]

	Density kg/m^3	**Uniaxial Compressive Strength (MPa)**	**Tangent Young's Modulus (GPa)**	**Poisson's Ratio**	**P-wave Velocity (km/s)**
Number of Samples	258	258	258	258	239
Range of Values	2.54-3.14	75-248	27.40-107.80	0.13-0.44	2.45-6.06
Mean Value	2.64	187	67.05	0.26	4.512
Standard Deviation	0.06	26	7.81	0.05	0.80

4.4 Rock Mass Properties and Rock Quality Designation

The properties that influence short and long-term behavior of the rock mass in response to excavation, are largely a function of the number, orientation and properties of the discontinuities that are present within the rock mass as well as in situ stresses. Discontinuities may include joints, fractures, faults, shear zones, or any other features that intersect an otherwise intact section of rock.

Geomechanical classification of a rock mass is typically completed by calculation of the Rock Quality Designation (RQD) [98]. The RQD is a standard qualitative measure of the rock mass quality calculated as the percentage of intact rock core greater than 100 mm to the total core run length [98] [99]. The RQD value provides an initial estimate of rock mass integrity based on core logs and can be used as a preliminary assessment of rock mass quality (Table 4-5).

Table 4-5: Relationship between RQD and Rock Mass Quality (after Deere et al., 1967 [98])

RQD%	Rock Mass Quality
< 25	Very Poor
25-50	Poor
50-75	Fair
75-90	Good
90-100	Excellent

The Lac du Bonnet batholith is generally of high strength rock; RQD varies by location but away from fracture zones at depth is typically 100% based on core logging. Nearer to the surface joint sets are more frequent (Section 2.5.4) and RQD can be locally reduced. The shallow boreholes drilled on the main campus showed that variable fractures and alteration of the rock near those fractures exists. The following fractures were noted in the shallow bedrock, this does not include rubble zones in the fractures. Examples of core photographs from these boreholes are provided in Figure 4-8 to Figure 4-11. Borehole 16-2E only shows rubblization of core near the rock surface. Borehole 16-4F shows some breaks with limited core loss. Borehole 16-7E shows rubblization near surface and in a potential fracture zone at approximately 23 m from surface. Borehole 16-8A shows several sub vertical breaks along fractures but with only minor core loss. Table 4-6 summarizes the fractures encountered in the shallow rock boreholes on the WL main campus.

Table 4-6: Fractures in the Shallow Boreholes near WR-1

Borehole	Healed Fracture	Dipping Fracture	Fracture Opened by Drill
16-2E	8	3	6
16-4F	9	4	12
16-7E	28	6	1
16-8A	67	16	9

Figure 4-8: Rock Core from Shallow Bedrock Borehole 16-2E. Broken core sections indicate areas of fractured rock, mafic banding, which may be related to a mafic dyke or xenolithic structure, are present.

Figure 4-9: Rock Core from Shallow Bedrock Borehole 16-4F. Mafic rock, likely due to the presence of a mafic dyke, is present.

Figure 4-10: Rock Core from Shallow Bedrock Borehole 16-7E. Zones of Rubblized core indicating fractured rock is present.

Figure 4-11: Rock Core from Shallow Bedrock Borehole 16-8A. Rock shows reddish alteration and dipping fractures.

4.5 Major Discontinuities and Structural Features

The WL site is located on the Lac du Bonnet batholith. Fracturing of the batholith decreases with depth and the majority of the recognized fracture zones are low dipping thrust faults with offsets limited mainly to metre-scale displacements on chloritic thrust faults (such as the Fracture Zone 2 at the URL shown in Figure 2-27). The surface exposures of the thrust faults are mostly concealed by overburden in linear valleys and have low to intermediate east-southeast, east-northeast, or west-northwest dips [62].

Major faulting in batholith aside from these fracture zones is not apparent in the Lac du Bonnet batholith. This is partly as a consequence of its large volume and its regional setting. The Lac du Bonnet batholith cooled slowly and responded to deformation in a ductile manner during much of its history of crystallization and cooling [80] [81] and due to its remote location from most post intrusion orogenic events.

Tammemagi, et al. [76] and McCrank [66] speculated that the Winnipeg River is structurally controlled. The WN boreholes indicate that fracture zones are present on the site [72] and one of the boreholes near the WR-1 location has rock alteration features that suggest the presence of a fracture zone. As described in Section 2.5.4, this is based on the presence of red granite similar to fracture zones at the URL. There is no geomagnetic or geological evidence of a large scale discontinuity or resulting in an offset. Lac du Bonnet batholith rock is present on both sides of the Winnipeg River (Cold Spring Quarry outcrop to the west, an outcrop near Highway 211 and other outcrops to the east of WL) suggesting limited potential for a major discontinuity.

4.6 Seismicity

There are ancient faults identified in and near the Lac du Bonnet batholith that may contribute to local features and perhaps river orientation, however, there is no recent seismic activity in the region. Based on a detection level of 2.5 on the Ritcher scale the WL area and the southern two-thirds of Manitoba are aseismic [100]. Detailed information on earthquakes that have occurred in Canada is contained in publications of Earthquakes Canada of Natural Resources Canada and their predecessor organizations.

A seismic zoning map for Canada has been developed on the basis of these studies and is used in the National Building Code of Canada (NBCC) [101]. The seismic hazard maps are derived from statistical analysis of past earthquakes and from advancing knowledge of Canada's tectonic and geological structure. On the maps, seismic hazard is expressed as the most powerful ground motion that is expected to occur in an area for a given probability level. Contours delineate regions likely to experience similarly strong ground motions. Figure 4-12 shows the seismic hazard risk from low to high [102]. Earthquakes Canada provides information on recent and historical earthquakes dating to 1627 (Figure 4-13). The results support the NBCC classification that seismic activity has not been noted or recorded in Manitoba over nearly a 400 year period, since record keeping and historical knowledge of seismic events was kept.

A seismic hazard analysis was conducted for the WL site [102]. In 1995, the seismic hazard for WL was recognized as being very low. NBCC 1995 recognized the acceleration at Pinawa as 0 g for the probability of exceedance of 0.0021. As the data is sparse, the NBCC 1995 data was not used for comparison purposes. The parameter used to represent seismic hazard for specific geographical locations is the horizontal Peak Ground Acceleration (PGA) value that has a 2% probability of being exceeded in 50 years [101].

The PGA for the 1/1,000 year probability of exceedance for all years from 2005, 2010, and 2015 is respectively 0.035 g, 0.019 g, and 0.017 g.

The PGA for the 0.000404 (defined as the probability associated with 2% exceedance in 50 years) or approximately 1/2500 year probability of exceedance for all years from 2005, 2010, and 2015 is respectively 0.059 g, 0.036 g, and 0.033 g.

The PGA for the 1/10,000 year probability of exceedance conservatively obtained by extrapolation of the 1/1,000 year and 1/0.000404 year for all years from 2005, 2010, and 2015 is respectively 0.131 g, 0.096 g, and 0.092 g [102].

Peak ground acceleration is the maximum acceleration that a rigid structure (has a natural frequency > 33 Hz.) would experience if it was located on bedrock. It is an important reference value when considering the effect of natural frequency and soil conditions on the design/assessment of SSCs (systems, structures and components). Standard shaped spectra Ground Response Spectrum (GRS) may also be created from PGA values to enable design of nuclear SSCs in accordance with CSA N289.3.

The seismic hazard data between 2005 and 2015 is given in Table 4-7. Considering the data from 2005, 2010, and 2015, the trend since 2005 is that for every probability of exceedance the seismic hazard at WL has decreased every year since 2005. For the 1/10,000 year probability of exceedance, the PGA is approximately 0.10 g or slightly less [102].

Comparatively, 0.10 g PGA represents an earthquake of about Moment Magnitude 4.5. This is considered a relatively small earthquake for which one wouldn't expect structural damage for NBCC designed buildings and components. There could be some non-structural damage such as fine cracking of non-ductile non-structural elements (e.g., plaster or drywall). Structures that could experience damage due to this size of earthquake are those located on soils that are susceptible to amplification (e.g., Mexico City) and/or have quite low natural frequencies (comparatively high mass and/or low stiffness). These structures may have characteristics that make them susceptible to earthquakes (i.e., tall structures with no bracing or shear walls, strongly asymmetric geometry, torsionally sensitive (centre of mass is far from the centre of stiffness), or constructed from brittle materials (e.g., unreinforced masonry). Conventionally designed structures using ductile materials (structural steel or reinforced concrete) following good engineering practices that incorporate bracing/shear walls, symmetric geometry, low horizontal eccentricity are not likely to be damaged by this level of earthquake [102].

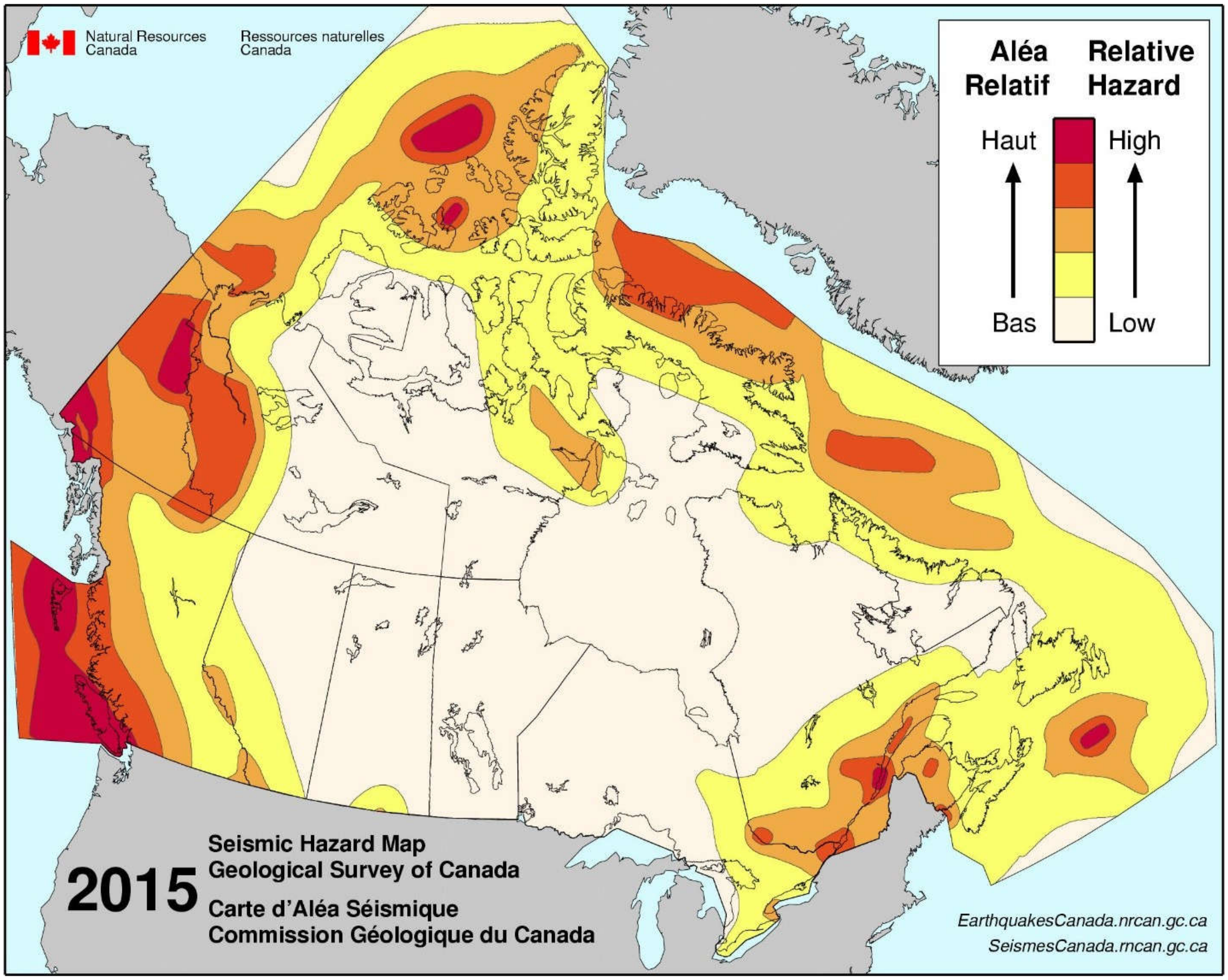


Figure 4-12: Seismic Hazard Map of Canada [103]

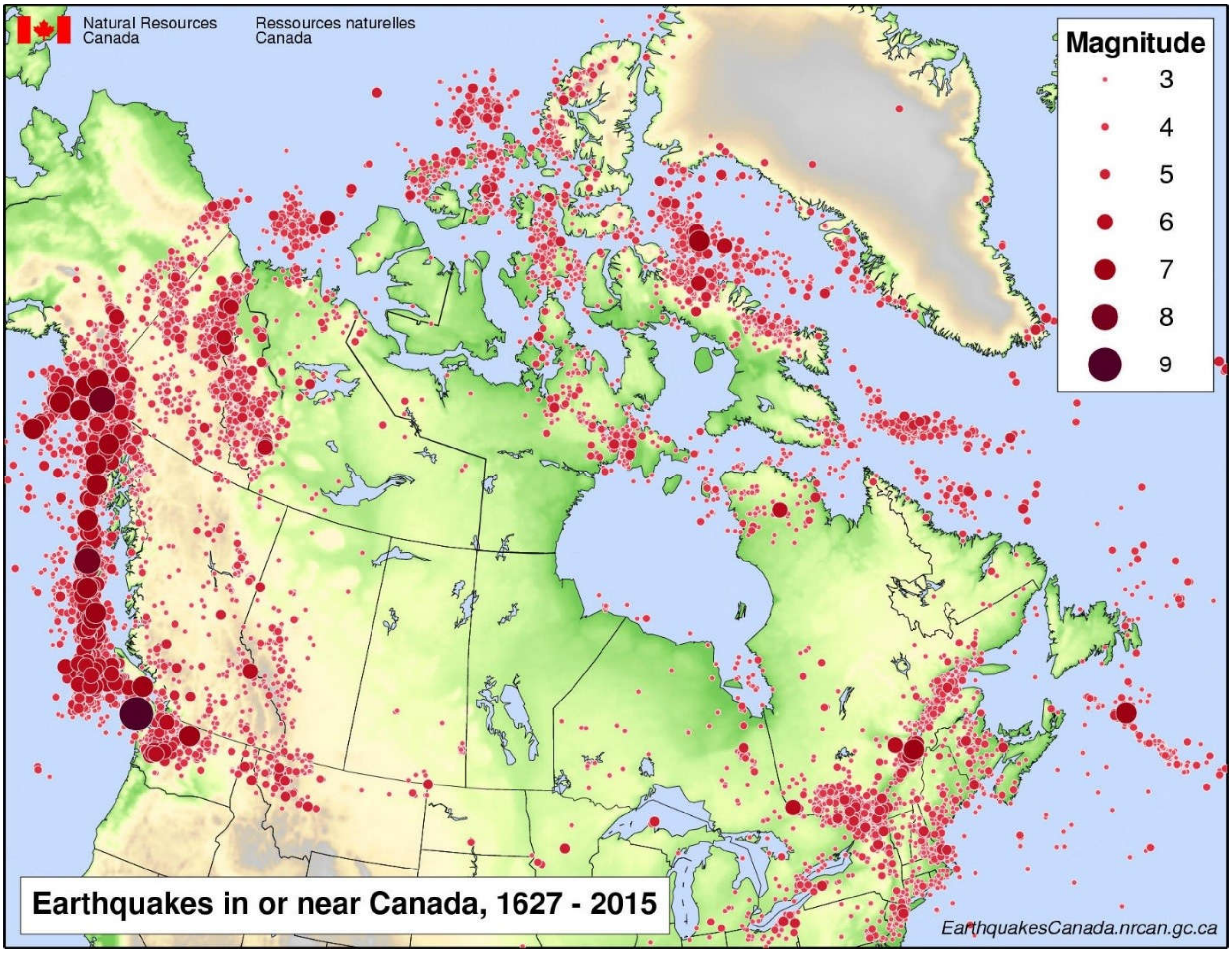


Figure 4-13: Seismic Activity in Canada 1627 to 2015 (Earthquakes Canada) [103]

Table 4-7: WL Seismic Hazard – PGA (g)

	Probability of Exceedance Per Annum				
NBCC Year	**0.01**	**0.0021**	**0.001**	**0.000404**	**0.0001**
1995		0			
2005	0.0066	0.021	0.035	0.059	0.131
2010	0.0032	0.011	0.019	0.036	0.096
2015	0.0019	0.0094	0.017	0.033	0.092

4.7 Liquefaction Potential

Liquefaction occurs when vibrations or water pressure within a mass of soil cause the soil particles to lose contact with one another. As a result, the soil behaves like a liquid, has an inability to support weight and can flow down even very gentle slopes. This condition is usually temporary and is most often caused by an earthquake vibrating water-saturated fill or unconsolidated soil [104]. Liquefaction most often occurs when three conditions are met: loose, granular sediment or fill; saturation by ground water, and strong shaking [104]. A similar process can occur in some types of low plasticity silts and clays termed cyclic loading for strong earthquakes [105]. Liquefaction is possible for cohesionless soils for M=4 to 6 earthquakes, which can produce ground shaking levels up to VIII on the Modified Mercalli Intensity [106]. Several hundred case histories indicate the liquefaction potential in cohesionless soils diminishes tremulously for earthquake magnitudes below 6 and that no lateral spreading is likely to occur in dense to very dense sands if the earthquakes magnitude is less than 8 [106].

The well graded (variety of grain sizes) of the basal sand suggests that pore pressures would be dissipated more rapidly than a poorly graded (similar grain-sized) sand or silty-sand as the variable pore size due to the presence of gravel would allow more rapid dissipation of pore water pressure [106]. The depth of the basal sand is deeper than the 15 to 18 m that would typically be impacted by liquefaction [106], which further suggests the material would be unlikely to liquefy if pore pressure could not be dissipated due to the overlying confining layers [106].

Cohesive (clayey) soils having the following combined properties: less than 15 percent (by weight) of particles smaller than 0.005 mm; a liquid limit less than 35%; and an in situ water content greater than 0.9 times the liquid limit may be susceptible to liquefaction [105].

Liquefaction is further influenced by age of the deposit (younger deposits are more like to liquefy), saturation (at least 80 to 85% saturation is generally deemed to be a necessary condition for soil liquefaction.), depth (shallower layers are more likely to liquefy), and low penetration resistance, less than 15 MPa on a cone penetrometer test [107].

Based on the liquid limits of the clay and clay till having particle sizes that have greater than 15% 0.005 mm, the clay has a liquid limit of 100%, while the clay till has a liquid limit of 29%. The moisture content of both the clay (25 to 35%) and clay till (~15 to 20%) are less than 0.9 of the liquid limit. This indicates the required combined properties are not present for the liquefaction of these soils.

To confirm that liquefaction is not an issue for the WL site, a Cone Penetration Testing (CPT) investigation was commissioned by CNL in 2019 [108]. CPT investigation to the west of the WL main campus indicated shear strength of approximately 60 kPa and shear wave velocity ranging from 130 – 207 m/s with an average of 136 m/s in the upper clay/silty clay layers. In the basal sand (silt till) layer, the normalized average shear wave velocity was measured at approximately 550 m/s. It was determined that under the Peak Ground Acceleration (PGA) value for 1 in 10,000 years, the Factor of Safety for cyclical liquefaction was greater than 3.0. A sensitivity analysis was performed that showed the Factor of Safety decreasing closer to 1.0 under extreme magnitude earthquake (M7.0). In general it was confirmed that the highly plastic clayey overburden soils are not susceptible to liquefaction.

4.8 Descriptive Geomechanical Model

The information on quaternary geotechnical properties and hazards, intact rock properties, rock mass properties, major discontinuities and structural features, seismicity, and seismic hazard assessment given in Section 4.6 are used to interpret and develop a descriptive geomechanical model for the WL site and surrounding area. The descriptive geomechanical model includes the following key elements and information:

- The quaternary deposits consists of three layers: a basal sand (sandy till), overlain by a clay till, which is in turn overlain by a glaciolacustrine clay. The clay has a plastic limit of 35% indicating a high expansion potential and the clay is known to contract when dry and expand when wet. It is considered insufficiently stiff to support large buildings. The clay till has a plastic limit of 16.6% and has a low to moderate expansion potential. It is sufficiently stiff to support piles from buildings.
- The glaciolacustrine clay displayed massive to varved structure and has localized sand seams. The varving is characteristic of seasonally changing deposition.
- Given the low seismic risk in Eastern Manitoba, the overconsolidated nature of the overburden geology and soil properties, liquefaction potential is not considered to be an issue for the WL site.
- The WL site is essentially flat except along the riverbanks where erosion is noted. Erosion risk at WR-1 is low like the rest of the site other than along the riverbanks where erosion risk is medium.
- Intact rock geomechanical properties indicate a strong granite crystalline rock with a density of 2.54 to 3.14 Mg/m^3, uniaxial compressive strength of 75 to 248 MPa, Young's Modulus of 27.40 to 107.80 GPa, Poisson's ratio of 0.13 to 0.44, and P-Wave Velocity of 2.45 to 6.06 m/s.
- The rock mass quality of the Lac du Bonnet batholith overall shows an excellent RQD away from fracture zones. Near surface RQD is high but some core loss and rubblization occurs near surface, and a fracture zone was noted to be present in some boreholes on the main campus.
- The only structural feature of note on the WL site is a fracture zone noted in the WN series boreholes, and rock alteration features and fractures noted in one shallow geology borehole on the WL main campus. The fracture zones encountered in the WN series holes suggests that fractures that could impact groundwater flow are present but their full extent is not known. Joint sets are expected to be present on the buried bedrock surface as they are present elsewhere on the Lac du Bonnet batholith. The course of the Winnipeg River may be structurally controlled but has not been explored through geological investigations.
- Primary uncertainties in the geomechanical model is in the connections of the bedrock fractures in the bedrock on the WL site, however flow is considered to be more likely along the basal sand bedrock interface so a fracture network may play a limited role in hydraulic transport.

5. Future Evolution of the WL Site

5.1 Introduction

This Geosynthesis includes the description of the future natural evolution of a site [3] [104] that has potential to affect the proposed undertaking. For the WL site, impacts from future evolution are evaluated as part of the EIS [1] and the Decommissioning Safety Analysis Report [2].

5.2 Natural Evolution

Natural processes that could affect the WL site in the long term include Winnipeg River flooding, erosion, and glaciation geological disturbances as described in the subsections below.

Geological disturbances are events and hazards assessed as part of future evolution of the WL site and are caused by glaciation, flooding, and potential for long term erosion of the Winnipeg River banks to reduce the length of flow path from WR-1 to the river.

Glaciation is a long term hazard and may not occur for 100,000 years. The rate of erosion is less well understood but in the short term, with the exception of the river banks erosion, potential is limited. Increased intense rainfall events may locally increase erosion rates.

5.2.1 Winnipeg River Flooding – Short Term

The Comprehensive Study Report [14] describes the potential for flooding of the WL site in the short term. Flooding is only possible from failure of the Seven Sisters Dam 7.5 km upstream from the WL site, from a rapid spring melt, ice jams or from extreme precipitation. A rise in river level in response to ice jams or extreme precipitation events is considered an unlikely event. Manitoba Hydro has contingency plans for comprehensive notification, warning, and response systems in case an emergency condition is detected.

The possibility of flooding from a dam failure is considered unlikely, and there has never been a failure of a hydroelectric dam in Canada [107]. The dams along the Winnipeg River are run-of-river type with limited storage. There are a number of dams upstream from Seven Sisters including Slave Falls and Pointe du Bois as well as dams in Ontario that would act to further limit the amount of water available for a flooding event and provide limited storativity. The WL site is elevated above the river level as well. Eastern Manitoba has no recorded seismic activity so the potential for dam failure is limited to failure from lack of maintenance or from extreme rainfalls that cannot be diverted through spillways.

Flood levels of the river at the WL site following a failure of the Seven Sisters Dam were previously estimated to take 1.5 hours to reach a peak at 7 m above normal water levels [14]. This is below the ground level of the WR-1 building, as such, a flooding incident of this magnitude would not flood the WR-1 site; it would affect the shoreline of the Winnipeg River adjacent to the WL site, but it would not flood the WL main campus.

5.2.2 Overland Flooding (Surface Waterflow)

Overland flooding is limited by the low runoff potential from heavy forest, marshes, sedge field and maintenance of site ditches. Two of the drainage ditches on the west end of the site and Provincial Road 211 are considered to be important for reducing surface storage and channel surface runoff directly to the Winnipeg River. One major drainage ditch, potentially diverting surface runoff from the eastern boundary of the WL site, crosses Provincial Road 520 and drains into the Pinawa Channel [1]. Runoff contribution was calculated [1]; it was determined that the peak runoff rate from the WR-1 site study area (0.7 ha) for a 1:25-year rainfall event is 0.012 m^3/s and for a 1:100-year event is 0.014 m^3/s. The runoff volume generated by the WR-1 site study area for a 1:25-year; 24-hour event is approximately 20 m^3 and for a 1:100-year event it is 25 m^3. Flow contribution to the Winnipeg River from the WL site is four or five orders of magnitude smaller than the river average flow. These average flow rates were measured at the nearby Seven Sisters Falls Hydroelectric Generating Station (approximately 7.5 km upstream of the WL site) typically vary between 600 to 1,800 m^3/s with a record low at 125 m^3/s and as high as 2,800 m^3/s [1].

5.2.3 Winnipeg River Flooding – Long Term

The potential for flooding of the WL site in the long term is assessed based on a review of the effects of climate changes to precipitation at the WL site. It does not assess the potential for a dam failure from societal break down. The assessment of climate change and its effect on precipitation at the WL site is provided in the Climate Change Assessment for WR-1 In Situ Decommissioning [109].

According to [110], the north, and southern and central Prairies of Canada will experience more of a warming trend than other regions. Warming is expected to vary seasonally, and will be more pronounced in the winter with nights warming more than days. As warm air can hold more moisture, changes in precipitation patterns and shifts in the frequency and intensity of extreme climate events are expected to accompany this warming [110]. Mean results for Canada show that even under lowered emission scenarios, summer and winter temperatures by the middle of the century are anticipated to warm by about 1.5°C to 2.5°C and 3°C to 7°C, respectively [111].

An analysis of the Pinawa Whiteshell Nuclear Research Establishment Climate Normals Station, located 0.25 km from WR-1 (WNRE; Climate ID 5032162; ECCC 2016), indicated the following [109]:

- an increasing trend in total precipitation;
- an increasing trend in spring total precipitation;
- an increasing trend in summer total precipitation;
- an increasing trend in winter total precipitation;
- an increasing trend in total rainfall;
- an increasing trend in the number of days with greater than 20 mm of rainfall; and
- an increasing trend in average fall temperatures.

Future climate projections were derived using General Circulation Models (GCM) for two time periods, the Mid Term (2041 through 2070) representing near the beginning of the post-closure phase (2024 onwards) and the Far Term (2070 through 2100) representing the continuation of the post-closure phase [109]. Climate projections were also considered for the Long Term (2100 through 3000) described using publicly available literature [109]. These models indicated increasing temperature and precipitation when compared to current climate norms (Table 5-1).

Table 5-1: Climate Normal and Model Projected Means for Annual Temperature and Precipitation Mid (2045-2070) and Long Term (2070-2100) Adapted from [109]

Period	Temperature (°C)		Precipitation (mm)	
	Climate Normal	Projected Mean	Climate Normal	Projected Mean
2041-2070	2.8	5.2	588.3	633.7
2070-2100	2.8	6.0	588.3	647.1

For the Long Term, based on Representative Concentration Pathways (RCPs) described in International Panel on Climate Change (IPCC) fifth assessment report, global temperatures are predicted to rise between 0.6°C and 7.8°C by the year 3000, with an estimated increase in global precipitation of 1% to 3% per degree Celsius of increase in temperature over the period from 2100 to 3000 [109] [112].

Changes in the frequency and/or intensity of extreme weather events are expected to accompany the general warming of surface air temperatures. Increased evaporation will result in more moisture in the air and warmer air can hold more moisture, therefore, more intense precipitation events (i.e., rainstorms and snow falls) are expected. Maintenance of site drainage and the engineered cover would be required to maintain current drainage characteristics of the site.

5.2.4 Glaciation

According to Peltier [113], there have been nine glacial cycles over the past million years in the northern hemisphere with climate variability dominated by the cyclic expansion of northern hemisphere land ice cover. In each such glacial cycle, the glaciation phase has lasted approximately 90,000 years and the deglaciation phase approximately 10,000 years. During the last glacial event, known as the Wisconsinan in North America, the Laurentian Ice Sheet extended over most of northern North America, extending to south of the present day Great Lakes. Glaciation extended over the WL site (Section 2.3) and the last active ice was gone 11,000 years B.P., from southern Manitoba except, possibly, in the extreme northeastern part [27].

Global warming, however, is anticipated to elongate the interglacial period and postpone the next glacial event by tens of thousands of years. The global warming projected until the year 3,000 (0.6 to 7.8°C over 1,000 years) represents a much higher warming rate than the rate seen at the end of the last glacial period (4°C over an estimated 8,000 years) [109] Section 4.3. While global warming may significantly delay the onset of an ice age, long term projections of climate are uncertain so consideration of glaciation is required [109].

Glaciation includes effects such as glacial erosion and deposition of surficial material, glacial loading, permafrost formation, changes in sea level, changes in topography, isostatic adjustment, and post-glacial effects such as flooding similar to historical glaciation that created the current landforms at the WL site [114]. Glacially-induced erosion occurs by abrasion, quarrying, and mechanical erosion by meltwater. Actual erosion of the surface by an ice sheet depends on a variety of factors including the nature of the underlying rock (hardness, permeability, roughness of the surface), hydrology at the base of the glacier, glacier dynamics, thermal regime in the glacier, and topographic relief on the rock [114].

The expected erosion of the Canadian Shield has a range of estimates, for example [115] [116], [117] [118], from several metres to several hundred. Aylsworth and Shilts [119] suggest erosion amounts are influenced by bedrock type, which may in part account for the variability in the other studies.

It is assumed that the previous Wisconsinan glaciation had eroded at least to the batholith bedrock as exposed outcrops around the URL show evidence of glacial advance in the form of abrasion marks and chatter marks from the northeast direction on batholith surface. Based on this it can be assumed that the entirety of the in situ disposal envelope would be removed by glaciation and redistributed with glacial action.

5.2.5 Erosion – Long Term

Erosion is a normal process, and present day erosion of Winnipeg River banks is noticeable in the vicinity of the WL site (see Section 2.4.3). The river banks are noted to have moderate erosion potential while the majority of the site has limited potential [18]. River bank erosion rates can be calculated from flow based erosion [120] if the soil properties are known. The critical shear stress and fluid shear stress and erosion rate are required input parameters that are not available for the soils on WL site, however, anecdotal evidence from the Winnipeg River has shown erosion is ongoing and it is recognized erosion does occur with operation of the hydroelectric dams [121].

6. Summary and Conclusions

6.1 Descriptive Geosphere Site Model

The descriptive geosphere site model of the WL site is outlined below based on the descriptive geological, hydrogeological and geomechanical models given in Sections 2.7, 3.3 and 4.7, respectively. The descriptive geosphere site model of the WL site includes geological, hydrogeological and geomechanical elements.

Geological Elements

- The WL site is located on quaternary glacial deposits in southeastern Manitoba. An access road, Ara Mooradian Way, parallels the east shore of the Winnipeg River north from Provincial Road 211. The main campus is at the north end of Ara Mooradian Way. Provincial Highway 11 is on the west side of the Winnipeg River approximately 1 km from the river near the WL site. The WL main campus buildings included WR-1 site on glacial lacustrine lake clay from glacial Lake Agassiz, which formed at the end of the last glacial period (Wisconsinan glaciation). Underlying the glacial lake clay is clay till, which is in turn underlain by a basal sand unit that sits unconformably atop the Precambrian rock of the Canadian Shield. The WR-1 building lower levels cut through the overburden layers and the base of the building rests on the bedrock. Surface soil types vary across the WL site. The overburden depth is up to 22 m thickness in the sandy upland area near the east side of the WL site, but is roughly 17 m thick at the main campus. The buried bedrock surface has a variable depth. The site is relatively flat but drops approximately 7 m from the ground level at WR-1 to the Winnipeg River. This drop occurs almost entirely at the river bank approximately 500 m from WR-1.
- The bedrock in the local and regional area of the WL site is of the Precambrian Canadian Shield, specifically the entire site is underlain by the Lac du Bonnet batholith located in the Winnipeg River Subprovince of the Winnipeg River Terrane, part of the Superior Province of the Canadian Shield. The Winnipeg River Subprovince is composed of Mesoarchean metaplutonic rocks variably intruded by Neoarchean plutons. Batholiths and plutons are intrusive magmatic rock formations. The Lac du Bonnet batholith includes five main phases: gneissic hornblende-biotite tonalite (possibly xenoliths), gneissic porphyritic hornblende-biotite granodiorite, gneissic to undeformed leucogranite, biotite granite (the main phase of the batholith), and late-tectonic biotite granodiorite dykes. Outcrops are rare in the vicinity of WR-1 but exposures are present along the river, at one location near Highway 211 and more extensive outcrops of the Lac du Bonnet batholith occur to the east of site. The rock mass was extensively studied as part of the CNFWMP.
- The Lac du Bonnet batholith was emplaced approximately 2.65 billion years ago. The fractured characteristics of the Lac du Bonnet batholith are attributed at least in part to its intrusion at or near the end of regional deformation and to prolonged cooling, which limited brittle deformation. This was in part due to the size of the batholith and its proximity to similarly emplaced intrusive bodies. The Lac du Bonnet batholith remained distant from later tectonic events in the Superior Province at the end of the Kenoran Orogeny. Faulting is known in the eastern end of the batholith, which is remote from the WL site. At the site of the URL, approximately 20 km from the WL site, extensive studies of the rock mass revealed the presence of shallow dipping (25-30°), metre-scale displacements on chloritic thrust faults, which are termed fracture zones. Most are concealed by overburden in linear valleys and have low to intermediate east-southeast, east-northeast, or west-northwest dips. These fracture zones act as conduits for groundwater flow. Discolouration of the granite to deeper pink and red along with notable more intense subparallel fractures are characteristic of these zones. Boreholes

on the north of the WL site identified more of these fracture zones. Shallow drilling on the WL main campus has shown the presence of fractures and similar rock alteration that may indicate a fracture zone. There is some speculation that the Winnipeg River trace that turns north as it passes the WL main campus may be controlled by the structural geology of the batholith.

- Lineament studies were performed in the 1980s for the Lac du Bonnet batholith as was surface mapping of exposed outcrops. Lineaments oriented in a northwest direction are noted to be present on the WL site, but due to the amount of overburden it was not possible to discern the probability of other lineaments in the bedrock near WR-1. From rock outcrop mapping, the most common fracture set trends north-northeast (010° to 040°) and accounts for 28% of the sample population. The southeast set of fractures is oriented from 120° to 140° and accounts for 19% of the sample population. The east and south-southeast sets are less common, and account for 12% and 13% of the sample population, respectively; they comprise fractures oriented from 080° to 100° and 160° to 180°, respectively.
- Drilling near the WR-1 location on the WL site indicates similar overburden to what is known elsewhere on the WL site, near the lagoon and WMA with glacial lake clay, clay till and basal sand over lying the Lac du Bonnet batholith rock. The basal sand is an aquifer that runs under the site from the eastern upland to the river. The rock in the vicinity of WR-1 varies from a coarse grained mafic dyke, to a heavily weathered granite reminiscent of fracture zones encountered elsewhere in the batholith, with decreasing fractures with depth and increasing quartz content.
- Economic geological resources in the vicinity of the WL site includes aggregate pits, dimensional stone quarries and somewhat more remote mining for rare metals. An aggregate pit for use in site operations is present on the east side of landfill site.
- Primary uncertainties in the geological model is the potential for the presence of fracture zone towards the Winnipeg River, an understanding of structural controls on the river trace and the impact of bedrock topography on basal sand-bedrock transport. Some of this uncertainty may be reduced through determination of fracture orientation and dips in the existing cores obtained from the WL site.

Hydrogeological Elements

- The groundwater flow at the WL site is influenced by regional, site wide and local systems. Regional systems are dominated by river levels in the Winnipeg River and lakes created and influenced by hydro dams. This influence suggests that the fracture network of the batholith plays a role in the groundwater head levels rock that in turn influences the head gradients in the overlying sediments.
- The available geological and hydrogeological data for the WL site indicate that hydrogeology of the WL main campus can be described with reference to four units: clay, clay till, basal sand and the upper fracture bedrock.
- A topographic high to the east of the WMA appears to dominate the flow direction across the WMA, lagoons and perhaps the WL main campus. Flow is in general

westwards from that point towards the Winnipeg River. The WR-1 building is situated in an overburden recharge area, with groundwater flow westward towards the Winnipeg River.

- Preliminary measurements on the WL main campus flow direction dominantly is towards the Winnipeg River. The backfill materials around WR-1 are expected to form a conduit to the basal sand unit, which would be the primary flow path towards the river. Fractures in the rock mass are expected to locally influence flow and flow direction but the overall trend towards the river is expected to dominate, the effect of the fracture zones is not known.
- WR-1 is nearly entirely within the quaternary overburden sediments and its base rests on the bedrock; the lowest point, the sump area (on the 100 Level) was cut into the bedrock. The overburden deposits are about 57 ft (17 m) thick at WR-1. The hydraulic conductivity of the basal sand unit averaged 7.25 x 10^{-8} m/s in initial testing at the WL main campus, which is lower than what has been noted elsewhere on the site in the vicinity of WMA and lagoon (10^{-5} to 10^{-7} m/s).
- The basal sand is the oldest quaternary unit deposit and has been assumed to be the primary hydrogeological transport path along the bedrock interface with the upper bedrock rock and basal sand having similar form characteristics at the WMA. As of 2016, the initial readings on the main campus wells had not developed fully to demonstrate a similar connection but it is anticipated this will be the case. The basal sand is considered a sand till but was noted to have an increased clay fraction from borehole logging at the WL main campus. Porosity and specific storage were not available from the initial sampling results on the WL main campus.
- The clay till is the second oldest quaternary unit deposit and the permeability was found on average to be lower in average hydraulic conductivity at 1.69 x 10^{-8} m/s than the overlying clay unit, which had an average hydraulic conductivity of 1.88 x 10^{-7} m/s. The hydraulic conductivity of the clay unit is in part due to the presence of sand lenses encountered by some of the boreholes. The clay unit has higher hydraulic conductivities towards the surface. The clay till has a higher degree of consolidation, which accounts for the lower hydraulic conductivity.
- The initial results of the groundwater testing at the WL main campus showed total dissolved solids (TDS) of 600 to 2500 mg/L. The groundwater type from the initial results showing both bicarbonate-sulphate from anion analysis and the cation analysis showed a predominately calcium-magnesium water type. Gross beta and gross alpha activity in overburden groundwater are low but exceeds Health Canada drinking water quality guidelines or screening levels of 0.5 Bq/L for gross alpha and 1.0 Bq/L for gross Beta due to presence of naturally occurring uranium and daughter isotopes in the groundwater.
- Some elevated sulphate readings have been noted in WL main campus wells as is the case elsewhere on the WL site.
- Despite dry conditions and the heterogeneity of the basal sand unit with large boulders, cobbles, sand, silt, and clay layers intersected in most of the recently drilled boreholes results overall in 2015, 2016, 2017, 2018 and 2019 indicate horizontal groundwater flow

through the basal sand unit and shallow bedrock westwards towards the Winnipeg River. The results are still locally (Nest 2) influenced by the drawdown cones of the buildings, especially WR-1. The hydrogeochemistry is based on a single set of samples for the WL main campus that does compare favourably to the WMA.

Geomechanical Elements

- The quaternary deposits consist of basal sand (sandy till), overlain by a clay till, which is in turn overlain by a glaciolacustrine clay. The clay has a plastic limit of 35% indicating a high expansion potential and the clay is known to contract when dry and expand when wet. It is considered insufficiently stiff to support large buildings. The clay till has a plastic limit of 16.6% and has a low to moderate expansion potential. It is sufficiently stiff to support piles from buildings.
- The glaciolacustrine clay is massive to varved in nature and has localized sand seams.
- Given the low seismic risk in Eastern Manitoba and the consolidated nature of the overburden geology, the liquefaction potential is considered too low for consideration at the WL site.
- The WL site is essentially flat except along the riverbanks where erosion is noted. Erosion risk at WR-1 is low like the rest of the site other than along the riverbanks where erosion risk is medium.
- Intact rock geomechanical properties indicate a strong granite crystalline rock with a density of 2.54 to 3.14 Mg/m^3, uniaxial compressive strength of 75 to 248 MPa, Young's Modulus of 27.40 to 107.80 GPa, Poisson's ratio of 0.13 to 0.44, and P-Wave Velocity of 2.45 to 6.06 m/s.
- The rock mass quality of the Lac du Bonnet batholith overall shows an excellent RQD away from fracture zones. Near surface RQD is high but some core loss and rubblization occurs near surface, and was noted in a potential fracture zone present in one borehole.
- The only structural features of note on the WL site are fracture zones noted in the WN series boreholes, and a potential fracture zone noted in some shallow boreholes on the WL main campus. Joint sets are expected to be present on the buried bedrock surface as they are present elsewhere on the Lac du Bonnet batholith. The course of the Winnipeg River may be structurally controlled but has not been explored through geological investigations.
- Primary uncertainties in the geomechanical model is in the connections of the bedrock fractures in the bedrock on the WL site, however flow is considered to be more likely along the basal sand bedrock interface so a fracture network may play a limited role in hydraulic transport.

6.2 CNSC RegDoc 2.9.1 Requirements

Appendix B.4 of CNSC Regulatory Document (REGDOC) 2.9.1 [5] indicates the expected geological and hydrogeological environment includes the bedrock and overburden geology at both the local and regional scales to assess licence applications for proposed new nuclear facilities or activities, licence applications for existing facilities or activities (renewals and amendments), and environmental protection measures. Table 6-1 summarizes baseline geological and hydrogeological characterization requirements listed in Appendix B.4 of CNSC REGDOC 2.9.1 [5] and how the Geosynthesis and EIS address these requirements. Outstanding data uncertainties are noted.

Table 6-1: Summary of CNSC REGDOC 2.9.1 Appendix B.4 Requirements

CNSC REGDOC 2.9.1 Appendix B.4 [5]	Geosynthesis/EIS Coverage
Geology	
Geomorphology	The Geosynthesis describes the terrain (Section 2.2.1) the topography (Section 2.2.2) and the river bathymetry and characteristics (Section 2.2.3) further details are provided in Section 2.4.3.
Topography	The Geosynthesis describes the topography in Section 2.2.2 and further details are provided in Sections 2.4 and 2.5.
Quaternary geology and soil characteristics	The Geosynthesis describes the regional and local quaternary geology in Section 2.4 and soil properties in Section 4.2. Additional soil properties to more fully understand erosion of the riverbanks are indicated in Section 5.2.5.
Structural geology (regional, local and site-specific documentation of fractures and faults, primary geological features and deformation fabrics).	The Geosynthesis describes the structural geology through lineament studies in Section 2.5.5 and further structural details are provided in Sections 2.5.1, 2.5.2, and 2.5.4.
Petrology and geochemistry	The Geosynthesis describes the petrology of the Lac du Bonnet batholith in Section 2.5.2.
Economic geology	The Geosynthesis describes the economic geology in Section 2.6.
Geomechanical properties	Geomechanical properties are described in the Geosynthesis in Section 4.3 for intact rock properties and Section 4.4 for rock mass properties.

CNSC REGDOC 2.9.1 Appendix B.4 [5]	Geosynthesis/EIS Coverage
Geotechnical properties of overburden (shear strength and liquefaction potential) to allow for slope stability and bearing capacity of foundations under both static and dynamic conditions.	Available geotechnical properties are described in Section 4.2.
Coastal geomorphology (characteristics of lakefront, shoreline, near-shore and offshore zones).	The Winnipeg River shoreline is discussed in Section 2.2.3 of the Geosynthesis.
Geological model incorporating all overburden and bedrock information including discussion of uncertainties and any needs for additional field investigations to reduce uncertainties.	Section 2.7 of the Geosynthesis provides a high level geological model of the WL site and outlines uncertainties.
Geotechnical and geophysical hazards (subsidence, uplift, seismicity [and active faulting]), and consider the potential for movement at the ground surface (co-seismic rupture) and earthquake ground motions.	Section 5.2 describes geotechnical and geophysical hazards. These are long term hazards in terms of future glaciation and erosion of the Winnipeg River shoreline that could occur at an increased rate due to climate change.
Seismic hazard assessment	Geosynthesis Section 4.6 provides a summary of seismic hazard assessment for the WL site. The WL site is essentially aseismic.
Where appropriate – narrative descriptions should be supplemented by geological maps, figures, cross-sections, borehole logs and photographs.	The Geosynthesis provides geological maps of the local and regional geology, a site soil map, lineament maps, core photographs of the rock core from the nearest boreholes to WR-1 and well as photographs of exposed soil.
Hydrogeology	
Physical and chemical properties of all overburden and bedrock units.	Section 4.2 of the Geosynthesis provides details on the overburden properties. Section 4.3 of the Geosynthesis provides details of the intact rock properties. Section 2.5.2 of the Geosynthesis provides

CNSC REGDOC 2.9.1 Appendix B.4 [5]	Geosynthesis/EIS Coverage
	details on the mineralogy of the Lac du Bonnet batholith.
Aquifer and aquitard identification including geochemical characteristics, vertical and lateral permeabilities, transport mechanisms (diffusion or advection) and directions of groundwater flow.	Section 3.5 of the Hydrogeological Study Report [16] and Section 2.4 of the Groundwater Flow and Solute Transport Modeling Report [37] provides hydraulic conductivity values, and the Geosynthesis Section 3 summarizes hydrogeologic behaviour. Groundwater chemistry information require further data to provide verification of the initial results.
Identification of groundwater recharge and discharge area, and detailed description of groundwater interactions with surface waters.	Section 3.4 of the Hydrogeological Study Report [16], Section 3 of the Geosynthesis and Section 2.4 of the Groundwater Flow and Solute Transport Modeling Report [37] describe the groundwater movement on the site. The site wells required additional readings as field data flow direction information in the bedrock and the clay layers were not fully developed.
Presentation of conceptual and numerical hydrogeological model that discusses hydrostratigraphy and groundwater flow systems.	Section 5.1 of the Hydrogeological Study Report [16] and Section 3.0 of the Groundwater Flow and Solute Transport Modeling Report [37] describe hydrogeology and the numerical modelling of the of the groundwater flow.
Description of baseline groundwater quality at the site and in the local study area.	Section 3.2.1 of the Geosynthesis summarizes the groundwater chemistry. Further information is provided in the Hydrogeological Summary report [16].
Description of local and regional potable water supplies including current use and potential for future use.	Section 6.9.4.2.5.2 of the EIS [1] describes water supplies for the main towns near the WL site. Section 2.2.3 of the Geosynthesis describes the Winnipeg River watershed. The Decommissioning Safety Assessment Report [2] describes the potential effect of a well on the site.

6.3 Geoscience Verification Plan

The data uncertainties identified in this Geosynthesis, the rationale for identification of the uncertainty and recommendations to address the uncertainties are provided in Table 6-2.

Table 6-2: Geoscience Verification Plan

Uncertainty	Rationale	Recommended Investigation Activity
There is a potential for the presence of a fracture zone towards the Winnipeg River based on the finding of shallow borehole drilling and trace of the river may also be structurally controlled.	An understanding of structural controls on the river trace and the impact of bedrock topography on basal sand-bedrock transport will improve the estimate of transport time. The presence of a fracture could either shorten, have minimal effect or lengthen the transport distance and time from WR-1 to the discharge.	The effect of variation in transport distance and time from WR-1 to the discharge at the Winnipeg River on the assessment results should be analysed through a sensitivity study in the Solute Transport Model. Sensitivity Study #1 'Preferential Pathway' examines the effects of an undiscovered pathway between WR-1 and the discharge with enhanced hydraulic connection.
The monitoring wells completed in the clay and clay till units that may not have fully stabilized, and groundwater level data should be considered preliminary.	Groundwater levels provide input in the flow model and indicate the effects of variations due to changes in precipitation that can influence contaminant migration. The potential uncertainty in groundwater levels can affect the estimation of hydraulic conductivity along the transport path, and thus the transport time from WR-1 to the discharge.	The model can be improved by analysis of data collected from 2017-2018 for hydraulic head and including ongoing sampling of the WL site wells. The effect of variation in hydraulic conductivity of the main transport path from WR-1 to the discharge at the Winnipeg River on the assessment results should be analysed through a sensitivity study in the Solute Transport Model. Sensitivity study #11

Uncertainty	Rationale	Recommended Investigation Activity
		‘Increased Hydraulic Conductivity of the Upper Bedrock’ examines the effects of uncertainty in the calculated hydraulic conductivity of the main transport path.
The hydrogeochemistry is based on a single set of samples for the WL main campus.	Hydrogeochemistry provides an indication of the potential for long term leaching and groundwater chemical attack on concrete and grout materials. This can affect the rate at which the concrete and grout may degrade.	Supplementing the water chemistry results with additional samples and including ongoing sampling of the WL site wells. The effect of early onset concrete degradation, and the rate at which degradation occurs should be analysed through a sensitivity study in the Solute Transport Model. Sensitivity study #8 ‘Timescales Associated’ examines the effects of varying the timescales over which complete degradation of the concrete occurs.
Erosional rate of the Winnipeg River.	Erosion is noted along the river bank and a moderate risk of erosion currently exists. It is possible to estimate riverbank erosion. The migration of the riverbank can either shorten, or lengthen the transport distance and time from WR-1 to the discharge.	The effect of variation in transport distance and time from WR-1 to the discharge at the Winnipeg River on the assessment results should be analysed through a sensitivity study in the Solute Transport Model. Sensitivity study #1 ‘Preferential Pathway’ examines the effects of an undiscovered pathway between WR-1 and the discharge with enhanced

Uncertainty	Rationale	Recommended Investigation Activity
		hydraulic connection. This scenario effectively reduced the travel time between the WR-1 and the Winnipeg River by 10 times, which can simulate the erosion of 90% of the current riverbank soil towards WRDF. Scenario #13 evaluates the effects of a "low river stage", which can simulate erosion on the west bank of the river, effectively moving the river away from WRDF.

7. References

[1] WLDP-26000-ENA-001, Environmental Impact Statement In Situ Decommissioning of WR-1 at the Whiteshell Laboratories Site, Revision 3, 2021 March.

[2] WLDP-26000-SAR-001, In Situ Decommissioning of Whiteshell Reactor 1 Project – Decommissioning Safety Assessment Report. Revision 4, 2021 December.

[3] Nuclear Waste Management Organization, Geosynthesis, OPG's Deep Geologic Repository for Low & Intermediate Level Waste, Report NWMO DGR-TR-2011-11, 2011 March.

[4] M. Jensen, T. Lam, D. Luhowy, J. McLay, B. Semec and R. Frizzell, Ontario Power Generation's Proposed L&ILW Deep Geologic Repository: An Overview of Geoscientific Studies, Proceedings 62nd Canadian Geotechnical Conference, 10th Joint CGS/IAH Groundwater Specialty Conference, pp. 1339-1347, Halifax, 2009 September.

[5] Canadian Nuclear Safety Commission, REGDOC-2.9.1: Environmental Protection: Environmental Principles, Assessments and Protection Measures, Version 1.2. September 2020.

[6] Canadian Nuclear Safety Commission, REGDOC-2.11.1, Volume III: Assessing the Long-Term Safety of Radioactive Waste Management. Version 1. 2018.

[7] WLDP-03704-041-000, Environmental Assessment Follow Up Program – 2015 Hydrogeological Assessment for Annual Safety Report.

[8] WLDP-03704-041-000, Environmental Assessment Follow Up Program – 2016 Hydrogeological Assessment for Annual Safety Report.

[9] WLDP-03704-041-000, Environmental Assessment Follow Up Program – 2017 Hydrogeological Assessment for Annual Safety Report.

[10] WLDP-03704-041-000, Environmental Assessment Follow Up Program – 2014 Groundwater Assessment Report.

[11] WLDP-03704-REPT-008, 2019 Hydrogeological Assessment for Annual Safety Report, Dillon Consulting.

[12] Shawinigan Engineering Company, Shawinigan Engineering Report 2410-2-60, Report on Proposed Site for Whiteshell Nuclear Research Establishment for Atomic Energy of Canada Limited, 1960.

[13] J.E. Guthrie and G.A. Scott, Pre-operational Environmental Survey Report of the Whiteshell Nuclear Research Establishment Area, 1988.

[14] WLDP-03702-041-000-0008, Atomic Energy of Canada Limited, Whiteshell Laboratories Decommissioning Project, Comprehensive Study Report, Vol. 1, 2001 March.

[15] WLDP-35000-041-000-0014, KGS Group, Whiteshell Laboratories Projects Branch Comprehensive Final Report on Installation of 7 Groundwater Monitoring Wells Nests, 2016 March.

[16] WLDP-26000-REPT-004, WR-1 Hydrogeological Study Report. 2018 November.

[17] R.A. Everitt, A. Brown, C.C. Davison, M. Gascoyne, and C.D. Martin, Regional and local setting of the Underground Research Laboratory, In Proceedings of the Symposium on Unique Underground Structures, Denver, Colorado, pp. 64-1 to 64-23, 1990.

[18] Agriculture and Agri-Food Canada, Municipality of Pinawa, Information Bulletin 99-25, 1999.

[19] Canada-Manitoba Soil Survey, 1980 - Canada-Manitoba Soil Survey, Physiographic Regions of Manitoba, Ellis Bldg., University of Manitoba, Winnipeg, Revised, 1980. Unpublished Report.

[20] Agriculture and Agri-Food Canada, Rural Municipality of Lac du Bonnet Information Bulletin 99-26.

[21] Natural Resources Canada, The National Atlas of Canada, 5th edition, 1985.

[22] S. St. George, Hydrological Dynamics in the Winnipeg River Basin, Manitoba; in Report of Activities 2006, Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, p. 226-230, 2006.

[23] www.charts.gc.ca, Canadian Hydrographic Service maps 6205 and 6206.

[24] D.S. Fullerton, R.B. Colton, C.A Bush, Limits of Mountain and Continental Glaciation East of the Continental Divide in Northern Montana and North-Western North Dakota, U.S.A, in Quaternary Glaciations Extent and Chronology, Part II North America, J. Ehlers and P.L. Gibbard, 2004.

[25] Simon Fraser University https://www.sfu.ca/archaeology/museum/exhibits/virtual-exhibits/glacial-and-post-glacial-archaeology-of-north-america/glaciation-of-north-america.html

[26] M.T. Corkery, Geology and Landforms of Manitoba, Chapter 2, The Geography of Manitoba: Its Land and Its People, Eds. John C. Everitt, John Welsted, Christoph Stadel, 1996.

[27] J.T. Teller and M.M. Fenton, Late Wisconsinan Glacial Stratigraphy and History of Southeastern Manitoba, Canadian Journal of Earth Sciences. v. 17, 1980.

[28] B. Redekopp, Lake Agassiz, The Rise and Demise of the World's Greatest Lake, Heartland Associates Inc. Winnipeg, Canada.

[29] J.T. Teller, Lake Agassiz Deposits in the Main Offshore Basin of Southern Manitoba; Canadian Journal of Earth Sciences, v. 13, p. 27-43, 1976.

[30] L. Clayton and S.R. Moran, Chronology of Late-Wisconsinan Glaciation in Middle North America, Quaternary Science Reviews, v. 1, p. 55-82, 1982.

[31] L.H. Thorleifson, The Eastern Outlets of Lake Agassiz, M.Sc. Thesis University of Manitoba, 1983.

[32] W.D. Robertson and J.A. Cherry, Review of the Hydrogeology of the Radioactive Waste Management Site, 1985 February.

[33] R.A. McPherson, Pleistocene Stratigraphy of the Winnipeg River in the Pine-Falls-Seven Sisters Area; M. Sc. thesis, University of Manitoba, Winnipeg, Manitoba, 61 p., 1968.

[34] J.A. Cherry, B.T. Beswick, and W.E. Clister, Hydrogeologic Regime of the Environmental Control Area and Vicinity, Whiteshell Nuclear Research Establishment, Manitoba, Preliminary Progress Report, 1970 November.

[35] J.A. Cherry, G.E. Grisak, and W.E. Clister, Hydrogeological Studies at a Subsurface Radioactive-Waste-Management Site in West-Central Canada, 1973 May.

[36] WLDP-03704-ENA-009, Atomic Energy of Canada Limited, Hydrogeology of the Waste Management Area, Lagoon and Landfill-Enhanced Monitoring Program, 2008 March.

[37] WLDP-26000-REPT-005, In Situ Decommissioning of WR-1 at the Whiteshell Laboratories Site Groundwater Flow and Solute Transport Modelling.

[38] G.P. Beakhouse, C.E. Blackburn, F.W. Breaks, J. Ayer, D. Stone, and G.M. Stott, Western Superior Province, Geologic Survey of Canada, Open File 3138, 1995.

[39] D.L. Ciceri, The Winnipeg River/Western Wabigoon Subprovince Boundary, Superior Province, Northwestern Ontario: Structural and Metamorphic Gradients in the Tustin-Bridges Vermilion Bay Greenstone Belt, University of Toronto, M.Sc. Thesis.

[40] G.P. Beakhouse, Winnipeg River Subprovince, in Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, p. 279-301, 1991.

[41] J.A. Percival, Geology and Metallogeny of the Superior Province, Canada, in W.D. Goodfellow, ed., Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods: Geological Association of Canada, Mineral Deposits Division, Special Publication, 2017.

[42] J.A. Percival, and R.M. Easton, Geology of the Canadian Shield in Ontario: an update; Ontario Geological Survey, Open File Report 6196, Geological Survey of Canada, Open File 5511, Ontario Power Generation, Report 06819-REP-01200-10158-R00, 65, 2007.

[43] H.R. Williams, G.M. Stott, P.C. Thurston, R.K. Sutcliffe, G. Bennett, R.M. Easton, and D.K. Armstrong, Tectonic Evolution of Ontario: Summary and Synthesis; in Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p. 1255-1334, 1991.

[44] J.A. Percival, M. Sanborn-Barrie, T. Skulski, G.M. Stott, H. Helmstaedt, and D.J. White, Tectonic Evolution of the Western Superior Province from NATMAP and Lithoprobe Studies, Canadian Journal of Earth Sciences, v. 43, p. 1085-1117, 2006.

[45] K.L. Buchan, and R.E. Ernst, Diabase Dyke Swarms and Related Units in Canada and Adjacent Regions, Geological Survey of Canada, Map No. 2022A, scale 1:5 000 000, 2004.

[46] I.A. Osmani, Proterozoic Mafic Dike Swarms in the Superior Province of Ontario, Chapter 17, Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 1, Eds. P.C. Thurston, H.R. Williams, R.H. Sutcliffe and G.M. Stott, 1991.

[47] Nicholas L. Swanson-Hysell, Jahandar Ramezani, Luke M. Fairchild, Ian R. Rose, Failed Rifting and Fast Drifting: Midcontinent Rift Development, Laurentia's Rapid Motion and the Driver of Grenvillian Orogenesis, Geological Society of America Bulletin, Volume 131, Number 5-6, 2019.

[48] C.C. Davison, A. Brown, R.A. Everitt, M. Gascoyne, E.T. Kozak, G.S. Lodha, C.D. Martin, N.M. Soonawala, D.R. Stevenson, G.A. Thorne, and S.H. Whitaker, The Disposal of Canada’s Nuclear Fuel Waste: Site Screening and Site Evaluation Technology, AECL-10713, COG-93-3.

[49] K.D. Card, and A. Ciesielski, DNAG #1, Subdivisions of the Superior Province of the Canadian Shield, Geoscience Canada, 13: 5-13, 1986.

[50] J.A. Percival, J.B. Whalen, K.Y. Tomlinson, V.J. McNicoll, and G.M. Stott, Geology and Tectonostratigraphic Assemblages, North-Central Wabigoon Subprovince, Ontario; Geological Survey of Canada, Open File 4270, Ontario Geological Survey, Preliminary Map P.3447, scale 1:250 000, 2002.

[51] J.A. Percival, V. McNicoll, J.L. Brown, and J.B. Whalen, Convergent Margin Tectonics, Central Wabigoon Subprovince, Superior Province, Canada; Precambrian Research, v. 132, p. 213-244, 2004.

[52] J.A. Percival, and H. Helmstaedt, 2004, Insights on Archean Continent–Ocean Assembly, Western Superior Province, from New Structural, Geochemical and Geochronological Observations: Introduction and Summary; Precambrian Research, v. 132, p. 209-212, 2004.

[53] G.R. Edwards, and R.H. Sutcliffe, Archean Granitoid Terranes of the Western Superior Province, Ontario; Geological Association of Canada–Mineralogical Association of Canada, Program with Abstracts, v. 5, p. 50, 1980.

[54] P.C. Thurston, and D.W. Davis, The Wabigoon Diapiric Axis as a Basement Complex; in Summary of Field Work and Other Activities, Ontario Geological Survey, Miscellaneous Paper 126, p. 138-141, 1985.

[55] F.W. Breaks, English River Subprovince, in Geology of Ontario, P.C. Thurston, H.R. Williams, R.H. Sutcliffe and G.M. Stott (ed.), Ontario Geological Survey, Special Volume 4, Part 1, p. 239–277, 1991.

[56] W.D. McRitchie, The Petrology and Environment of the Acidic Plutonic Rocks of the Wanipigow - Winnipeg Rivers Region, Southeastern Manitoba, in Geology and Geophysics of the Rice Lake Region, Southeastern Manitoba (Project Pioneer), edited by W. D. McRitchie and W. Weber, Manitoba Mines Branch, Publication 71-1, pp. 7-61, 1971.

[57] Bezys, R.K., Matile, G.L.D. and Keller, G.R. 2001: Investigations of Precambrian Monadnocks (NTS 62I/1 and 62I/8); in Report of Activities 2001, Manitoba Industry, Trade and Mines, Manitoba Geological Survey, p. 133-137, 2001.

[58] G.P. Beakhouse, A Subdivision of the Western English River Subprovince, Canadian Journal of Earth Sciences 14: 1481-1489, in Everitt et al., 1996.

[59] R.A. Everitt, J. McMurry, A. Brown, and C. Davison, Geology of the Lac du Bonnet Batholith, Inside and Out: AECL's Underground Research Laboratory, Southeastern Manitoba Field Trip Guidebook B5, Geological Association of Canada/Mineralogy Association of Canada Annual Meeting, Winnipeg, Manitoba, 1996 May 27-29.

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

[61] T.E. Krogh, G.L. Davis, I. Ermanovics, and N.B.W. Harris, U-Pb Isotopic Ages of Zircons from the Berens Block and English River Gneiss Belt, Proceedings of 1976 Geotraverse Conference, University of Toronto, 12-1, 46.

[62] D.C. Kamineni, D. Stone, and Z.E. Peterman, Early Proterozoic Deformation in the Western Superior Province, Canadian Shield, Geological Society of America Bulletin, 102: 1623-1634, 1990.

[63] J.A. Percival, W. Bleeker, F.A. Cook, T. Rivers, G. Ross, and C.R. van Staal, Panlithoprobe Workshop IV: Intra-Orogen Correlations and Comparative Orogenic Anatomy, Geoscience Canada, 31: 23-39, 2004.

[64] Gascoyne, M., A. Brown, R.B. Ejeckam, R.A. Everitt, Dating fractures and Fracture Movement in the Lac du Bonnet Batholith AECL-11725, COG-96-634-1, 1997.

[65] J.W. Ambrose, Exhumed paleoplains of the Precambrian Shield of North America, American Journal of Science, September 1964, 262 (7) 817-857.

[66] G.F.D. McCrank, A Geological Survey of the Lac du Bonnet Batholith, Manitoba, AECL-7816, 1985.

[67] P. Cerny, B.J. Fryer, F.J. Longstaffe, and H.Y. Tammemagi, The Archean Lac du Bonnet Batholith, Manitoba: Igneous History, Metamorphic Effects, and Fluid Overprinting, Geochimica et Cosmochimica Acta, 51: 421-438, 1987.

[68] T.J. Katsube, and J.P. Hume, Geotechnical Studies at Whiteshell Research Area (RA-3), Mining Research Laboratories Divisional Report, CANMET-MRL-87-52 TR, 1987.

[69] R.A. Everitt, and A. Brown, Geological Mapping of AECL Research's Underground Research Laboratory - A Cross Section of Thrust Faults and Associated Fractures in the Roof Zone of an Archean Bathotith, Proceedings of Fractured and Jointed Rock Masses, A Regional Conference of the International Society for Rock Mechanics, June 14, 1992, Granlibakken, California Vol. 1, p. 1-1 1, 1996.

[70] R.S. Read, and C. D. Martin, AECL-11311, COG-95-171, Technical Summary of AECL's Mine-by Experiment Phase 1: Excavation Response, 1996.

[71] S.S. Lim, C.D. Martin, and U., Akesson, In-situ Stress and Microcracking in Granit Cores with Depth, Engineering Geology s 147-148: 1-13, 2012 October.

[72] C.C. Davison, Physical Hydrogeology Measurements Conducted in Boreholes WN-1, WN-2 and WN-4 to Assess the Local Hydraulic Conductivity and Hydraulic Potential of a Granitic Rock Mass, Atomic Energy of Canada Limited Technical Record, TR-26, 1980.

[73] R.A. Everitt, and A. Brown, Subsurface Geology of the Underground Research Laboratory: An overview of Recent Developments. In Proceedings of the 20th Information Meeting of the Canadian Nuclear Fuel Waste Management Program, Winnipeg, Manitoba, 1985, Atomic Energy of Canada Limited Technical Record, TR-375, 1986.

[74] D.R. Stevenson, E.T. Kozak, C.C. Davison, M. Gascoyne, and R.A. Broadfoot, Hydrogeologic Characteristics of Domains of Sparsely Fractured Rock in the Granitic Lac du Bonnet Batholith, Southeastern Manitoba, Canada, AECL-11558, COG-96-117, 1996.

[75] P. Pehme, S. Chapman, and B. Parker, G360 Institute for Groundwater Research, Technical Memo: Summary of Geophysical Data Processing, Temporary Transducer Deployment Design and Implementation in Borehole 16-8A CNL Whiteshell Laboratories Facility, near Pinawa, Manitoba, Canada, 2017 June 20.

[76] H.Y. Tammemagi, P.S. Kerford, J.C. Requelma, and C.A. Temple, A Geological Reconnaissance Study of the Lac du Bonnet Batholith, AECL-6439, 1980.

[77] D.L. Trueman, Stratigraphic, Structural and Metamorphic Petrology of the Archean Greenstone Belt at Bird River, Manitoba, Ph.D. thesis, University of Manitoba, Winnipeg, Canada, 1980.

[78] P. Cerny, D.L. Trueman, D.V. Ziehlke, B.E. Goad, and B.J. Paul, The Cat Lake Winnipeg River and Wekusko Lake Pegmatite Fields, Manitoba, Manitoba Department of Energy and Mines, Mineral Resources Division, Economic Geology Report ER80-1, 1981.

[79] H.P. Gilbert, Stratigraphic Investigations in the Bird River Greenstone Belt Manitoba, part of NTS521.5, 6 in Report of Activities 2008 Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, p. 121-138.

[80] D.C. Kamineni, A. Brown, Z. Peterman, and D. Stone, Radiometric Ages, Cooling Rates and Deformation of Two Granitic Plutons in the Superior Province, Canadian Shield, Geological Society of America, Abstracts with Program 22(7): A244, 1990.

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

[82] https://web33.gov.mb.ca/mapgallery/mgm-md.html

[83] K.A. Phillips, Minerals of Manitoba, Volume II Metallic Minerals, MRD Educational Series 78/2, Manitoba Department of Mines, Natural Resources and Environment.

[84] B. Schmidtke, and J. Bamburak, Industrial Minerals of Southeastern Manitoba (Field Trip B7), Geological Association of Canada/Mineralogy Association of Canada Annual Meeting, Winnipeg, Manitoba, 1996 May 27-29.

[85] T. Martens, P. Kremer, and P. Vanstone, The Tanco Mine: Geological Setting Internal Zonation and Mineralogy of a World-Class Rare Element Pegmatite Deposit, Field Trip Guidebook FT-C1, Geological Association of Canada-Mineralogical Association of Canada Joint Annual Meeting, Winnipeg, 2013 May.

[86] S.D. Anderson, Preliminary Bedrock Geology of the Eastern Extension of the Rice Lake Mine Trend, Rice Lake Greenstone Belt, southeastern Manitoba (parts of NTS 52M3, 4), in Report of Activities 2013, Manitoba Mineral Resources, Manitoba Geological Survey, p. 46–59, 2013.

[87] R.N. Betcher, M. Gascoyne, and D. Brown, Uranium in Groundwaters of Southeastern Manitoba, Canada, Canadian Journal of Earth Sciences, Volume 25, pages 2089-2103, 1988.

[88] R. Betcher, G. Grove, C. Pupp, Groundwaters in Manitoba: Hydrogeology, Quality Concerns, Management, National Hydrology Research Institute Environment Canada, Contribution No. CS-93017, 1995 March.

[89] KGS Group, Geotechnical Site Investigation for New Waste Storage Structures and Site Characterization of Future WMA Expansion Site Area – Final Report 2007 September, Atomic Energy of Canada Ltd., 07-0080-01, 2007.

[90] KGS Group, Phase II Geotechnical Investigation – Final Report, Shielded Modular Above Ground Storage (SMAGS) Project, Atomic Energy of Canada Ltd., 07-0080-01, 2009.

[91] J. Graham, and D.H. Shields, Influence of Geology and Geological Processes on the Geotechnical Properties of a Plastic Clay, Eng. Geol.,22: 109-126, 1985.

[92] R. Jackson, J.S.O. Lau, and A. Annor, Mechanical, Thermo-Mechanical and Joint Properties of Rock Samples from AECL's Underground Research Laboratory, Lac du Bonnet, Manitoba, 42nd Canadian Geotechnical Conference, Winnipeg, MB, 1989.

[93] R. Jackson, Anisotropic Properties Study of Lac du Bonnet Granite Specimens: Report #7 MRL 92-060(TR), 1992.

[94] J.S.O. Lau, Biaxial Tests of Some Overcored Samples from AECL'S Underground Research Laboratory , Lac du Bonnet, Manitoba, Mining Research Laboratories Divisional Report MRL 89-55(TR), 1989.

[95] R. Jackson, Dilatational Velocity, Young's Modulus, Poisson's Ratio and Uniaxial Compressive Strength for URL-2 and URL-5 Samples, Mining Research Laboratories Divisional Report 82-60(TR), 1992.

[96] A. Annor, The Effects of Pressure and Temperature on the Permeability and Porosity of Selected Crystalline Rock Samples, Mining Research Laboratories Divisional Report MRL 86-8(INT), 1986.

[97] A. Annor, G. Larocque, and P. Chernis, Uniaxial Compression Tests, Brazilian Tensile Tests and Dilatational Velocity Measurements on Rock Specimens from Pinawa and Chalk River.

[98] D.U. Deere, A.J. Hendron, F.D. Patten, and E.J. Cording, Design of Surface and Near Surface Construction in Rock, in Failure and Breakage of Rock, proc. 8th U.S. Symp. Rock Mech., (ed. C. Fairhurst), pp. 237-302, New York: Soc. Min. Engrs, Am. Inst. Min. Metal, 1967.

[99] D.U. Deere, and D.W. Deere, The Rock Quality Designation (RQD) Index in Practice, in: Rock Classification Systems for Engineering Purposes, (ed. L. Kirkaldie), ASTM Special Publication No. 984, pp. 91-101, Philadelphia, Am. Soc. Test. Mat, 1988.

[100] R.J. Wetmiller, M.G. Cajka, G.S. Lodha, and Y. Ates, Comparison of Seismic Ground Motions at Surface and Underground/Developing Design of Nuclear Fuel Waste Repositories Proceedings of International Conference on Deep Geological Disposal of Radioactive Waste, Winnipeg, Manitoba, 1996 September 16-19.

[101] The National Building Code of Canada 2015, National Research Council of Canada.

[102] WLDP-26000-021-000, Memo, J. Van Meter to J. Miller, Whiteshell Seismic Hazard.

[103] Earthquakes Canada, http://www.earthquakescanada.nrcan.gc.ca//index-en.php

[104] https://geology.com/usgs/liquefaction/

[105] R.W. Boulanger, and I.M. Idriss, Evaluating the Potential for Liquefaction or Cyclic Failure of Silts and Clays, Department of Civil and Environmental Engineering, College of Engineering, University of California at Davis Report UCD/CGM-04/01, 2004.

[106] State of New York Department of Transportation, Geotechnical Engineering Bureau, Geotechnical Design Procedure: Liquefaction Potential of Cohesionless Soils, GDP-9, 2015.

[107] Ohio EPA, Geotechnical and Stability Analyses for Ohio Waste Containment Facilities Chapter 5, Liquefaction Potential Evaluation and Analysis, Geotechnical Resource Group (GeoRG) Ohio Environmental Protection Agency Columbus, Ohio 43216-1049.

[108] WLDP-26000-041-000. KGS Group. Cone Penetration Testing Investigation for Whiteshell Main Campus – Final. 2019 December.

[109] WLDP-26000-REPT-007, Climate Change Assessment for WR-1 In Situ Decommissioning.

[110] NRCan, Climate Change Impacts and Adaption: A Canadian Perspective, ISBN: 0-662-33123-0, 2004.

[111] NRCan. Canada in a Changing Climate: Sector Perspectives on Impacts and Adaption. F.J. Warren and D.S. Lemmen, editors, ISBN: 978 1 100 24143 2, 2014. Available at http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/earthsciences/pdf/assess/2014/pdf/Full- Report_Eng.pdf.

[112] IPCC (Intergovernmental Panel on Climate Change), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013, [T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)],

Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

[113] W.R. Peltier, Long-Term Climate Change, Nuclear Waste Management Organization Report, NWMO DGR-TR-2011-14, Toronto, Canada, 2011.

[114] 64-509410-REPT-010, Geosynthesis Report - NPD Closure Project.

[115] B. Hallet, Glacial Erosion Assessment, Nuclear Waste Management Organization, Report NWMO DGR-TR-2011-18, Toronto, Canada, 2011.

[116] C.A. Kaszycki, and W.W. Shilts, Glacial Erosion of the Canadian Shield – Calculation of Average Depths, Atomic Energy of Canada Ltd., Technical Record, TR-106, 1980 August.

[117] W. White, Deep Erosion by Continental Ice-Sheets, Geological Society of America, Bulletin Vol. 83, pp. 1037–1056, 1972.

[118] R. Flint, Glacial Geology and the Pleistocene Epoch, J. Wiley and Sons, New York, from several metres to several hundred, Aylsworth and Shilts, 1947.

[119] J.M. Aylsworth, and W.W. Shilts, Glacial Features of the West-Central Canadian Shield; & Current Research, Part B, Geological Survey of Canada, Paper 05-18, p. 375-381, 1985.

[120] L. Fernando, The Effect of Flow Induced Erosion on Riverbank Stability Along the Red River in Winnipeg, 2007.

[121] Manitoba Hydro Open Literature.