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Supplier Document

2021 UPDATE TO GEOSYNTHESIS NUCLEAR POWER DEMONSTRATION CLOSURE PROJECT ROLPHTON, ONTARIO

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Revision 2

Accepted by: [signature] 2021 Jan 13

Katie Shorter — Date

Manager NPD Regulatory Approvals

ARCADIS

With Support From:

Quintessa And,

Geofirma Engineering Ltd

Canadian Nuclear Laboratories

2021 UPDATE TO GEOSYNTHESIS NUCLEAR POWER DEMONSTRATION CLOSURE PROJECT ROLPHTON, ONTARIO

Revision 0

December 2021

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Revision 0

CNL Acceptance:

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Manager, NPD Regulatory Approvals, CNL

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EXECUTIVE SUMMARY

Geofirma Engineering Ltd. was retained by Arcadis Canada Inc. on behalf of Canadian Nuclear Laboratories to complete a 2021 Updated Geosynthesis Report in support of decommissioning of the current Nuclear Power Demonstration Waste Facility (NPDWF) located in the Town of Laurentian Hills, Renfrew County, Ontario. Geosynthesis is the geoscientific explanation of 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. For the decommissioning of the NPDWF, Geosynthesis is the integration and presentation of site geological, hydrogeological and geomechanical data and information within the broader context of regional geoscientific data and information, and the detailed data and information available for the nearby Chalk River Laboratories site, which has been subject to extensive and detailed geoscientific characterization for waste management purposes for over 40 years. The 2021 Updated Geosynthesis Report is a revision and update to the initial 2018 Geosynthesis Report (Arcadis Canada Inc., 2018a) and the 2019 Updated Geosynthesis Report (Arcadis Canada Inc., 2019). The 2021 Updated Geosynthesis Report provides additional geoscientific information and interpretation to address Canadian Nuclear Safety Commission (CNSC) staff comments on the 2019 Updated Geosynthesis Report, and also includes results of a soil liquefaction and slope stability assessment of the NPD site (Arcadis Canada Inc., 2021) under earthquake loading completed in 2021.

This 2021 Updated Geosynthesis Report reviews and presents available site-specific, local and regional geoscientific data and information as part of defining the geological, hydrogeological and geomechanical frameworks for the NPDWF site. Geological framework includes information on physiography and geomorphology, Quaternary geology and history, bedrock geology (lithology and structure, including a lineament study), and economic geology at site, local and regional scales. Hydrogeological framework includes information on conceptual groundwater flow systems in the Canadian Shield, hydrogeological investigations of the NPDWF site, hydrostratigraphic units, hydrogeochemistry and groundwater quality, local groundwater flow systems, potable water supplies, and hydrogeological modeling. Geomechanical framework includes information on overburden geotechnical properties and hazards including earthquake-induced soil liquefaction and slope instability, intact rock properties, rock mass properties, major discontinuities and structural features, regional and local in-situ stresses, neotectonics and paleoseismicity, and regional and local seismicity. Descriptive geological, hydrogeological and geomechanical models of the NPDWF site are presented based on the geological, hydrogeological, and geomechanical frameworks. Future evolution of the Nuclear Power Demonstration Disposal Facility (NPDDF – term that refers to the NPDWF following decommissioning) site is summarized considering flooding, glaciation, geological disturbances and hazards, and seismic hazard assessment.

Current descriptions of the geosphere generated in the 2021 Updated Geosynthesis Report are reasonably accurate, best estimates of geological, hydrogeological and geomechanical frameworks based on utilization of site-specific and off-site regional and local geoscientific data. Current descriptions of the geosphere at the NPDWF site, while inevitably including some uncertainty in selected areas, support and enhance the existing geosphere model as outlined in the current Postclosure Safety Analysis Report (Arcadis Canada Inc., 2017a) and the conceptual and numerical groundwater flow models (Calder, 2018; 2019a) that form part of the Postclosure Safety Analysis.

The 2021 Updated Geosynthesis Report addresses baseline geological and hydrogeological characterization requirements listed in Appendix B.4 of CNSC RegDoc 2.9.1, using site-specific geoscientific data or inferred best estimates of site-specific data based on local and regional understanding.

The 2021 Updated Geosynthesis Report identifies the following geoscientific data uncertainties considered important to NPDWF site characterization and geosynthesis:

1. Presence and hydrogeological properties of the permeable fluvial sand and gravel layer that sub-parallels the Ottawa River and extends tile drain capture of overburden groundwater northwest of the NPDWF;
2. Hydrogeochemistry and groundwater quality of shallow bedrock; and
3. Geotechnical properties of the soils located north of the NPDWF to support a more rigorous and reliable assessment of earthquake-induced soil liquefaction and slope stability.

Addressing these identified geoscientific data uncertainties, while beneficial for overall site characterization and geosynthesis, is unlikely to change the summary and conclusions of this 2021 Updated Geosynthesis Report.

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LIST OF ACRONYMS AND ABBREVIATIONS

AECL – Atomic Energy of Canada Limited

AFE – Annual Frequency of Exceedance

ATV – (borehole) acoustic televiewer

Bq/L – Becquerel per Litre

BH – borehole

CDED – Canadian Digital Elevation Data

CMT – Continuous Multi-channel Tubing

CNL – Canadian Nuclear Laboratories

CNSC – Canadian Nuclear Safety Commission

CRL – Chalk River Laboratories

DBE – Design Basis Earthquake

DDGS – Deep Doorstopper Gauge System

DEM – Digital Elevation Model

Eh – redox potential

EIS – Environmental Impact Statement

g – gravitational acceleration

GCM – General Circulation Model

GPa – gigapascal

HEPC – Hydro-Electric Power Commission of Ontario

IPCC – Intergovernmental Panel on Climate Change

ISRM – International Society for Rock Mechanics

J – joint number

km/s – kilometre per second

kN/m^3 – kilonewton per cubic metre

kPa – kilopascal

K – hydraulic conductivity

LIO – Land Information Ontario

Litho – lithology

m – metres

mASL – metres Above Sea Level

mg/L – milligram per Litre

mV – millivolt

M – Nuttli earthquake magnitude

MECP – Ontario Ministry of Environment, Conservation and Parks

MNDM – Ontario Ministry of Northern Development and Mines

MNR – Ontario Ministry of Natural Resources

MRD – Miscellaneous Release Data

Mg/m^3 – megagram per cubic metre

MPa – megapascal

MW – monitoring well

nT – nano Tesla

NPD – Nuclear Power Demonstration

NPDDF – Nuclear Power Demonstration Disposal Facility

NPDWF – Nuclear Power Demonstration Waste Facility

NRCan – Natural Resources Canada

NSDF – Near Surface Disposal Facility

NWMO – Nuclear Waste Management Organization

OGS – Ontario Geological Survey

PAHs – Polycyclic Aromatic Hydrocarbons

PGA – Peak Ground Acceleration

PHCs – Petroleum Hydrocarbons

PSHA – Probabilistic Seismic Hazard Assessment

PTS – polished thin section

QEMSCAN – quantitative evaluation of materials by scanning electron microscopy

RMR – Rock Mass Rating

RQD – Rock Quality Designation

SIGÉOM - Système d'information géomine du Québec

STF – Siting Task Force

SRF – Stress Reduction Factor

TDS – total dissolved solids

TSD – Technical Support Document

µg/L – microgram per Litre

UCS – Uniaxial Compressive Strength

UTM – Universal Transverse Mercator

VOCs – Volatile Organic Compounds

WQSZ – Western Quebec Seismic Zone

WSM – world stress map

XRD – X-ray diffraction

1 INTRODUCTION

1.1 Background

Canadian Nuclear Laboratories (CNL) is completing an Environmental Impact Statement (EIS) for the safe decommissioning of the current Nuclear Power Demonstration Waste Facility (NPDWF) located in parts of Lots 43 and 44 in Rolph Township in the Town of Laurentian Hills, Renfrew County, Ontario. Following decommissioning, the NPDWF is referred to as the Nuclear Power Demonstration Disposal Facility (NPDDF). 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 (Arcadis Canada Inc., 2017b). The NPDWF site is located adjacent to the Ottawa River, about 27 km northwest and upstream of the Chalk River Laboratories (CRL) property at Chalk River, Ontario. Figure 1.1 shows the location of the NPD and CRL sites.

Figure 1.1 Location of NPD Site

This report presents a 2021 Updated Geosynthesis prepared in support of the NPDDF closure EIS (Arcadis Canada Inc., 2017b). Geosynthesis is the geoscientific explanation of 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 (Nuclear Waste Management Organization, 2011; Jensen *et al*., 2009), which in the current context is the decommissioning of the NPDWF.

The 2021 Updated Geosynthesis Report is a revision and update to the initial 2018 Geosynthesis Report (Arcadis Canada Inc., 2018a) and the 2019 Updated Geosynthesis Report (Arcadis Canada Inc., 2019). The 2021 Updated Geosynthesis Report includes the results of detailed geoscientific characterization work of the NPD site (Geofirma Engineering Ltd., 2019) undertaken in late 2018 and early 2019, and the results of a soil liquefaction and slope stability assessment of the NPD site under earthquake loading completed in 2021.

For the decommissioning of the NPDWF, Geosynthesis is the integration and presentation of site geological, hydrogeological and geomechanical data and information within the broader context of regional geoscientific data and information and the detailed data and information available for the nearby CRL site, which has been subject to extensive and detailed geoscientific characterization for waste management purposes for over 40 years. In short, Geosynthesis typically involves placing a detailed geoscientific description of a particular site within the broader regional geoscientific understanding.

Decommissioning of the NPDWF is proposed to be undertaken using an in-situ approach to contain and isolate the contaminated systems and components inside the below-grade structure (Arcadis Canada Inc., 2017b). The below-ground surface structure was constructed at average depths of up to 24 m below ground surface and 18 m into bedrock. It is proposed that all below-grade areas will be sealed with grout and concrete from an on-site batch mixing plant. Grouting will involve the process of placing a mixture of Portland cement, blast furnace slag, sand and water that produces a pourable, concrete-like mixture to ensure the sufficient filling of voids throughout the facility. All above-ground surface structures will be demolished and placed into the space below grade prior to final grouting. The footprint above the nuclear area will be covered with reinforced concrete and the entire NPDDF covered with an engineered barrier. The existing ventilation stack will be retained as it is currently used a nesting habitat for chimney swifts. The NPD site will then be restored and prepared for long-term care and maintenance activities carried out under an amendment of the current decommissioning license.

1.2 Objectives and Scope of Work

The objectives of the work described in this report are four-fold:

1. Completion of a 2021 Updated Geosynthesis Report in support of the EIS for decommissioning of the NPDWF;
2. To address and update geoscientific data uncertainties as identified in Table 6.2 of the initial 2018 Geosynthesis Report;
3. Ensuring the 2021 Updated Geosynthesis Report incorporates feedback received from theme meetings with the CNSC, as well as dispositions to FPTR (Federal Provincial Technical Review) comments provided on the EIS; and
4. To address CNSC staff comments on the Updated 2019 Geosynthesis Report provided in early February 2021.

Geosynthesis for the decommissioning of the NPDWF focusses on assembly and review of available geological, hydrogeological and geomechanical information including detailed historic and recent geoscientific site characterization information, local geoscientific data, published scientific literature, and digital mapping from the Ontario Geological Survey, the Quebec Ministry of Energy and Natural Resources and the Geological Survey of Canada, as well as local and regional geoscientific data relevant to safety assessment of the proposed undertaking. Given the abundance of relevant geoscientific data available for the nearby CRL property, an important element of the Updated Geosynthesis is assessment of the extent to which local CRL geoscientific data can be used to describe or infer geoscientific conditions on the NPD property.

Key geoscientific data for the CRL property includes the results of site characterization activities undertaken by the Canadian Nuclear Fuel Waste Management Program (1976-1986) in support of geoscientific site characterization research, the Federal Ministerial Siting Task Force (1992-1995) in support of finding a disposal facility for Port Hope area low-level wastes, and by Atomic Energy of Canada Ltd./Canadian Nuclear Laboratories (2006-2016) in evaluating the feasibility of a geological waste management facility at the CRL property for storage of on-site low and intermediate level wastes.

This report distinguishes the 2.4 ha NPDWF which includes the licensed area with fencing from the larger approximate 382 ha NPD site. For ease of reference, the approximate 260 ha, updated 2019 NPDWF groundwater model domain that includes the NPDWF and parts of the NPD site (Calder, 2019a) is shown on most local site figures.

1.3 Report Organization

This report is organized by seven sections.

Section 1 provides an introduction summarizing background, objectives and scope of work, as well as report organization.

Section 2 describes the geological framework for the NPDWF site based on assembly and review of available regional, local and site geological information and completion of a lineament study. Section 2 discusses physiography and geomorphology, Quaternary geology and history, bedrock structural geology and lithology, economic geology, and development of a descriptive geological framework based on these data.

Section 3 describes the hydrogeological framework for the NPDWF site based on assembly and review of available regional, local and site hydrogeological information. Section 3 discusses conceptualization of groundwater flow systems, regional and site estimates of hydraulic properties of overburden and bedrock, identification of hydrostratigraphic units, hydrogeochemistry and groundwater quality, local groundwater flow systems, potable water supplies and Ontario Ministry of the Environment, Conservation and Parks (MECP) water well records, conceptualization and results of hydrogeological modeling of the NPDWF site, and development of a descriptive hydrogeological framework based on these data.

Section 4 describes the geomechanical framework for the NPDWF site based on assembly and review of available regional, local and site geomechanical information. Section 4 discusses overburden geotechnical properties and hazards including earthquake-induced soil liquefaction and slope instability, intact rock properties, rock mass properties, major structural discontinuities and structural features, in-situ stresses, seismicity, and development of a descriptive geomechanical framework based on these data.

Section 5 presents the long-term future evolution of the NPDDF site considering Ottawa River flooding, glaciation (loading, erosion and permafrost), geological disturbances and hazards (e.g., reactivation of structures, volcanism and neotectonics), and seismic hazard assessment.

Section 6 provides summary and conclusions, including description of the geosphere site model, and a comparison of EIS and 2021 Updated Geosynthesis information and CNSC (2017) RegDoc 2.9.1 Appendix B.4 requirements for geological and hydrogeological baselining for environmental assessments under the Canadian Environmental Assessment Act. Section 6 provides an updated listing of geoscience data uncertainties and recommended investigation activities to address data uncertainty provided in the initial 2018 Geosynthesis Report and how the recommended investigations have been incorporated into the 2021 Updated Geosynthesis Report. Section 6 also summarizes overall conclusions of the 2021 Updated Geosynthesis.

Section 7 lists references cited in the 2021 Updated Geosynthesis Report.

2 GEOLOGICAL FRAMEWORK

2.1 Introduction

The regional, local and site geological frameworks for the NPDWF site are described based on provincial and federal government overburden and bedrock geological mapping, Canadian Digital Elevation Data (CDED, Geobase, 2011), Land Information Ontario mapping, completion of a lineament study, and review of the scientific literature and local historic and 2019 investigation and site characterization work completed at and in the vicinity of the NPDWF site and at the CRL site.

2.2 Physiography and Geomorphology

Physiographic terrain features and the key landforms (i.e., geomorphology) including land topography and bathymetry of the adjacent Ottawa River of the NPDWF and surrounding area are outlined below.

2.2.1 Terrain Physiographic Features

Figure 2.1 shows the regional and local physiography or terrain features in the vicinity of the NPD site based on Chapman and Putnam (2007). Figure 2.1 and subsequent local figures show the NPDWF site defined based on the updated groundwater model domain of Calder (2019a). Figure 2.1 shows that the physiography of the vicinity of the NPDWF site is classified into a set of five physiographic units based on the presence of sediment deposits as shallow till and rock and distinct landforms as eskers, sand plains, kame moraines and spillways. Spillways and shallow till and rock are the main physiographic terrain features on the NPD site. Sand and gravel deposits comprise most of the spillway landforms that border the Ottawa River and extend for about a kilometre southwest of the Ottawa River at the NPD site.

All of the identified landforms and sediment deposits are the result of glacial and fluvial processes (Gadd, 1963a). The shallow till and rock physiographic unit occupies the majority of the map area shown in Figure 2.1 and is present in the southern part of the NPD site near the highland proximate to Highway 17. Fluvial spillway landforms associated with major through-going drainage of post-glacial flows occupy most the NPD site adjacent to the Ottawa River. These spillway landforms are occasionally terraced (e.g., southeast of the site). Ice-contact glaciofluvial kame moraines and esker landforms consisting of gravel and sand are evident southeast, southwest and northwest of the NPDWF site. These outwash deposits are not evident at the site. Southeast of the site uniformly fine-grained sand plains deposited by glacial and post-glacial stream and river flows are present. These sand plains represent the northern extent of the Petawawa Sand Plain and do not extend onto the site.

2.2.2 Topography

Figure 2.2 shows the elevation of the ground surface in the vicinity of the NPDWF site based on Canadian Digital Elevation Data (Geobase, 2011). The ground surface at the NPD site rises sharply from the Ottawa River with average elevation of 111 metres above sea level (mASL) to about 128 mASL near the current NPDWF building. Southwest of the current NPD building the ground surface rises to an elevation of about 164 mASL at Highway 17 reflecting the rising bedrock surface

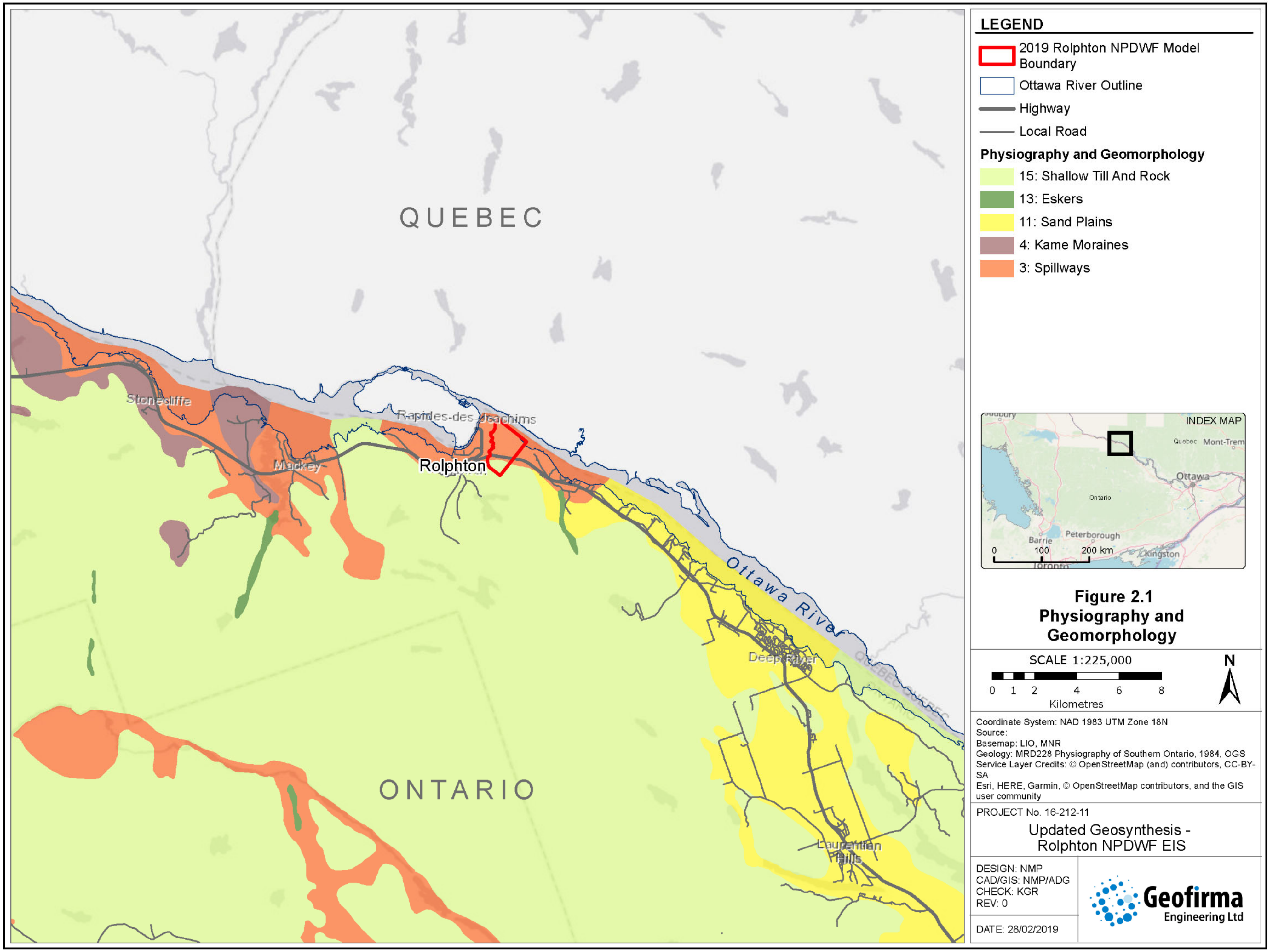

Figure 2.1 Physiography and Geomorphology

G:\Data\Project\ChalkRiver\Map\16-212-11_NPDWF_Geosynthesis\16-212-11_Fig2_1_Physiography.mxd

LEGEND

- 2019 Rolphton NPDWF Model Boundary
- Highway
- Local Road
- Resource / Recreation Road
- Ottawa River Outline
- Waterbody
- Stream

Elevation (mASL)

High : 374

Low : 120

Figure 2.2
Elevation of Ground Surface

SCALE 1:40,000

0 200 400 800 1,200 1,600

Meters

N

Coordinate System: NAD 1983 UTM Zone 18N
Source: MNR, obtained 2012-2015
DEM: NRCan, MNR, 2016
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA
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PROJECT No. 16-212-11

Updated Geosynthesis - Rolphton NPDWF EIS

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR
REV: 0

DATE: 28/02/2019

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G:\Data\Project\ChalkRiver\Map\16-212-11_NPDWF_Geosynthesis\16-212-11_Fig2_2_ElevationGS.mxd elevations. Southwest of Highway 17 the ground surface rises to elevations of 215 to 220 mASL north of Tee Lake to elevations of 230 to 245 mASL southwest of Tee Lake.

Ground surface elevation on the Quebec side of the Ottawa River, the horst or raised fault block, rises rapidly to about 345 to 370 mASL due to the up-thrown normal faulting along the Mattawa River Fault that is present below the Ottawa River within the larger Ottawa-Bonnechere graben structure.

Average ground slopes on the NPD site range from 0% near the NPD buildings to 33% northeast of the buildings adjacent to the Ottawa River. The average ground slope between the buildings and Highway 17 approximates 5%.

2.2.3 Bathymetry

Bathymetric data on depth of water in the Ottawa River opposite the NPDWF site are summarized in Figure 8.3-10 of the EIS after Lee (2014). These local bathymetric data show the maximum depth of the Ottawa River is about 19-20 m (elevation of 91-92 mASL) in the central part of the river. The base of the river uniformly slopes upward from the middle to the southwest and northeast shores in Ontario and Quebec.

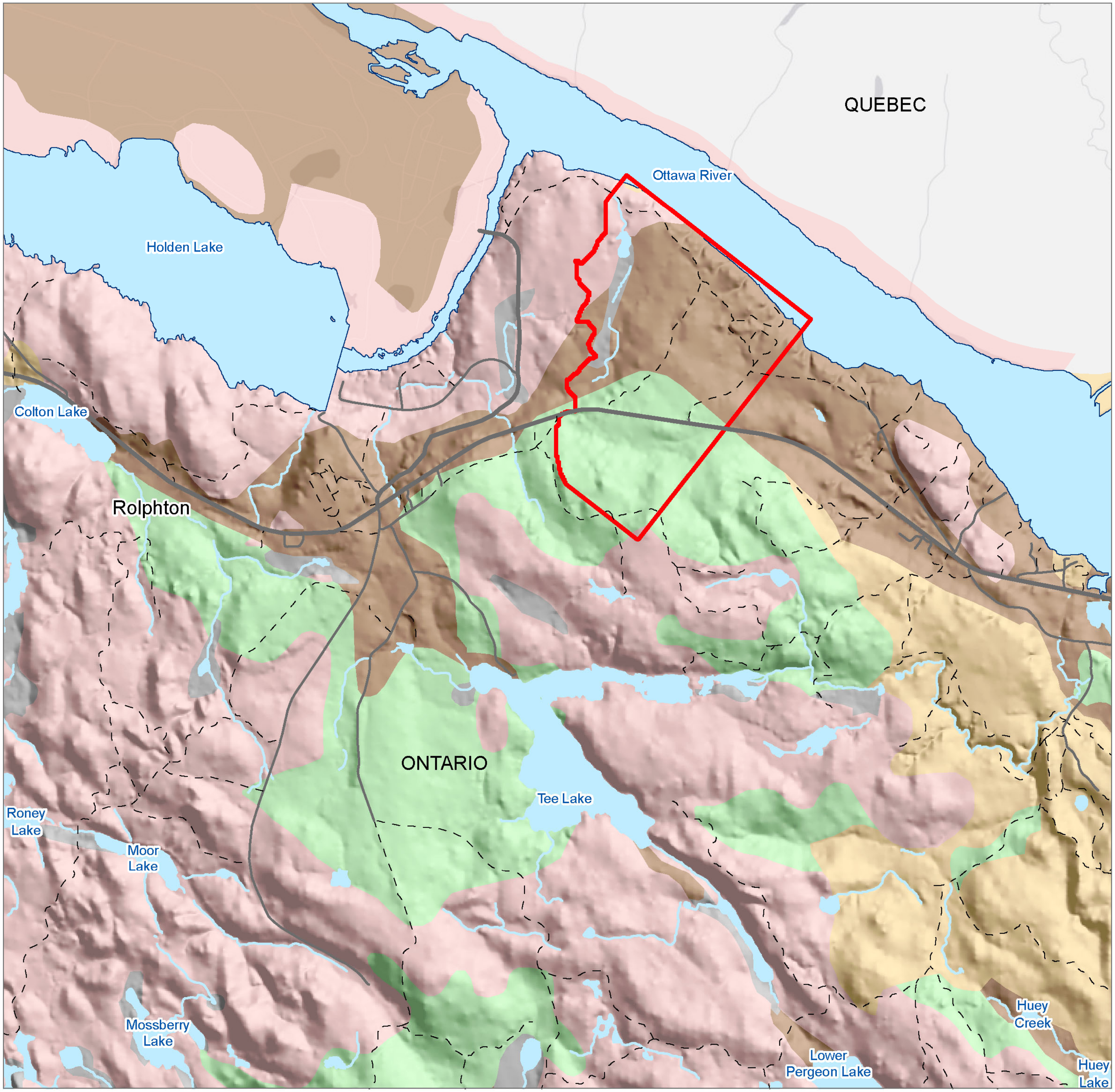
2.3 Quaternary Geology and History

2.3.1 Regional and Local

Figure 2.3 shows the surficial geology of the NPDWF site and surrounding area based on Ontario Geological Survey (OGS, 2010) digital mapping. Figure 2.3 shows the overburden units and areas of exposed bedrock or thin (<2 m thick) overburden cover. OGS (2010) mapping is largely based on earlier Quaternary mapping by Gadd (1963a) of Pleistocene and recent overburden units in the Chalk River area. Gadd (1963a) observed that the overburden deposits of the map area recorded a single glacial event of Wisconsinan (75,000 to 11,000 years ago) and younger age.

OGS (2010) identified five surficial map units in Figure 2.3 comprising from oldest to youngest: Precambrian bedrock, shield-derived silty to sandy till, glaciofluvial deposits, older alluvial deposits and organic deposits. Based on Figure 2.3, older alluvial deposits (predominately) accompanied by Precambrian bedrock and glacial till are present at the NPDWF site northeast of Highway 17, and glacial till is present southeast of Highway 17.

Gadd (1963a) identified the bedrock geology as mainly pink and grey Precambrian granitic gneisses with some granite, pegmatite, amphibolite and Grenville-type metasedimentary gneisses. Gadd (1963a) provides a more detailed and local description of overburden deposits on and near the NPD site that are worth repeating here. The OGS glacial till map unit is described by Gadd (1963a) as non-calcareous, sandy grey till comprising material from silt to boulder size in a heterogeneous mixture. Both Gadd (1963a) and Gadd (1963b) describe the upper metre or so of the till as a poorly sorted lag gravel having enhanced permeability due to removal of fine material caused by fluvial and marine wave action. This enhanced permeability of the upper till surface is an important hydrogeological characteristic of the glacial till unit at the NPD site.



LEGEND

- 2019 Rolphton NPDWF Model Boundary
- Highway
- Local Road
- Resource / Recreation Road
- Ottawa River Outline
- Waterbody
- Stream

Surficial Geology

- 1: Precambrian bedrock
- 5a: Shield-derived silty to sandy till
- 7: Glaciofluvial deposits
- 12: Older alluvial deposits
- 20: Organic deposits

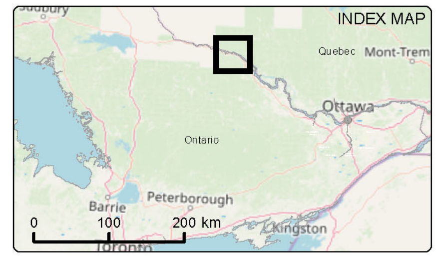


Figure 2.3
Surficial Geology

SCALE 1:40,000

0 200 400 800 1,200 1,600
Meters

N

Coordinate System: NAD 1983 UTM Zone 18N
Source: MNR, obtained 2012-2015
Surficial Geology: MRD 128_REV, OGS, 2010
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA
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DESIGN: NMP
CAD/GIS: NMP/ADG
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REV: 0

DATE: 28/02/2019

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The OGS glaciofluvial map unit is described by Gadd (1963a) as consisting of two units: an older glacial gravel unit and a younger sand unit. The older glacial gravel unit is described by Gadd as bouldery sand and gravel, mainly in esker, kame and outwash deposits. The younger sand unit is described by Gadd as uniform fine-grained grey to yellow-buff sand mainly deltaic includes dunes, some gravel, and minor banded silt deposits. The OGS older alluvial map unit is described by Gadd (1963a) as fluvial gravel comprised of medium to coarse gravel in abandoned river terraces. The OGS organic map unit is described by Gadd (1963a) as bog deposits; mainly peat, some muck.

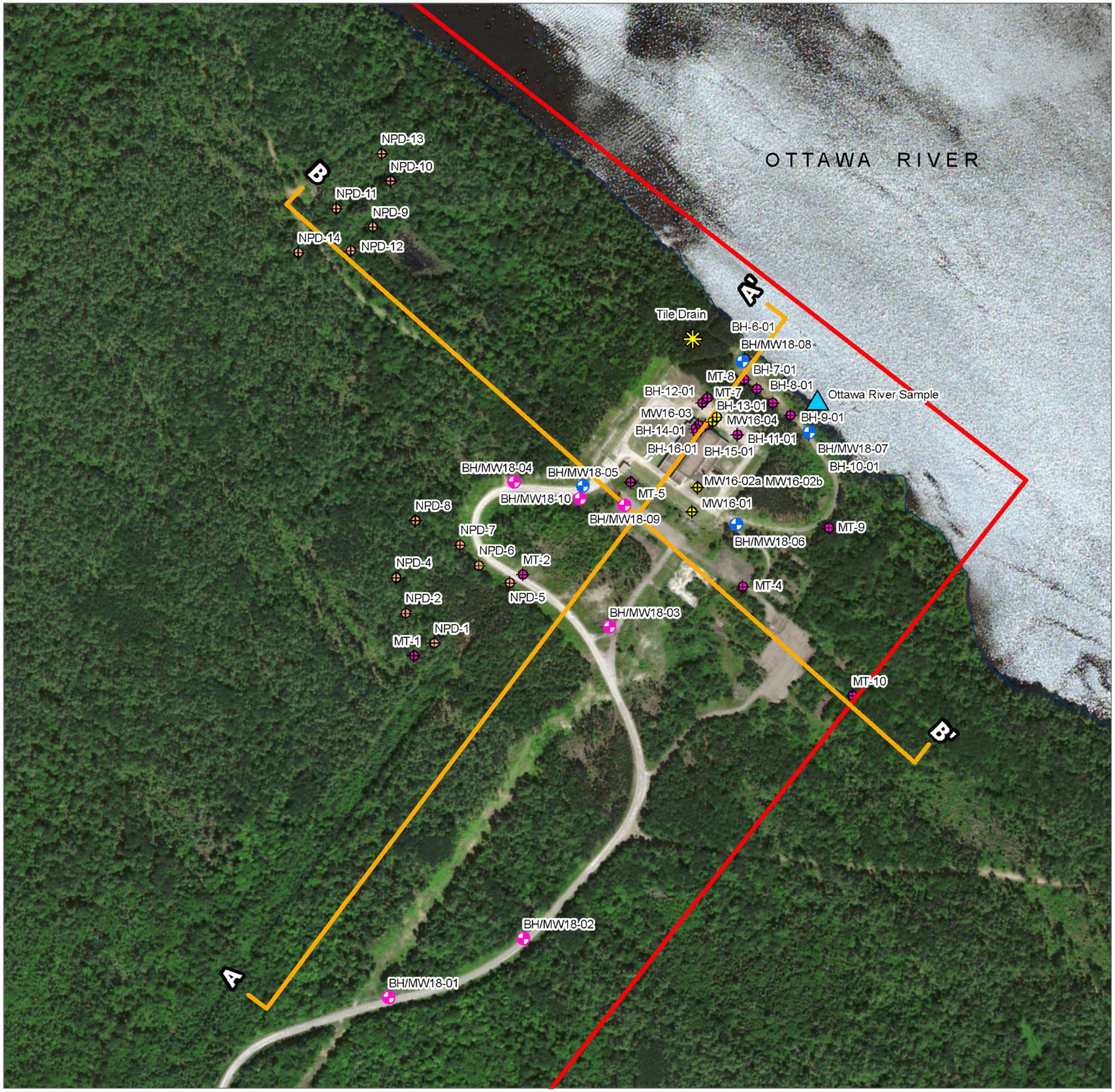
The glacial gravel unit and the sand unit of Gadd (1963a) are not present on the NPD site, but are situated southeast, southwest and northwest of the site as evident by the kame moraine and esker deposits shown on Figure 2.1. The fluvial gravel unit is the dominant overburden type at the location of the NPD buildings and downslope to the Ottawa River.

2.3.2 NPD Site

Investigations of the NPD site (see Figure 2.4 for locations of recent and historical boreholes and monitoring wells) show the surficial overburden at the site consists of fluvial sands and gravels and fills around the building and along the shoreline, overlying silty sand till to sand, gravel and cobble till overlying a boulder glacial till deposited upgradient of the building (Hydro-Electric Power Commission of Ontario, 1956; Killey and Munch, 1988; 1989; MacLarentech Inc., 1990; John D. Paterson and Associates, 2002; Killey, 2014; Geofirma Engineering Ltd., 2019). In undisturbed areas across the region and locally, a “boulder pavement”, consisting of rounded stones up to 2 m in diameter, covers the surface (Killey and Munch, 1989), similar to the soil below without the fine fraction, consistent with descriptions by Gadd (1963a). Coarse sand is the major component of the fluvial sands and gravels, with sand and gravel strata common (Killey, 2014).

Based on Killey and Munch (1988), a “dense silty very stony sand till” underlies the sands and gravels at boreholes NPD-1 and NPD-5 and is assumed to lie directly on the bedrock for an unknown thickness throughout the Landfill 1 area located southwest of the NPD building. Figure 8.5-8 of the EIS shows the locations of the NPD landfills and boreholes. Till does not lie below the fluvial sands and gravel throughout the site, as Killey (2014) notes that fluvial sands and gravel lie directly over bedrock in some areas. Killey and Munch (1989) differentiate the till from the fluvial sand and gravels by increasing return of silt-sized materials. They note that the surface exposures of till in the region are sand and gravel with silt and boulders up to 2 m in diameter, and that the till is geochemically different than the fluvial sands and gravels, indicative of lower permeability sediments. MacLarentech Inc. (1990) identifies mainly till in the overburden of several wells near the shoreline (e.g., MT-7 and MT-8 north of NPD building), however, these are identified as disturbed native glacial till used as fill.

Hydro-Electric Power Commission of Ontario (1956) describes the thick overburden sequence in the middle of the NPD site as moderately dense, fine- to medium-grained sand with gravel and boulders with pervious layers present. Historical descriptions of the overburden at the NPD site have been limited by the difficulty of recovering samples of the gravel, cobble and boulder overburden with conventional augering and soil sampling equipment. In most historical boreholes, the identification of gravel, cobble and boulder fluvial and glacial deposits was based on difficult drilling conditions and the inability to recover representative samples of these materials.



LEGEND

- 2019 Rolphton NPDWF Model Boundary
- Ottawa River Outline
- Ottawa River Sampling Location
- Tile Drain Sampling Location

Boreholes and Monitoring Wells

- Geofirma Overburden
- Geofirma Bedrock
- Golder
- AECL
- MacLarentech / J.D. Paterson
- Cross Sections

Figure 2.4
Location of Boreholes/ Monitoring Wells and Cross Sections

SCALE 1:6,000

0 25 50 100 150 200
Meters

N

Coordinate System: NAD 1983 UTM Zone 18N
Source: MNR, obtained 2012-2015
Surficial Geology: MRD 128_REV, OGS, 2010
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

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Geofirma Engineering Ltd

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To overcome these limitations, overburden drilling completed in 2018 was completed using PQ soil coring equipment with bedrock coring to confirm the upper surface of competent bedrock (Geofirma Engineering Ltd., 2019).

Figures 2.5 and 2.6 show geological-hydrogeological cross sections A-A' and B-B' constructed perpendicular and parallel to the Ottawa River in the vicinity of the NPDWF based on recent and historical borehole data and the surficial mapping of OGS (2010) and Gadd (1963a). Cross sections A-A' and B-B' show a downward overburden sequence consisting of pockets of sand and gravel fill, fluvial sand and gravel, and silty sand to cobble till and boulder till. The boulder till identified on these cross sections occurs in the vicinity of NPDWF and consists of metre-size boulders directly overlying competent crystalline bedrock. Although historical boreholes inferred till to be bouldery based on poor sample recovery, such till is assumed to be primarily sand, gravel and cobble till in this Updated Geosynthesis Report. Southwest of the NPDWF to Highway 17, the glacial till has a silty sandy texture consistent with overburden mapping of Gadd (1963a).

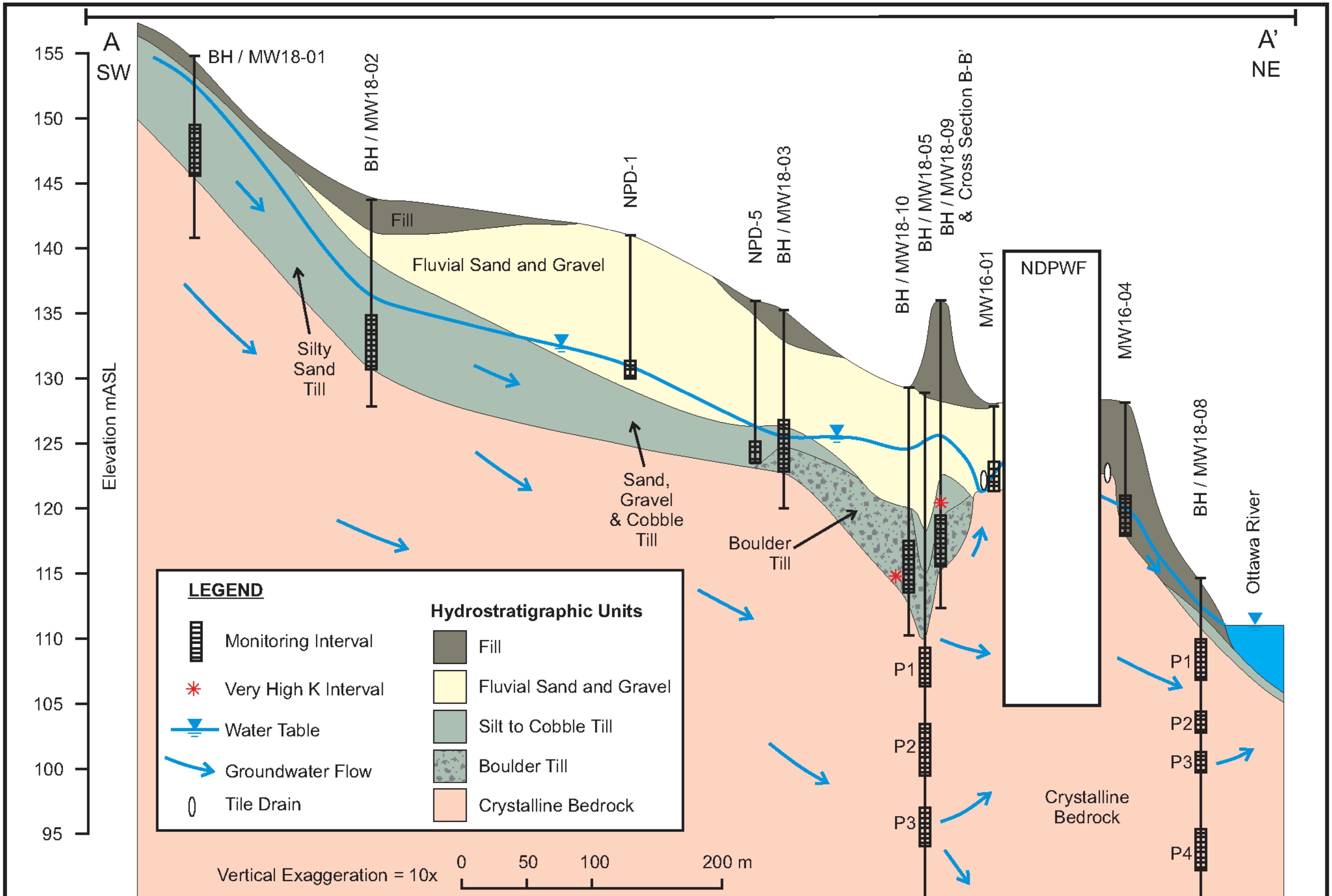
Based on geological cross sections shown in Figures 2.5 and 2.6 as well as those constructed by Hydro-Electric Power Commission of Ontario (1956), Killey and Munch (1988; 1989), and MacLarentech Inc. (1990), overburden thickness at the NPD site ranges from about 2 m near the Ottawa River up to about 15-18 m southwest of the NPDWF and thinning to 5 to 7 m near Highway 17. Overburden thickness adjacent to the NPDWF building averages 5 to 6 m. Overburden thickness northwest and southeast of the NPDWF as shown in cross section B-B' is interpreted to average about 10 to 15 m based on available borehole data and OGS (2010) and Gadd (1963a) overburden mapping. The noteworthy bedrock high at MW18-06 creates an overburden thickness of about 3.0 m and limits the southeastward extent of the fluvial sand and gravel unit from the area of the NPDWF.

2.4 Bedrock Geology

2.4.1 Regional Geological Setting

Information on the regional geological setting and tectonic history of the NPD site is available from provincial regional mapping studies (Lumbers, 1972; 1974; 1976; 1982; Katz, 1969, 1976; Easton, 1992), the national earthquake database (NRCan, 2018), the geoscientific literature (Kay,1942; Kumarapeli and Saul, 1966; Wynne-Edwards, 1972; Kumarapeli, 1976; Forsyth, 1981; Hanmer, 1988; Thomas, 1989; Rivers *et al*., 1989; Dickin and McNutt, 1991; Easton, 1992; Hyodo *et al*., 1993; Kamo *et al*., 1995; Carr *et al*., 2000; Ketchum and Davidson, 2000; Davidson, 1986; 2008; Davidson *et al*., 2009; Bleeker *et al*., 2011; Halls *et al*. 2015), from geological mapping (Raven Beck Environmental Ltd., 1994a) for the Federal Ministerial Siting Task Force, and from preliminary geological synthesis (Thivierge, 2011), descriptive geosphere site model (McCrank, 2016a) and integrated geosynthesis (McCrank, 2016b) studies undertaken for the proposed CRL Geological Waste Management Facility.

Historical regional mapping of the Precambrian bedrock by the OGS (Easton, 1992) places both the NPD and CRL sites within the lithostructural Opeongo Domain of the Algonquin (Lac Dumoine) Terrane of the Central Gneiss Belt, of the Grenville Province of the Canadian Shield. Both sites are also located near the northern limit of the Ottawa-Bonnechere Graben proximate to the regionally extensive Mattawa Fault that defines the location of the Ottawa River. Consequently, both sites have a similar lithostructural setting (see Figures 2.7 and 2.8).



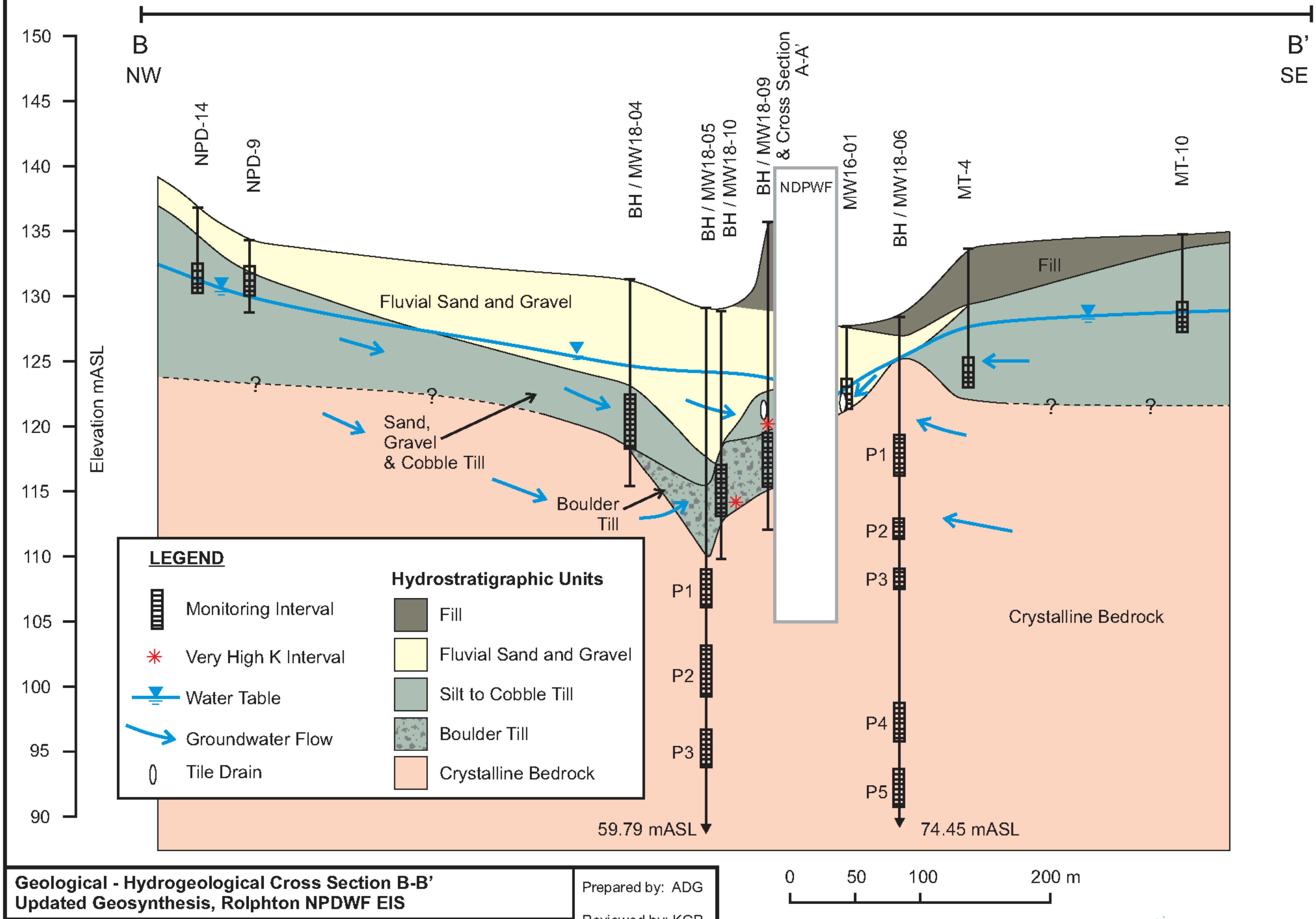
Geological - Hydrogeological Cross Section A-A'
Updated Geosynthesis, Rolphton NPDWF EIS

FIGURE 2.5

Doc. No.: "P:\Projects\2016\16-212-1 Arcadis CNL Chalk River\Figures\16-212-11_Figures\WorkingFigures\16-212-11_Fig2_5_CrossSectionA.cdr"

Prepared by: ADG
Reviewed by: KGR
Date: 19-Feb-19

Geofirma Engineering Ltd



Geological - Hydrogeological Cross Section B-B'
Updated Geosynthesis, Rolphton NPDWF EIS

FIGURE 2.6

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Reviewed by: KGR
Date: 19-Feb-19

Geofirma Engineering Ltd

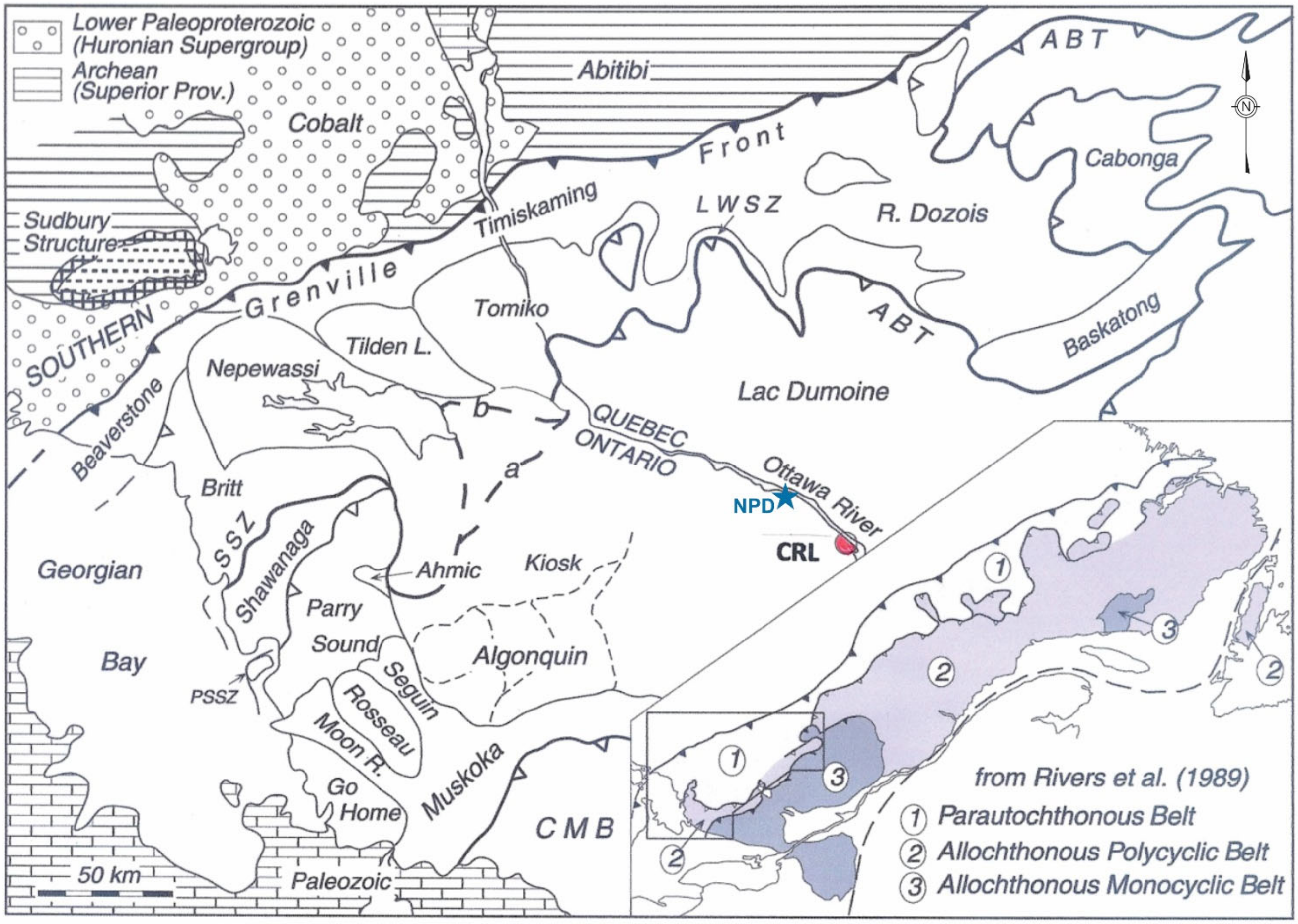
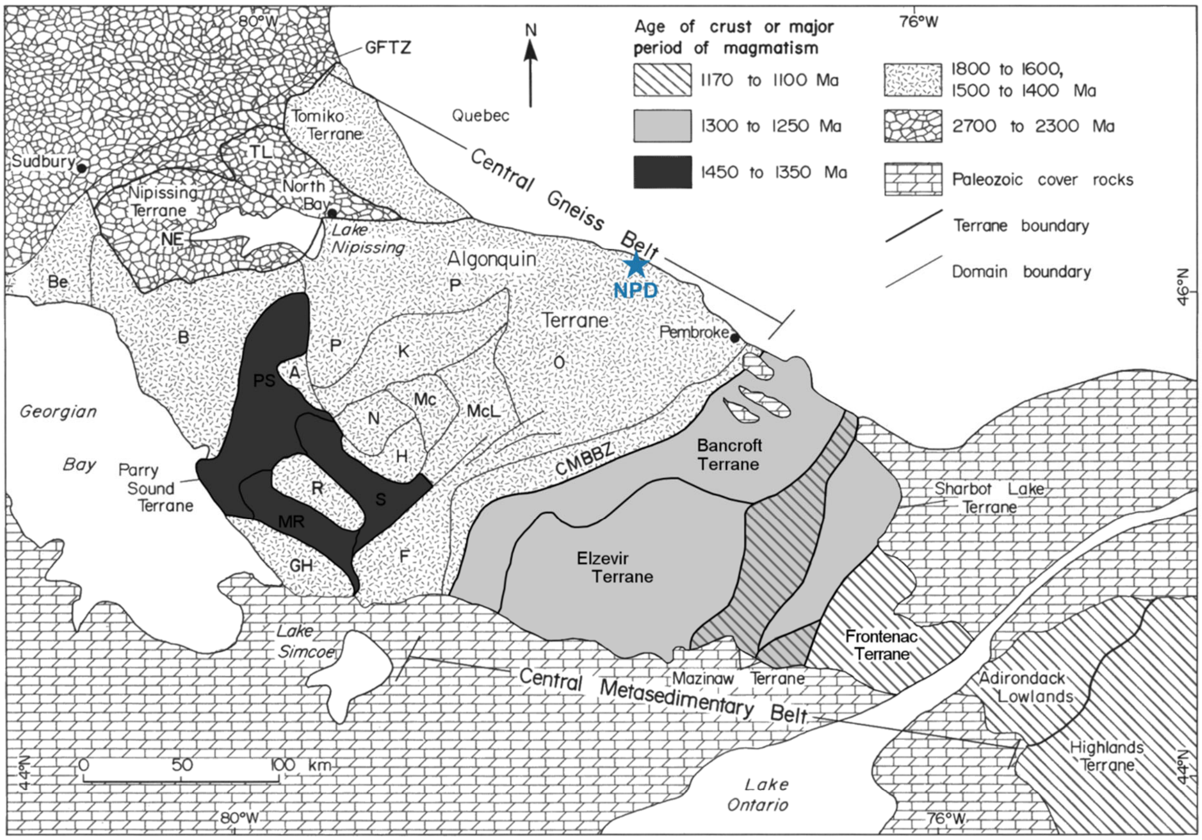


Figure 2.7 Lithotectonic Subdivisions of the Southwest Grenville Province (from Ketchum and Davidson, 2000)

The Grenville Province is a complex orogenic belt circa 1100 million years in age that truncates several older geologic provinces (Easton, 1992; Wynne-Edwards, 1972). It extends from Georgian Bay in Ontario to the Labrador and the Atlantic Ocean. Rivers *et al*. (1989) (see Figure 2.7) subdivided the Grenville Province into three broad belts or terranes; a northwestern parautochthonous (meaning in-situ or slightly displaced) polycyclic belt at the orogenic front, a central allochthonous (meaning transported from its site of origin) polycyclic belt that contains the NPDWF site, and a southeastern allochthonous monocyclic belt. The northwestern and central polycyclic belts, that collectively make up the Central Gneiss Belt (CGB), are older rocks that have been subject to Grenville and older orogenic deformations. The southeastern monocyclic belt, that relates to the Central Metasedimentary Belt (CMB), consists of younger rocks only subject to deformation during the Grenville orogeny that occurred about 1190 to 1060 million years ago.

The Allochthon Boundary Thrust (ABT) shown in Figure 2.7 is a cryptic continental suture that separates the parautochthonous belt from the allochthonous polycyclic belt. Part of the ABT (dashed line ‘b’) is modified from an earlier position (dashed line ‘a’) proposed by Davidson (1986). The Parry Sound shear zone (PSSZ) and Lac Watson shear zone (LWSZ) form parts of the ABT shown on Figure 2.7. SSZ in Figure 2.7 stands for Shawanaga shear zone.

The Grenville Province in Ontario is subdivided, from northwest to southeast into the Grenville Front Tectonic Zone, the Central Gneiss Belt and the Central Metasedimentary Belt (Figure 2.8). Figure 2.8 shows the lithotectonic subdivisions of the Central Gneiss Belt and Central Metasedimentary Belt based on work of Easton, 1992; Davidson, 1986; Dickin and McNutt, 1991; Carr *et al*., 2000; and Ketchum and Davidson, 2000. The Central Gneiss Belt, which contains both NPD and CRL sites, consists mainly of upper amphibolite and local granulite facies, quartzofeldspathic gneisses chiefly of igneous origin (orthogneiss) with subordinate paragneisses (sedimentary origin).



Abbreviations

A	Ahmic Domain	GH	Go Home Domain	NE	Nepewassi Domain
B	Britt Domain	H	Huntsville Domain	O	Opeongo Domain
Be	Beaverstone Domain	K	Kiosk Domain	P	Powassan Domain
CMBBZ	Central Metasedimentary Belt Boundary Zone	Mc	McCraney Domain	PS	Parry Sound Domain
F	Fishog Domain	McL	McClintock Domain	R	Rosseau Domain
GFTZ	Grenville Front Tectonic Zone	MR	Moon River Domain	S	Seguin Domain
		N	Novar Domain	TL	Tilden Lake Domain

Figure 2.8 Lithotectonic Terranes, Domains and Crustal Ages within the Central Gneiss Belt and the Central Metasedimentary Belt in Ontario (from Easton, 1992).

The NPD and CRL sites are located within the Opeongo Domain of the Algonquin Terrane north of Pembroke which extends into Quebec as the Lac Dumoine domain. The Algonquin Terrane in Ontario consists of quartzofeldspathic gneisses of plutonic and supracrustal origin characterized by a complex pattern of structural domains (Easton, 1992, Davidson, 1986). The Opeongo Domain is underlain by large circa 1450-million-year-old monzonitic plutons including the Algonquin Batholith that underlies most of the eastern and northern parts. Between these plutons are paragneisses of amphibolite facies

(Easton, 1992). Figure 2.9 shows a regional compilation of bedrock geology from Ontario mapping (Lumbers, 1976; 1982) and Quebec mapping (Katz, 1969; 1976) prepared by Thivierge (2011) that includes the NPDWF and CRL sites. Figure 2.9 identifies the bedrock geology of the NPD site as biotite gneiss.

2.4.2 Regional Tectonic History

The Grenville orogeny, likely resulting from continental collision from the southeast, involved protracted folding and north-west directed thrusting, juxtaposition of several contrasting lithotectonic domains across broad ductile shear zones within the Central Gneiss Belt and emplacement of the Central Metasedimentary Belt upon the Central Gneiss Belt (Hanmer, 1988).

Five periods of magmatic activity have been recognized within the Central Gneiss Belt of Ontario (Easton, 1992):

1. 1740 to 1680 million years ago – plutonism in the Algonquin Terrane;
2. 1450 to 1420 million years ago – most widespread magmatic episode in the Central Gneiss Belt;
3. 1350 to 1320 million years ago – associated with tonalite-granodiorite gneiss intrusion in the Opeongo Domain;
4. 1250 million years ago – associated with localized granite plutonism;
5. 1170 million years ago – associated with mafic gabbroic to locally ultramafic intrusions (only magmatic event of Grenvillian age).

Major periods of Grenville deformation that resulted in stacking of domains and terranes within the Central Gneiss Belt occurred from circa 1180 to 1030 million years ago (Easton, 1992). Post-Grenville intrusive and tectonic events include intrusion of Grenville swarm diabase dykes and activation of faulting associated with the Ottawa-Bonnechere graben system (see Figures 2.10 and 2.11). Grenville dyke swarms, which occurred about 570-590 million years ago (Halls *et al*., 2015; Davidson *et al*., 2009; Kamo *et al*., 1995), are discontinuous, occupying narrow, long, linear east-west striking, fault-controlled valleys. Diabase dykes range in thickness from 0.5 to 30 m with some dykes sheared and brecciated by post-emplacement faulting (Lumbers, 1976).

Carbonatite and alkalic complexes shown in Figure 2.10 are mappable bedrock domains for mineral exploration purposes based on the mineralogy of igneous intrusive complexes including dykes, sills, breccias and veins. Carbonatites are igneous rocks with >50% carbonate minerals (calcite, dolomite) present in intrusive complexes. Alkalic complexes are igneous rocks enriched with Na and K minerals such as feldspathoids, pyroxenes and amphiboles in intrusive complexes. Other than providing mapping of bedrock domains for metallogeny purposes, they provide no significance to the 2021 Updated Geosynthesis Report.

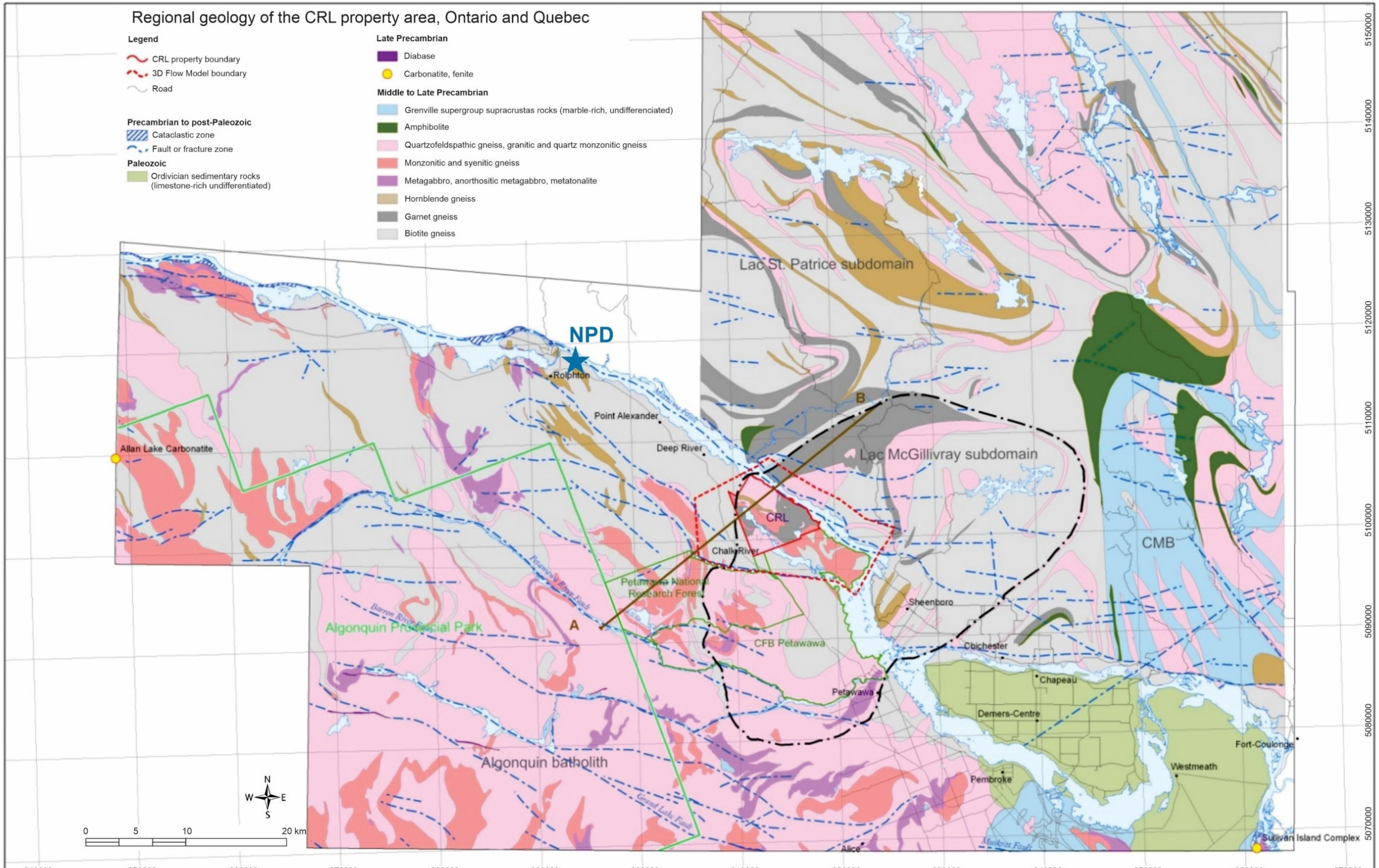


Figure 2.9 Regional Bedrock Geology of NPD and CRL Sites (from Thivierge, 2011)

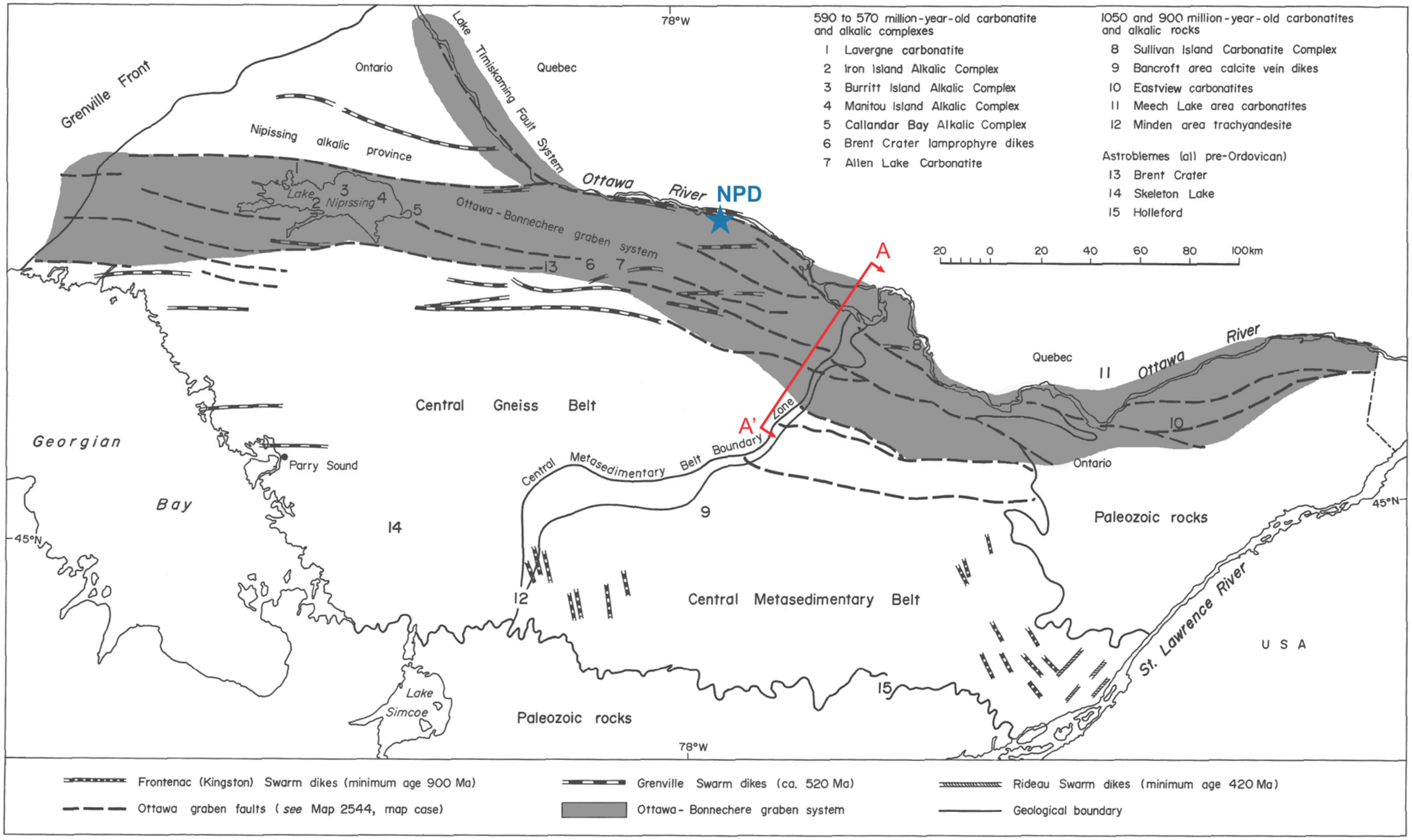


Figure 2.10 Distribution of post-Grenville Orogeny Dykes and the Ottawa-Bonnechere Graben System. Cross Section A-A' is illustrated in Figure 2.12. Original Figure is from Easton (1992), Cross Section Line is Added from Bleeker *et al*. (2011) based on Original Work of Kay (1942).

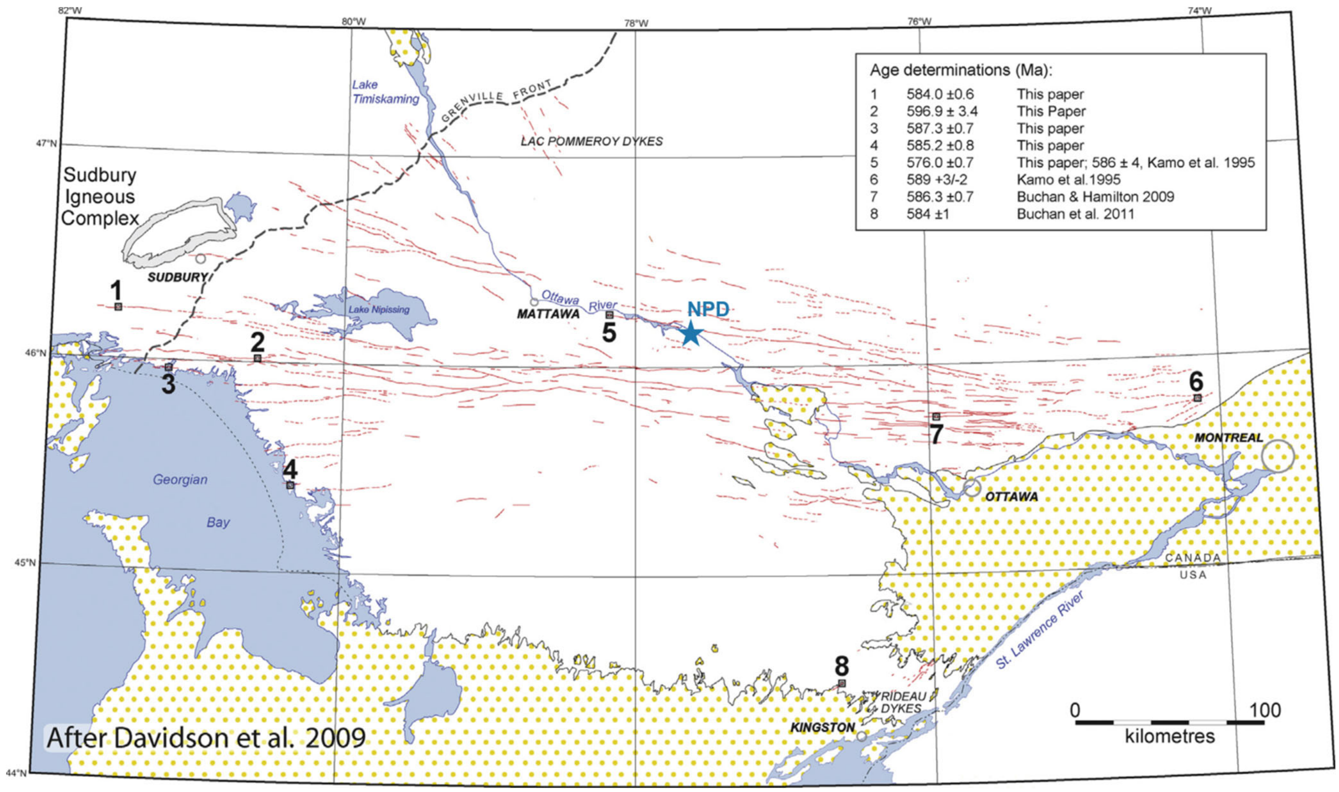


Figure 2.11 Regional Map of Grenville Dyke Swarm based on Davidson *et al*., (2009) and Dyke Ages (from Halls *et al*., 2015) The Dykes are shown in Red Thin Lines

The Ottawa-Bonnechere graben system (Kay, 1942) runs from Montreal to Lake Timiskaming, displays a rift valley morphology and is about 60 km wide and 700 km long (Kumarapeli and Saul, 1966; Kumarapeli, 1976; Kamo *et al*., 1995). In the area of the NPDWF, the graben trends west-northwesterly with the major, steeply southwest-dipping, Mattawa Fault defining the northeast margin of the graben. The graben probably developed as a plume-generated failed rift related to the opening of the proto-Atlantic (Iapetus) Ocean. The graben system is characterized by a network of faults and lineaments that strike east-west and northwest-southeast. This fault system developed after the peak of Grenville metamorphism and has been active intermittently since that time, with nodes of activity about 575, 450-420, and 190-170 million years ago (Easton, 1992). Figure 2.12 shows a geological northeast-southwest cross section of the Ottawa-Bonnechere graben system constructed from Quebec to Ontario. The location of this original Kay (1942) cross section is shown on Figure 2.10.

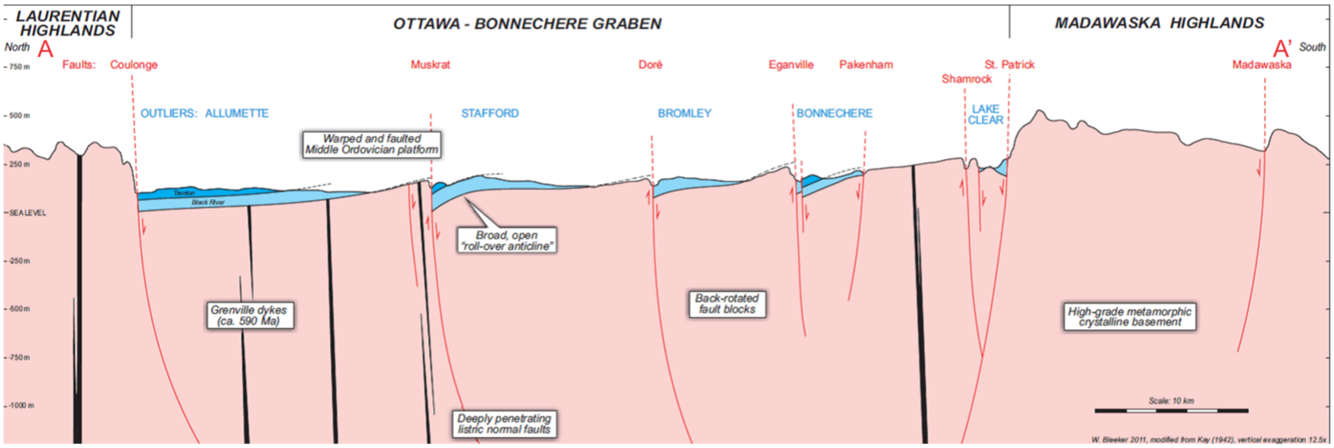


Figure 2.12 Northeast-Southwest Cross Section of Ottawa-Bonnechere Graben System from the Laurentian Highlands in Quebec to the Madawaska Highlands in Ontario (from Bleeker *et al*., 2011)

2.4.3 Local Geological Setting

Figures 2.13 and 2.14 show the currently available digital bedrock geological mapping including mapped faults for the local Ontario and Quebec areas proximate to the NPD site. Figure 2.13, based on Ontario Geological Survey (2011), shows the local bedrock geology at the NPD site to be layered biotite gneisses and migmatites of uncertain protolith with minor amphibolite mafic gneiss.

Other noteworthy Ontario local bedrock lithologies include anorthosite and alkalic igneous rocks and tonalite, granodiorite, monzonite, granite and syenite derived felsic gneisses. Northwest-southeast and east-west striking OGS-mapped faults are located south of the NPD site. No OGS-mapped faults intersect or are projected to intersect the NPDWF.

Figure 2.14, based on Système d'information géomine du Québec (SIGÉOM, 2018), shows that the bedrock geology in Quebec opposite the NPDWF site is similarly mapped as primarily hornblende biotite paragneiss and migmatitic granitic gneiss. Secondary lithologies of hornblende and amphibolite, biotite gneiss and diabase dykes are mapped in the local area of Quebec. These Quebec lithologies are essentially the same bedrock lithologies mapped by OGS (2011) in Ontario. SIGÉOM (2018) also shows the presence of east-west and northeast-southwest striking faults northeast of the NPDWF site. No SIGÉOM-mapped faults intersect or are projected to intersect the NPDWF.

OGS detailed preliminary mapping of local bedrock geology was also reported by Lumbers (1976). Preliminary Map P1197 of the Mattawa-Deep River Area (Eastern Half) reproduced in Figure 2.15 shows the lithological and structural information recorded in local bedrock outcrops. Figure 2.15 shows the following bedrock geological information from local bedrock outcrops:

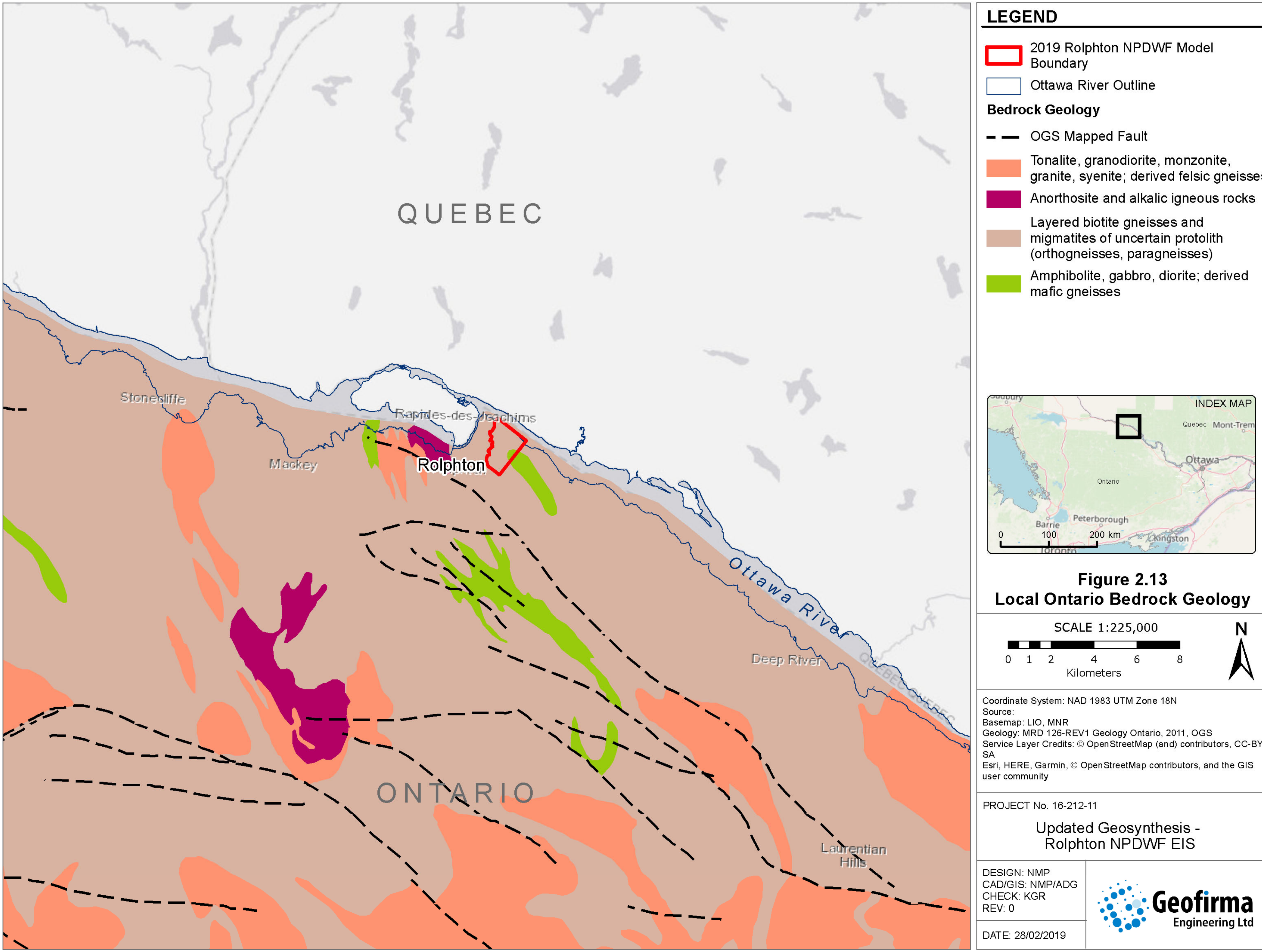


Figure 2.13
Local Ontario Bedrock Geology

Coordinate System: NAD 1983 UTM Zone 18N
Source:
Basemap: LIO, MNR
Geology: MRD 126-REV1 Geology Ontario, 2011, OGS
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA
Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS user community

PROJECT No. 16-212-11

Updated Geosynthesis - Rolphton NPDWF EIS

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR
REV: 0

DATE: 28/02/2019

Geofirma Engineering Ltd

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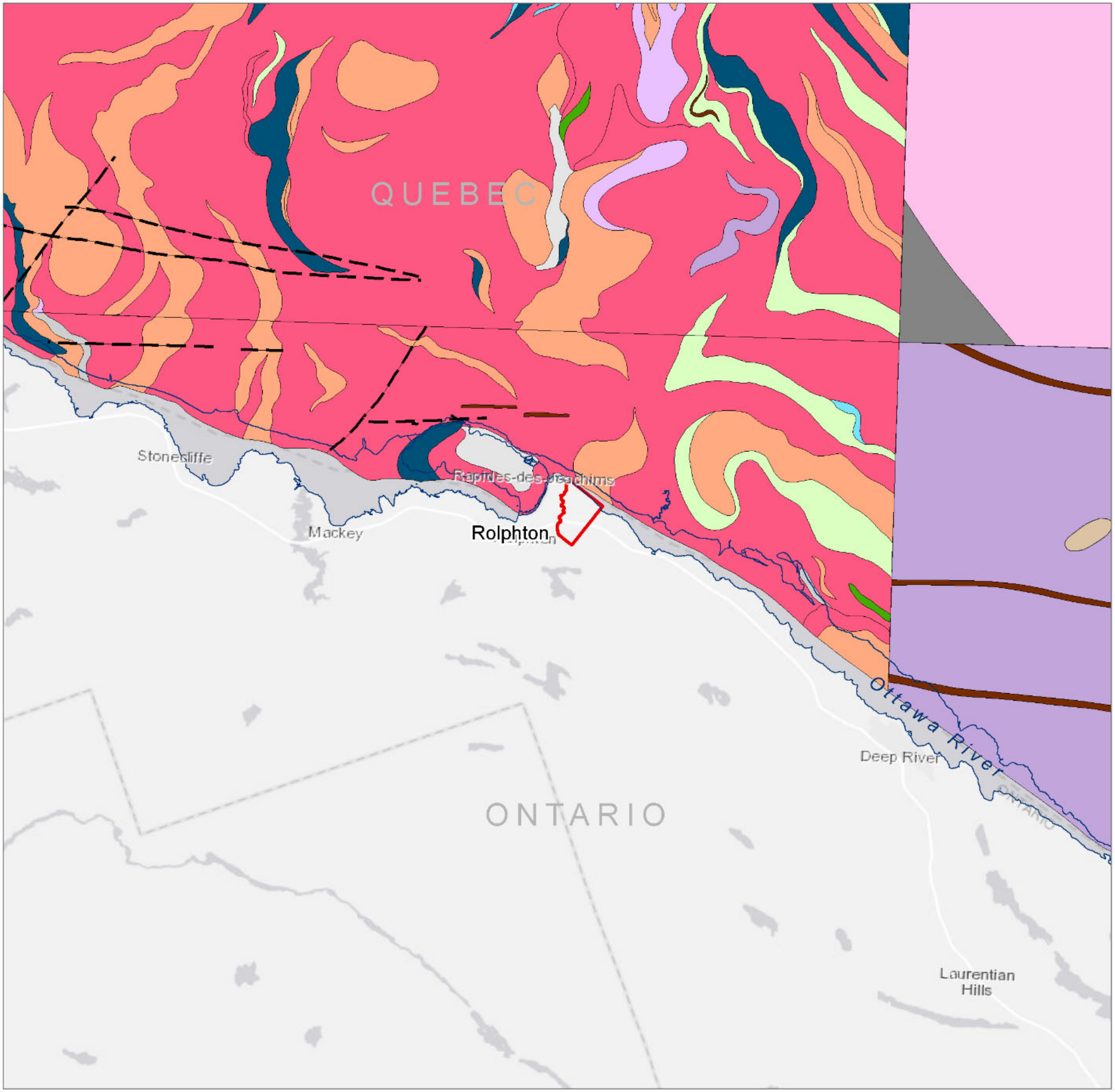

LEGEND

- 2019 Rolphton NPDWF Model Boundary
- Ottawa River Outline

Geology

- SIGEOM Mapped Fault
- Sand, gravel, silt, till
- Diabase dyke
- Metagabbro
- Garnet biotite paragneiss
- Hornblende biotite paragneiss
- Biotite gneiss
- Hornblende and amphibolite
- Amphibolite
- Tonalitic dioritic granitic and granulitic gneisses, migmatites
- Undifferentiated gneissic complex
- Migmatitic granitic gneiss

Figure 2.14
Local Quebec Bedrock Geology

SCALE 1:225,000

0 1 2 4 6 8
Kilometers

N

Coordinate System: NAD 1983 UTM Zone 18N
Source: Basemap: LIO, MNR
Geology: SIGEOM, QC
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA
Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS user community

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Updated Geosynthesis - Rolphton NPDWF EIS

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR
REV: 0

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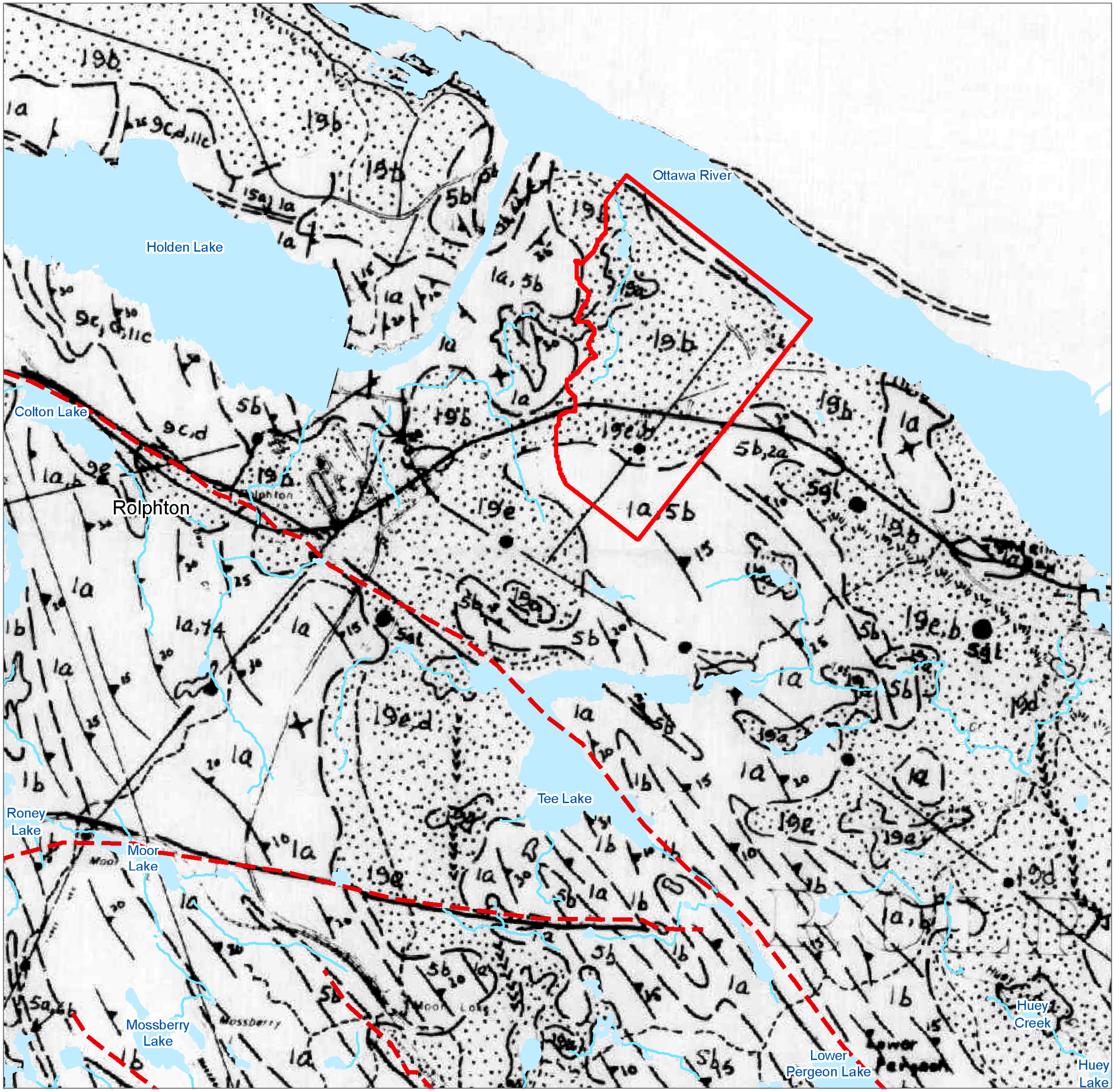

LEGEND

- 2019 Rolphton NPDWF Model Boundary
- Waterbody
- Stream
- OGS Mapped Fault
- Geologic Contact
- Gneissosity - horizontal, inclined
- Esker

Overburden and Bedrock Geology

19a - Swamp, bog and peat
19b - Fluvial and lacustrine silt, sand and gravel
19d - Glaciofluvial sand, gravel and boulders
19e - Sandy bouldery glacial till
15a - Diabase dykes
9c,d - Anorthosite and related mafic rocks
5a,b - Hornblende gneiss
2a - Biotite gneiss
1a,b - Migmatitic biotite gneiss

Figure 2.15
Lumbers' Preliminary Local Bedrock Geolgy

SCALE 1:40,000

0 200 400 800 1,200 1,600
Meters

N

Coordinate System: NAD 1983 UTM Zone 18N
Source: LIO, MNR
Faults: MRD 126-REV1 Geology Ontario, 2011, OGS
Geology: Lumbers 1976, P1197, OGS
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA

PROJECT No. 16-212-11
Updated Geosynthesis - Rolphton NPDWF EIS

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR
REV: 0

DATE: 28/02/2019

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- Bedrock lithology (i.e., Units 1, 5 and 2) proximate to the NPDWF are generally mapped as migmatitic biotite gneiss with subordinate hornblende biotite gneiss and biotite gneiss. Unit 1a is specifically mapped as medium-grained biotite, K-feldspar, quartz, plagioclase gneiss. Unit 5b is specifically mapped as dark green to dark grey, fine- to medium-grained, garnetiferous, biotite, amphibole, quartz, plagioclase gneiss and schist. Unit 2a is specifically mapped as fine- to medium-grained biotite, K-feldspar, quartz, plagioclase gneiss. Collectively, these rocks are simply identified as migmatitic biotite gneiss.
- An east-southeast trending diabase dyke (Unit 15a) is mapped on the north shore of Holden Lake west of the NPDWF site, that if extending eastward might intersect the NPDWF site.
- The bedrock is a folded and faulted suite of gneissic rocks with gneissosity and schistosity oriented parallel to the Ottawa River and dipping moderately to the northeast.

Extensive core drilling, mapping and testing undertaken in support of design and construction of the Des Joachims Power Site (Hydro-Electric Power Commission of Ontario, 1943) located immediately upstream of the NPD site provides additional information on the local geological setting of the NPDWF site. These investigations show:

- The dominant bedrock lithologies are light and dark hornblende biotite gneiss with relative mineralogical composition of biotite ~ hornblende < quartz < plagioclase. Relative abundance of ferro-magnesium minerals and quartzofeldspathic minerals distinguish light versus dark gneisses.

The bedrock is complexly folded and faulted, with planes of weakness associated with schistosity, jointing, tight folds, faults and shear zones.

Geological mapping of bedrock outcrops on and near the NPD site was recently completed by Geofirma Engineering Ltd. (2019a). The results of this local structural and lithological mapping are described in Section 2.4.6.

2.4.4 Regional and Local Structural Geology

Regional and local structural geology of the NPD site is dominated by the major regional structural feature of the Mattawa Fault that defines the course of the Ottawa River and the northern limit of the regional Ottawa-Bonnechere graben system. As shown in Figures 2.9, 2.10, 2.13, 2.14 and 2.15 mapped faulting at both regional and local scales strikes predominantly northwest-southeast to east-west mostly paralleling the alignment of the Mattawa Fault and the Ottawa-Bonnechere graben system.

Abundant regional structural geological information including ductile and brittle structures is available for the CRL property located about 27 km downstream of the NPDWF site based on bedrock outcrop mapping, airborne and ground geophysical surveys and extensive bedrock drilling and testing (Thivierge, 2011; McCrank, 2016a; 2016b). Given the similar structural setting of the NPD and CRL sites, CRL data on regional and local structural geology is applicable to the NPD site.

Rocks at the CRL property and in the surrounding region show shallow- to moderately-dipping gneissosity and mineral aggregate foliation which is extensively folded in surface outcrops and boreholes cores. These mesoscopic ductile structures are part of larger macroscopic folds and synforms and antiforms defined based on grouped bedrock unit assemblages. Thivierge (2011) identifies a series of ductile structural elements in the area of the CRL property that include mineral layering, lineation and folding. Most of these planar ductile structures strike north-northwest with shallow to moderate dip to the northeast toward the Ottawa River and to the southwest. Most of the mineral stretching lineation and fold axes plunge shallowly to the north-northwest.

Brittle structures including faults, major fracture zones and diabase dykes at the CRL property have been tentatively identified based on lineament mapping using air photos, Lidar surveys and airborne and ground geophysical surveys (Raven, 1980; Raven Beck Environmental Ltd., 1994a; Thivierge, 2011; McCrank, 2016a; 2016b). Figure 2.16 illustrates an example of the resultant identified linear features that likely represent brittle structural features in the CRL bedrock. Review and analysis of these and other data shows the following bedrock brittle structural features are interpreted for the CRL site (Raven Beck Environmental Ltd., 1994a; Thivierge, 2011, McCrank, 2016a):

- The large regional-scale northwest-southeast striking, steeply southwest dipping (65º) Mattawa Fault defining the course of the Ottawa River northeast of the CRL site;
- Two site-wide east-west striking regional Grenville diabase dykes in the centre of the CRL site; and
- Interpreted faults generally striking northwest-southeast (parallel to the Mattawa Fault), east-west to east-southeast - west-northwest (such as the Upper Bass Lakes Fault), and subordinate north-northeast - south-southwest (perpendicular to the Mattawa Fault) across the entire CRL site.

These macroscopic brittle structural features are also expressed as steeply dipping fractures with similar orientations in CRL bedrock outcrops (Thivierge, 2011). Interpretation of subsurface borehole fracture logging also shows the dominant presence of fractures subparallel to shallow-dipping gneissosity (Thivierge, 2011) as well as the ubiquitous presence of subhorizontal sheeting joints in shallow bedrock (Raven, 1986). Thivierge (2011) also interpreted subvertical north-northeast trending fractures as the earliest expression of syn- to post-tectonic brittle to brittle-ductile behaviour occurred in the last stages or after the Grenville ductile deformation since these fractures are mainly occupied by syn- to post-tectonic granitic/pegmatitic veins that are representative of high temperature (>700º C) filling materials.

The association of fractures with gneissosity or foliation of Grenville gneisses has also been reported from regional studies of Benson *et al*. (1974) and Raven and Gale (1986). These works described the occurrence of foliation shear zones in underground excavation sites in gneissic rock of the Grenville Province in the Canadian Shield. These studies concluded that foliation shear zones or zones of faulting and fracturing will occur in gneissic rocks of the Grenville Province at orientations parallel to gneissosity. These studies also concluded that typical site investigation techniques (e.g., lineament mapping, drilling and coring) often do not detect some foliation shear zones, and hence such zones should be expected in underground excavations regardless of the results of site investigations.

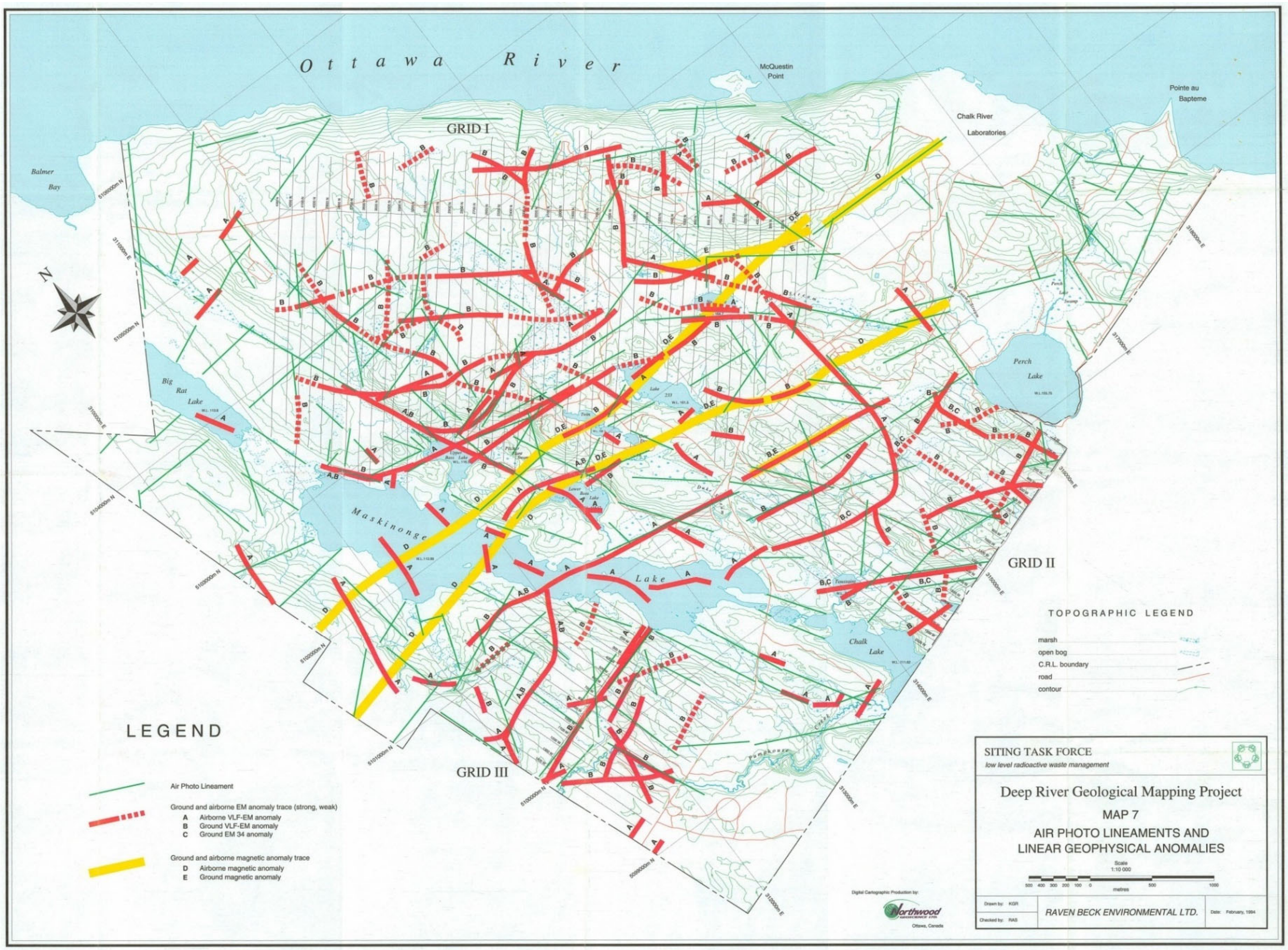


Figure 2.16 Air Photo Lineaments and Airborne and Ground Linear Geophysical Anomalies at CRL

Lumbers (1976) and Hydro-Electric Power Commission of Ontario (1943) provide information on the local structural geology of the NPDWF site. As shown on Figure 2.15, the local bedrock near the NPDWF site as mapped by Lumbers is tightly folded with gneissosity striking northwest-southeast, parallel to the Ottawa River and dipping shallowly to moderately (10º to 30º) to the northeast toward the Ottawa River. Lumbers also mapped northwest-southeast striking faults southeast of site through Tee Lake, and northwest of the site within the Ottawa River. Lumbers also maps distortions in bedrock gneissosity in the area of the Des Joachims hydroelectric power development located immediately northwest of the NPDWF site, with gneissosity primarily striking north-south and moderately dipping east.

Extensive drilling investigations of the Rapides des Joachims site, in particular the main dam site located at the east end of Holden Lake, by Hydro-Electric Power Commission of Ontario (1943) provide important information on the local structural geology. These investigations identified the following bedrock structures at the Rapides des Joachims site:

- Schistosity (foliation or gneissosity) parting planes or fractures;
- Tight folds where folding is extreme such that the fold apex is sheared and crushed resulting in a plane of weakness parallel to schistosity;
- Network of faults evident as topographic lineaments that intersect one another at roughly 45º and 90º; and
- Shear zones located between faults and adjacent to faults, some of which are large and highly fractured creating erosional and weathering depressions in the bedrock surface.

Schistosity, sheared tight folds and thrust faults parallel to schistosity all striking approximately north-south were significant at the east end of Holden Lake, such that the main dam was relocated and realigned to its current location from a previous northeastern location.

2.4.5 Lineament Study

A lineament study was completed to identify major brittle structures in the bedrock of NPDWF and surrounding area using available data sets. Lineaments or linear features in the bedrock identified using topography, satellite imagery and/or airborne geophysics are examined because they provide evidence of the occurrence of major brittle structures (e.g., faults, shear zones) present in bedrock and hence provide information on the regional structural framework and the potential for such major structural features to intersect the NPDWF. The lineament study also supplements the existing regional and local scale geological mapping that has been summarized in previous sections.

2.4.5.1 Data Sources

A review of publicly-available surficial information (digital elevation models and satellite imagery), geological and structural mapping, and geophysical (aeromagnetic) datasets was completed for the NPDWF site and surrounding area. Available data were assessed for quality and potential use and processed as necessary prior to use in the lineament interpretation. A summary of the primary (digital elevation model [DEM] and geophysics) and supporting data (satellite imagery) are presented in Table 2.1.

Table 2.1 Summary of Source Data Information for Lineament Study, NPD Area

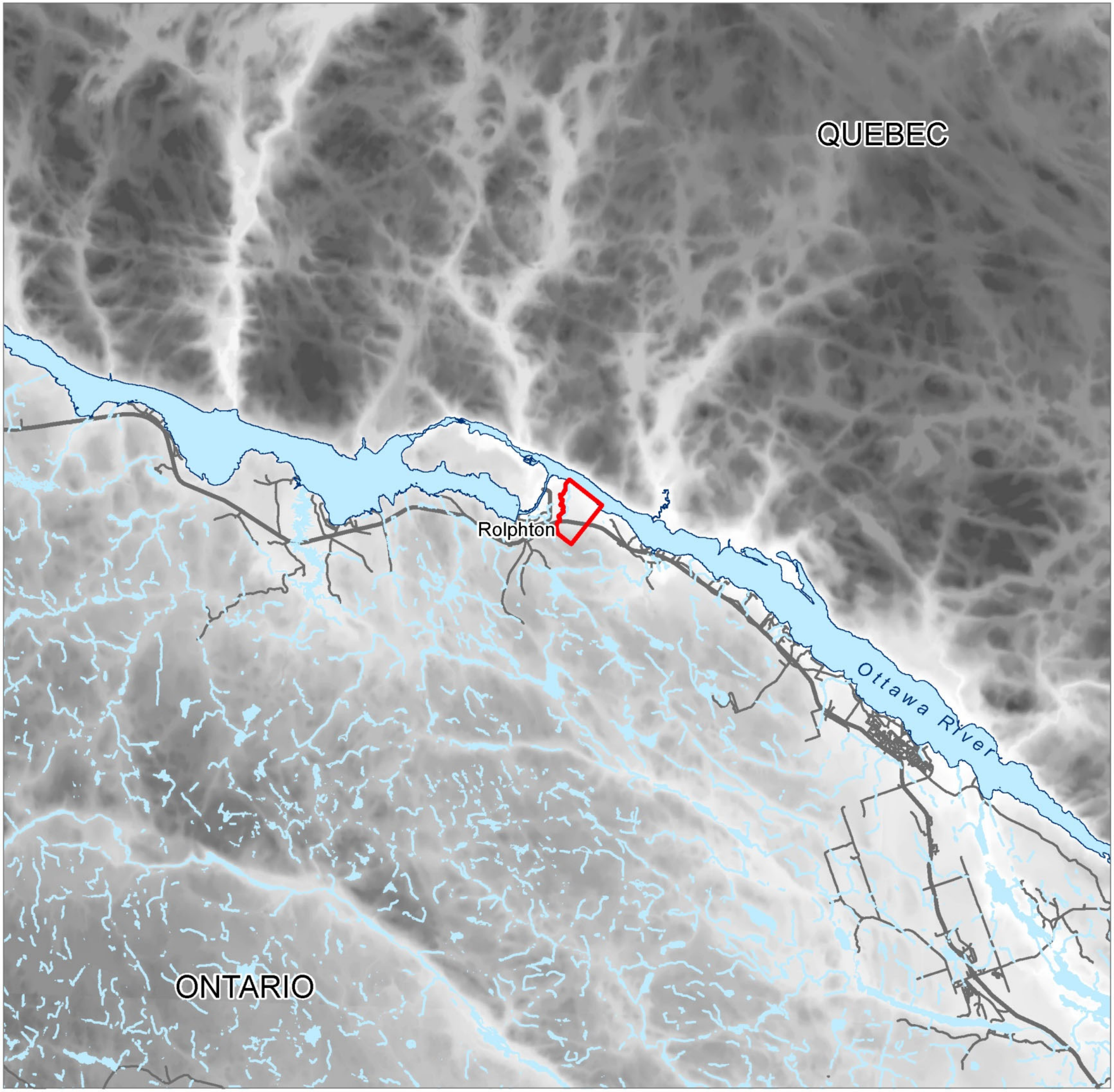
Dataset	Source	Resolution	Coverage	Acquired	Additional Comments
DEM	Canadian Digital Elevation Data (CDED)	0.75 arc seconds (20 m)	Quebec (north of Ottawa River)	2016 Edition 1.1	Hill-shaded and vertical exaggeration (5x)
	Land Information Ontario (LIO), Ministry of Natural Resources	10 m	Ontario	2013	Hill-shaded and vertical exaggeration (5x)
Satellite Imagery	Spot5; Orthoimage, Geobase, 2010, NRCan	10 m (panchromatic) 20 m (multispectral)	Canada	2005-2010	
Geophysics	Residual Total Magnetic Field, SIGEOM, QC	300 m flying altitude, 800 m line spacing	Quebec	2018 (accessed online)	No coverage available for Ontario
	Vertical Gradient of Total Magnetic Field, SIGEOM, QC	300 m, flying altitude, 800 m line spacing	Quebec with overlap into Ontario	2018 (accessed online)	No coverage available for Ontario

Given the limited overburden cover and elevated topography, brittle structural features are relatively clearly displayed on site DEMs. A composite DEM for the site and surrounding area was prepared having 10 m pixel resolution on the Ontario side of the Ottawa River and 20 m pixel resolution on the Quebec side and is shown on Figure 2.17. An enhanced composite DEM, Figure 2.18, was prepared by applying a vertical exaggeration of five times and adding hill shading to aid in the identification of structural features.

Supporting information, including geological and structural mapping was also referenced during the lineament study to support interpreted features. This included geological and structural mapping for the NPDWF site and surrounding study area, as presented in Figures 2.9 (and as discussed in Section 2.4.6), 2.13, 2.14 and 2.15. Satellite imagery and airborne geophysical data, shown on Figure 2.19, 2.20 and 2.21, are often incorporated into lineament analysis to assist in identifying and differentiating between brittle or dyke lineaments. However, the poor spectral response of the SPOT5 satellite imagery and poor resolution of the aeromagnetic datasets rendered them of limited use in identifying lineaments at the study area scale, but they were useful as supporting data showing broad regional scale trends of structural and lithological features.

2.4.5.2 Methodology

The lineament study for the NPDWF site was completed by analyzing a 20 x 20 km study area around the site (Figure 2.18). Given the lack of high-quality geophysical data available for the study area, lineament interpretation relied heavily upon DEM data for the site and surrounding area, primarily the LIO data for Ontario and CDED for Quebec.



LEGEND

- 2019 Rolphton NPDWF Model Boundary
- Highway
- Local Road
- Ottawa River Outline
- Waterbody
- Stream

Base Digital Elevation Model (mASL)

High : 453

Low : 112

Figure 2.17
Base Digital Elevation Model

SCALE 1:225,000

0 1 2 4 6 8
Kilometers

N

Coordinate System: NAD 1983 UTM Zone 18N
Source: MNR, obtained 2012-2015
DEM: NRCan, MNR, 2016
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA

PROJECT No. 16-212-11

Updated Geosynthesis -
Rolphton NPDWF EIS

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR
REV: 0

DATE: 28/02/2019

Geofirma Engineering Ltd

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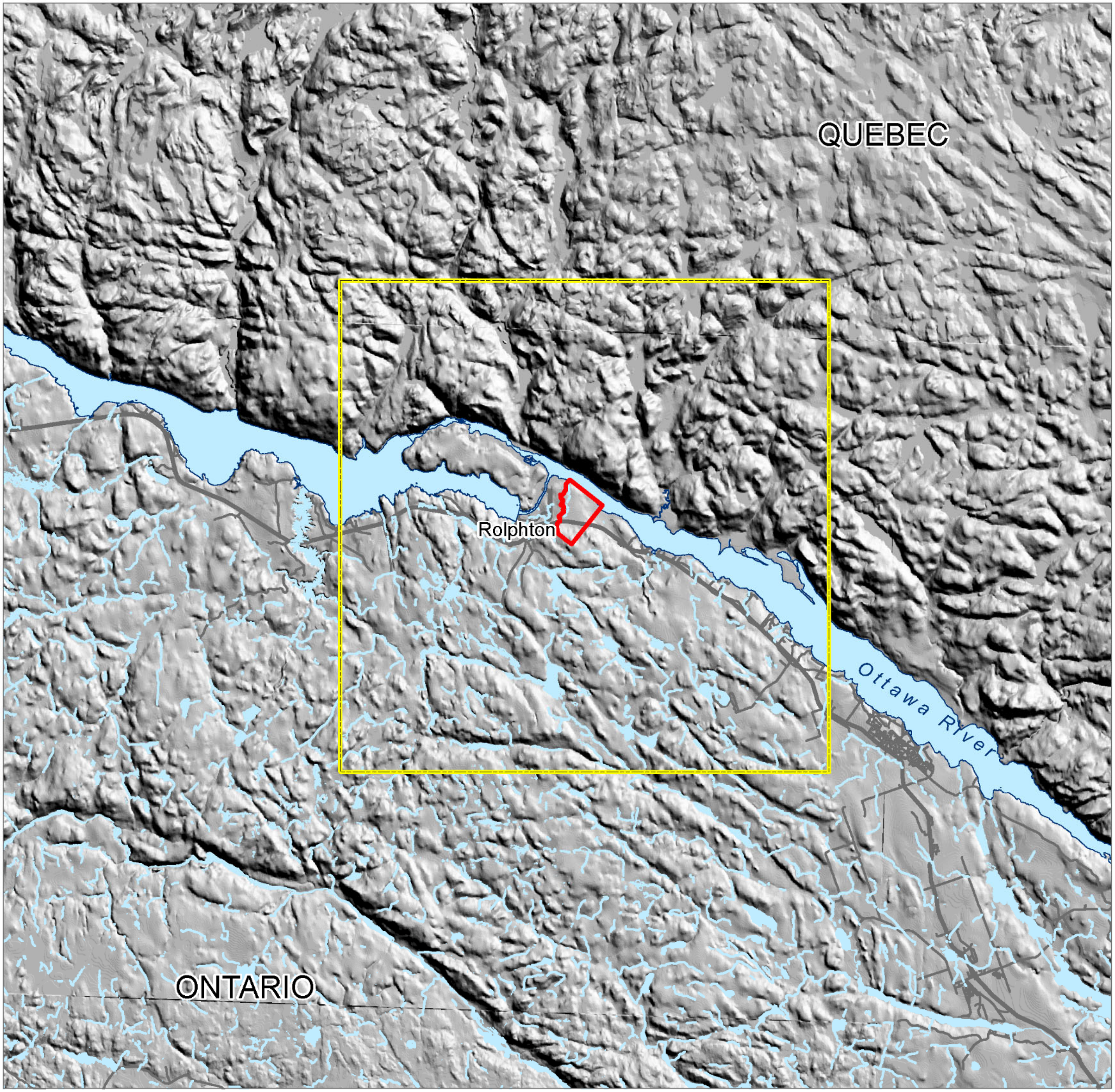

Figure 2.18
Enhanced Digital Elevation Model

Coordinate System: NAD 1983 UTM Zone 18N
Source: MNR, obtained 2012-2015
DEM: NRCan, MNR, 2016
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA

PROJECT No. 16-212-11

Updated Geosynthesis - Rolphton NPDWF EIS

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR
REV: 0

DATE: 28/02/2019

Geofirma Engineering Ltd

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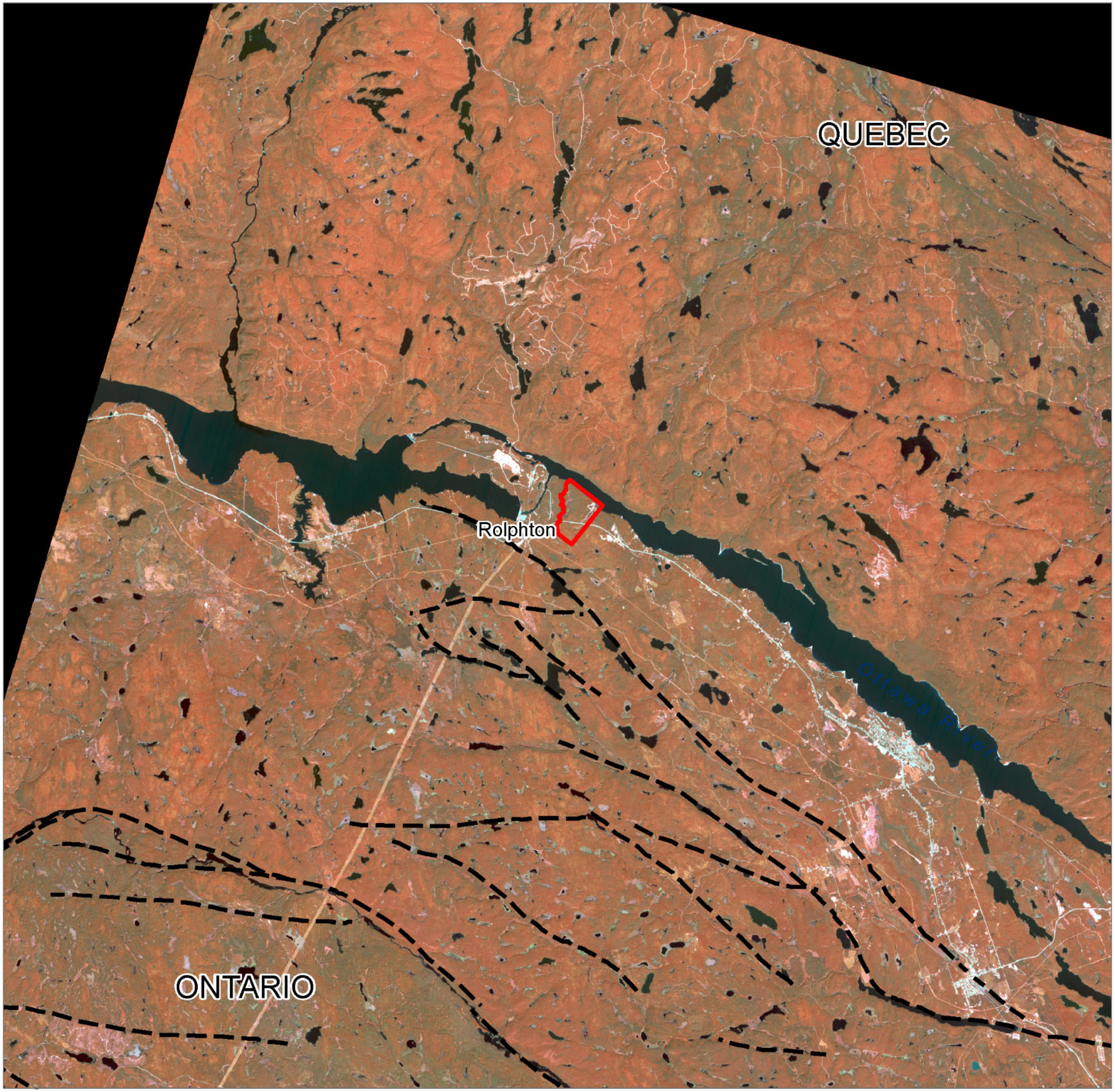


LEGEND

2019 Rolphton NPDWF Model Boundary

OGS Mapped Fault

Figure 2.19
SPOT5 Satellite Imagery

SCALE 1:225,000

0 1 2 4 6 8
Kilometers

N

Coordinate System: NAD 1983 UTM Zone 18N
Source:
SPOT5: GeoBase, 2010
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA

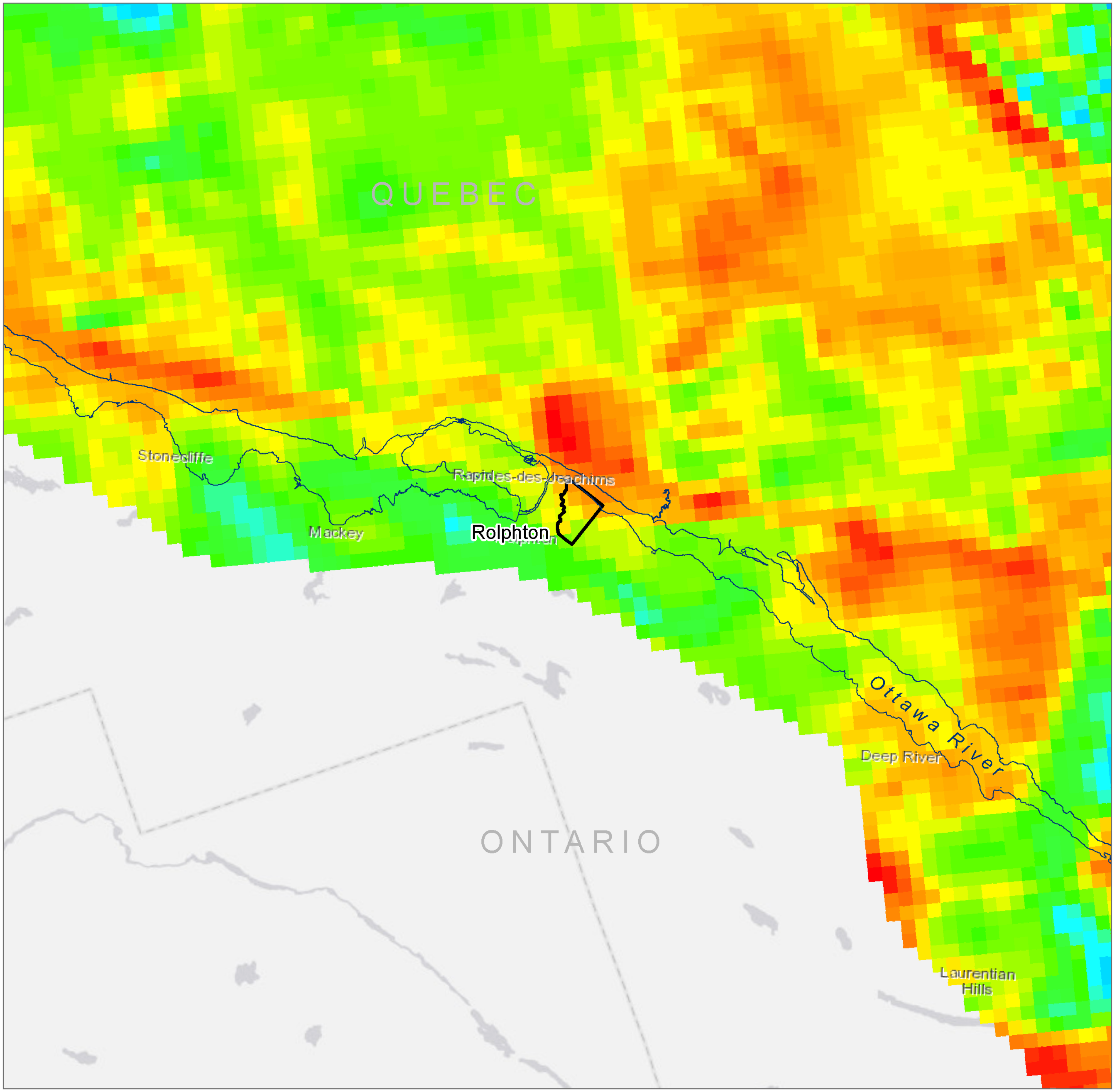
PROJECT No. 16-212-11

Updated Geosynthesis -
Rolphton NPDWF EIS

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR
REV: 0

DATE: 28/02/2019

Geofirma Engineering Ltd



LEGEND

2019 Rolphton NPDWF Model Boundary

Ottawa River Outline

Residual Total Magnetic Field

482
306
214
157
111
74
43
16
-9
-34
-60
-87
-114
-144
-176
-218
-265
-327
-477

nT

Low resolution aeromagnetic surveys, with a 300 m flying altitude and a 800 m line spacing.

Figure 2.20
Geophysical (Aeromagnetic) Data - Residual Total Magnetic Field

SCALE 1:225,000

0 1 2 4 6 8
Kilometers

N

Coordinate System: NAD 1983 UTM Zone 18N
Source:
Basemap: LIO, MNR
Geophysic: Magnetic, SIGEOM, QC
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA
Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS user community

PROJECT No. 16-212-11

Updated Geosynthesis -
Rolphton NPDWF EIS

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR
REV: 0

DATE: 28/02/2019

Geofirma Engineering Ltd

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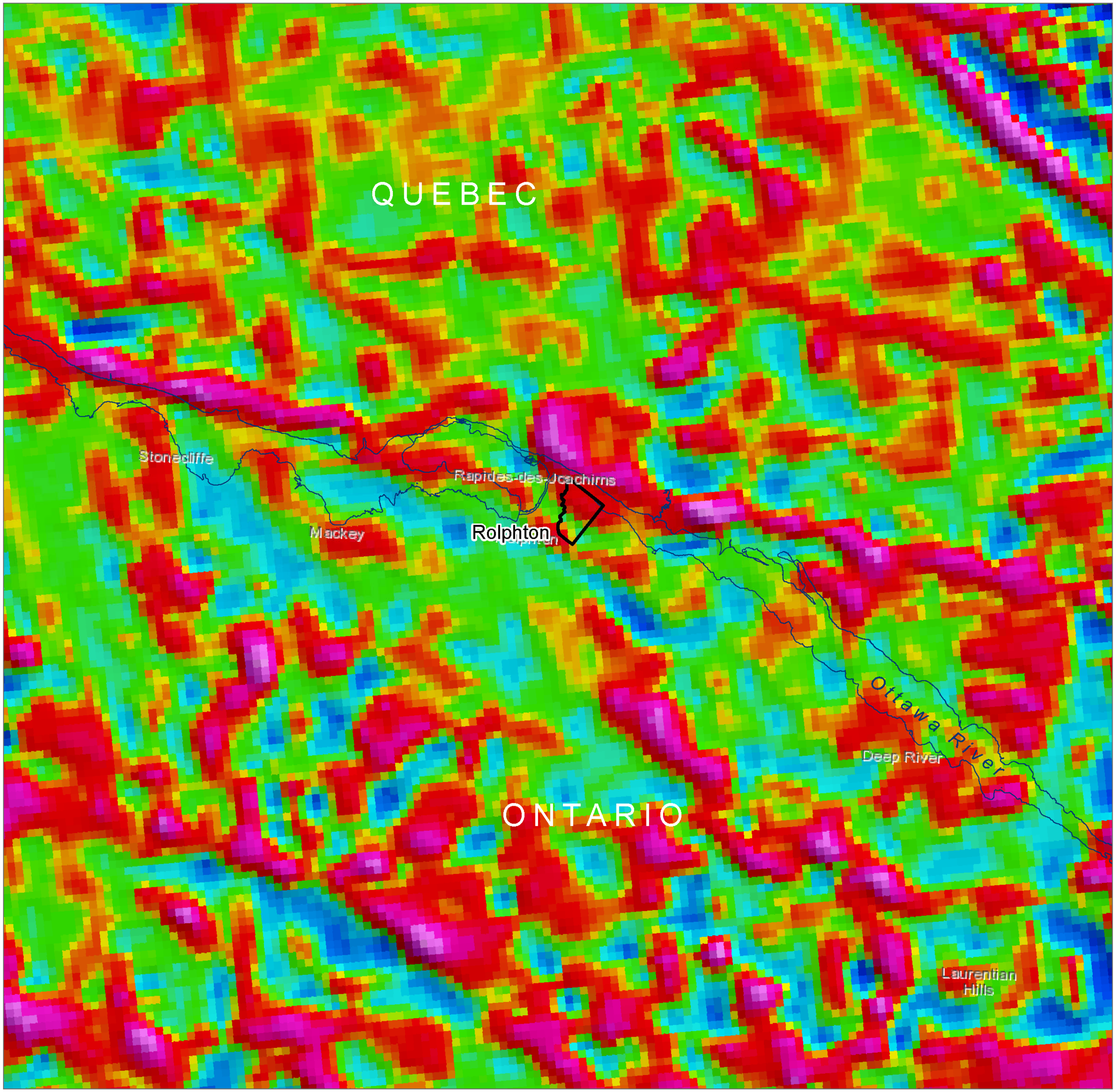


LEGEND

2019 Rolphton NPDWF Model Boundary

Ottawa River Outline

Vertical Gradient of Total Magnetic Field

0.700
0.364
0.217
0.128
0.072
0.035
0.009
-0.007
-0.021
-0.038
-0.056
-0.079
-0.106
-0.140
-0.183
-0.247
-0.343
-0.520
-1.016

nT/m

Low resolution aeromagnetic surveys, with a 300 m flying altitude and a 800 m line spacing.

Figure 2.21
Geophysical (Aeromagnetic) Data - Vertical Gradient of Total Magnetic Field

SCALE 1:225,000

0 1 2 4 6 8
Kilometers

N

Coordinate System: NAD 1983 UTM Zone 18N
Source:
Basemap: LIO, MNR
Geophysic: Magnetic, SIGEOM, QC
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA
Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS user community

PROJECT No. 16-212-11

Updated Geosynthesis - Rolphton NPDWF EIS

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR
REV: 0

DATE: 28/02/2019

Geofirma Engineering Ltd

Using ArcGIS, two independent assessors traced interpreted lineaments within the pre-defined lineament study area. Lineaments extending beyond the study area were traced to their full length, where practical. Each lineament was assigned a certainty from 1 to 3, with 1 being the most certain and 3 being the least certain. In general, the certainty of the interpreted feature was a function of the length and strength of expression. The final interpreted lineament set was developed by subjectively comparing and merging the two independent sets and to define one integrated lineament map.

Supporting data, including regionally-mapped faults and study area geology shown on Figures 2.13 and 2.14 for the Ontario and Quebec portion of the study area, respectively, were reviewed to ensure consistency between observed lineament features and mapped features. Airborne geophysical data are only available for Quebec with some overlap into Ontario. These airborne geophysical data include residual total magnetic field and vertical gradient of total magnetic field are shown on Figures 2.20 and 2.21, respectively. The geophysical data were reviewed to determine the general trend of major regional lineaments; however, the low resolution of the available geophysical data set was too coarse to allow for lineament interpretation at the study area scale.

2.4.5.3 Results

The final interpreted lineament dataset, showing the distribution of lineaments and colour-coded by certainty level, is shown on Figures 2.22 and 2.23. In total, 195 independent lineaments were identified within the 20 x 20 km study area. These lineaments ranged in length from 0.3 to 41.6 km, with an average (mean) length of 3.8 km. The average length of lineaments with a high degree of confidence (i.e., certainty = 1) is 14.6 km, where the average length of lineaments with the least certainty is 1.6 km. The orientations of interpreted lineaments are presented on rose diagrams, where Figure 2.24 represents the length-weighted distribution of lineament trends and Figure 2.25 illustrates the unweighted distribution of interpreted lineament orientations.

As shown on Figure 2.24, the first and strongest lineament orientation is east-southeast – west-northwest (120-140º azimuth), which is roughly parallel to the major regional structural features (i.e., the Mattawa Fault and Ottawa-Bonnechere graben structure) and the Ottawa River. The east-southeast – west-northwest trending lineaments tend to be more regionally pervasive and extend beyond the lineament study area boundaries. The orientations of these lineaments are consistent with historical observations made at CRL and summarized by McCrank (2016b) as discussed in Section 2.4.4 of this report. There is no evidence of this set of lineaments crossing through the NDPWF site, although the north boundary of the site, along the south shore of the Ottawa River, is interpreted to be a major lineament trending parallel to the Mattawa Fault.

The second and most frequently occurring lineament set is oriented approximately north-south, as shown on Figure 2.25. Unlike the east-southeast – west-northwest trending lineaments, the north-. south trending lineaments tend to be less well defined topographically and shorter in length, generally less than 5 km.

A third minor set of lineaments was identified in the study area trending northeast-southwest, approximately normal to the east-southeast – west-northwest primary structurally-controlled lineament set.

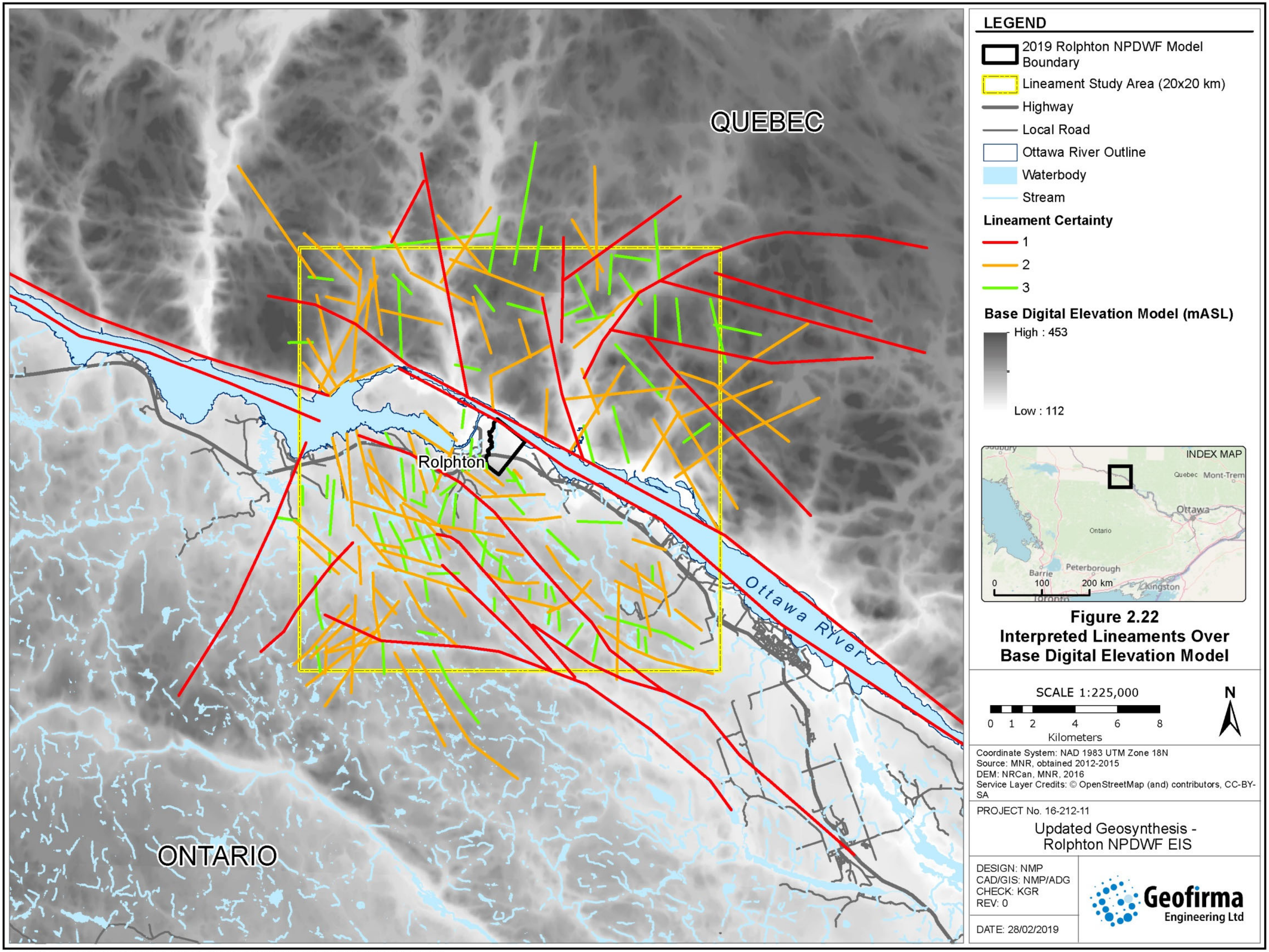
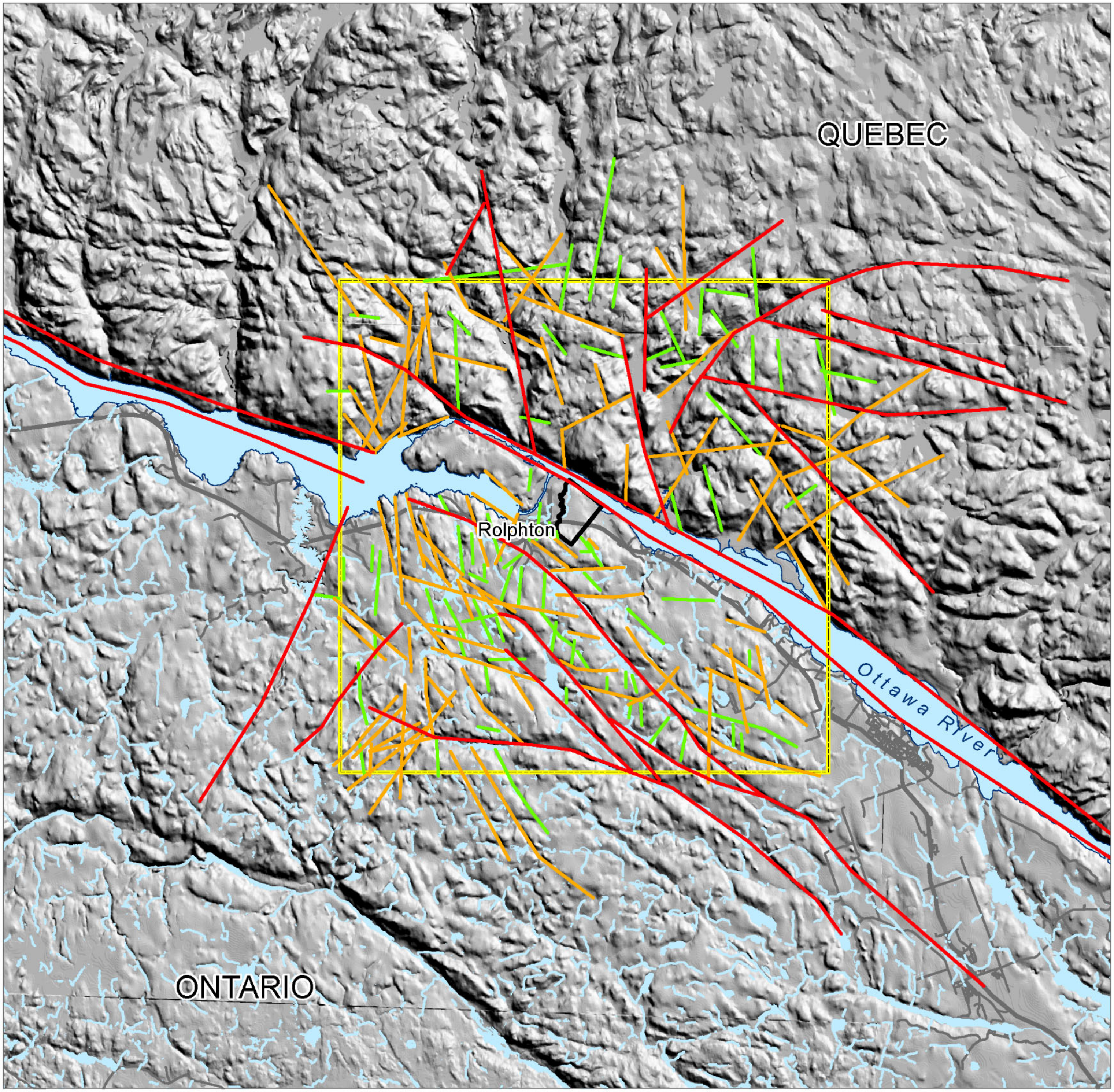


Figure 2.22 Interpreted Lineaments Over Base Digital Elevation Model



LEGEND

- 2019 Rolphton NPDWF Model Boundary
- Lineament Study Area (20x20 km)
- Highway
- Local Road
- Ottawa River Outline
- Waterbody
- Stream

Lineament Certainty

- 1
- 2
- 3

Figure 2.23
Interpreted Lineaments Over Enhanced Digital Elevation Model

SCALE 1:225,000

0 1 2 4 6 8
Kilometers

N

Coordinate System: NAD 1983 UTM Zone 18N
Source: MNR, obtained 2012-2015
DEM: NRCan, MNR, 2016
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA

PROJECT No. 16-212-11

Updated Geosynthesis - Rolphton NPDWF EIS

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR
REV: 0

DATE: 28/02/2019

Geofirma Engineering Ltd

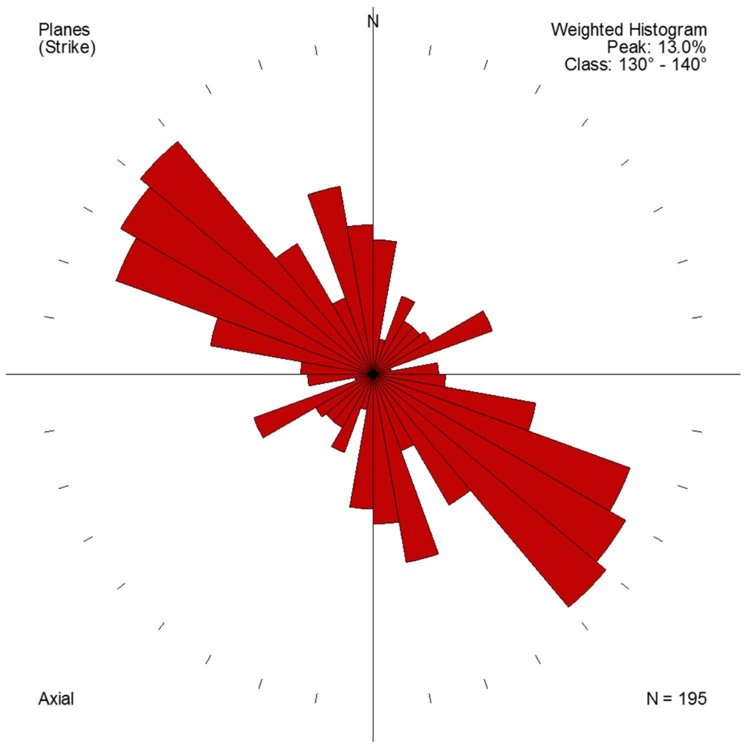


Figure 2.24 Rose Diagram of Length-Weighted Lineament Azimuth in 10 Degree Bins (N = 195)

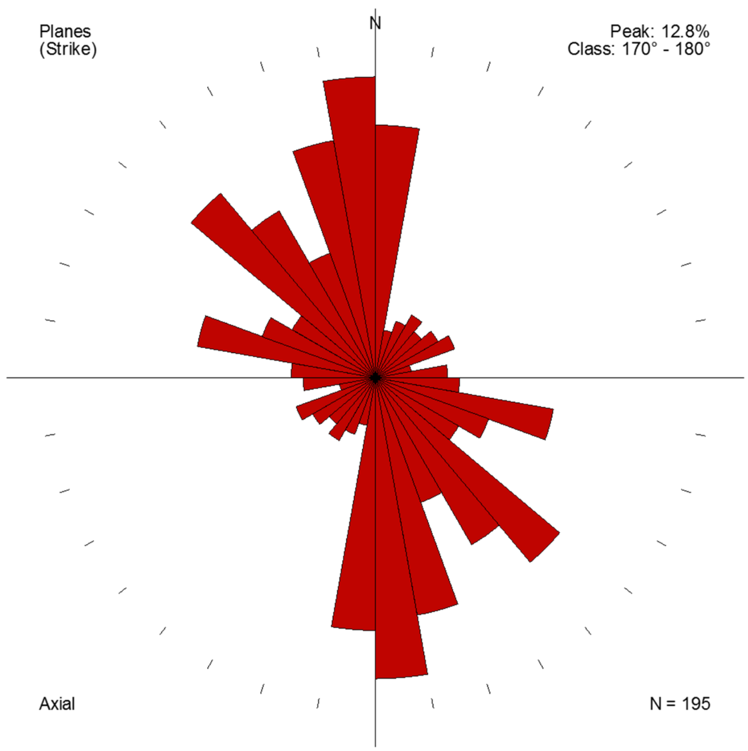


Figure 2.25 Rose Diagram of Unweighted Lineament Azimuth in 10 Degree Bins (N = 195)

This third set of lineaments is moderately well defined by the topography and is shorter in length than the major lineament structure.

A fourth poorly-defined set of east-west trending lineaments was observed throughout the study area, which may be related to the east-west trending Grenville dyke swarm, as shown on Figure 2.11.

The lineament study shows that major lineaments are located north of the site, along the Ottawa River and south of the site in line with a series of small lakes including Colton Lake, Tee Lake, Lower/Upper Pergeon Lake (from northwest to southeast, see Figure 2.15). A series of less well-defined east-southeast – west-northwest, north-south and east-west trending lineaments are located within close proximity to the site; however, there is no evidence to suggest that these lineaments extend to within the NPDWF site boundary.

2.4.6 NPD Site Structure

Information on the structural conditions of the bedrock is available from on-site drilling investigations completed before and after NPD construction, from pre-construction interpreted bedrock surface elevation contours, from observations of the bedrock excavations completed as part of NPD construction, from the lineament analysis completed as part of this Updated Geosynthesis study, and from 2019 bedrock outcrop mapping and shallow bedrock drilling and coring investigations. As there are no outcrops in the immediate vicinity of the NPDWF, structural information from bedrock exposures near the NPDWF site are not available.

2.4.6.1 Historical Diamond Drillholes

Shallow bedrock diamond coring (S-series drillholes, typically drilled to depths of 6 to 9 m into rock) of the area of the NPD was undertaken by Hydro-Electric Power Commission of Ontario (1956) and summarized by Canadian General Electric Company Ltd., (1962). Based on high core losses, highly fractured core and drill water losses in drillholes S-3 and S-11, a 90 m-wide shear zone was interpreted to exist in the bedrock at the NPD site. Appendix 10 of Canadian General Electric Company Ltd. (1962) describes the shear zone as:

> *“Diamond drilling indicates that the bedrock is sheared over an approximate width of 300 feet. The shear zone strikes easterly and is located between holes S-13 and S-10. Dip of the shearing is 30°-50°, probably in a southerly direction.”*

Based on the above data, Figure 2.26 shows the historical interpreted location and extent of the suspected shear zone at the NPDWF site.

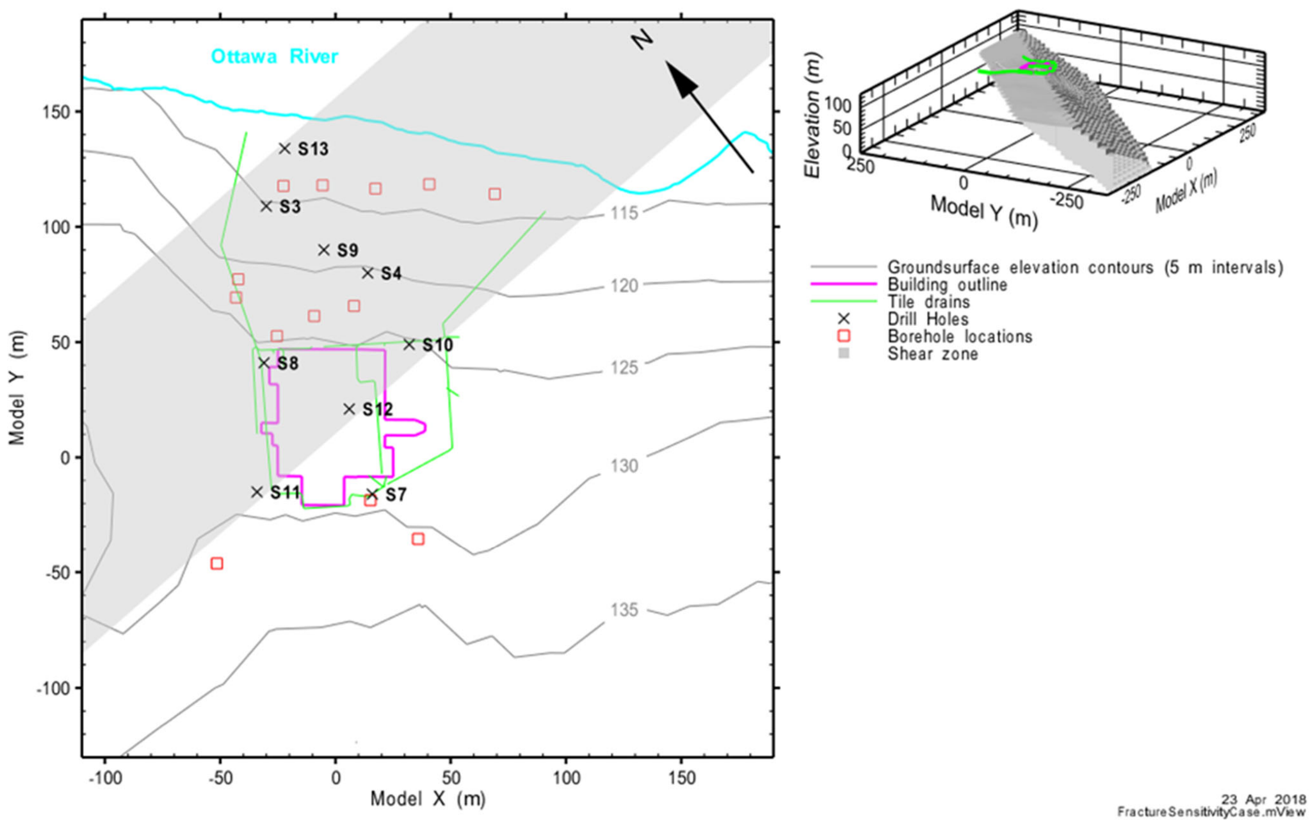


Figure 2.26 Location and Extent of Historical Interpreted Shear Zone

2.4.6.2 Pre- and Post-Construction Bedrock Surface

Hydro-Electric Power Commission of Ontario (1958; 1959), as part of pumphouse and powerhouse excavation plans, prepared contoured bedrock surface elevation drawings. These pre-construction drawings were based on an extensive set of subsurface investigations using diamond drillholes and soil probing holes. Drawing NA25-f-2201 (Hydro-Electric Power Commission of Ontario, 1958) shows the bedrock surface elevation in the area of the powerhouse contoured at 1-foot intervals and the area downslope of the powerhouse to the Ottawa River contoured at 5-foot intervals.

Major structural features such as shear zones and faults are often expressed as erosional and weathering depressions in the bedrock surface (e.g., see Section 2.4.4 on adjacent Rapides des Joachims fault and shear zone expressions). The pre-construction contoured bedrock surface elevations for the powerhouse and pumphouse do not show evidence of erosional and weathering depressions in the area of inferred 90-m wide shear zone. This suggests that either the shear zone is not heavily fractured relative to adjacent rock or the shear zone is not present at the locations interpreted by Canadian General Electric Company Ltd. (1962).

2019 overburden and bedrock drilling investigations provide additional information on the elevation of the competent bedrock surface. These investigations indicate that elevation of competent bedrock surface is depressed in the area of BH18-05 (110.04 mASL) and to a lesser degree at BH18-10

(113.64 mASL) and at BH18-09 (115.29 mASL) relative to upslope and downslope measurements. These data do not indicate the presence of major fault or shear zone in the bedrock of the NPDWF.

2.4.6.3 NPD Excavations

Photographs of the NPD bedrock excavations provide important observational information on the nature and extent of structure and fracturing of bedrock at the NPDWF site. These data are more useful than bedrock diamond drilling and contoured bedrock surface elevation figures in that they provide direct large-scale full exposure of the bedrock conditions on the walls and floors of the NPD excavations. However, they represent poorer rock quality than in-situ conditions based on core drilling due to the additional fracturing introduced during the bedrock excavation process.

Figures 2.27 to 2.29 show historical photographs taken during excavation of the bedrock at the NPD powerhouse site. Figure 2.27 shows the excavation of the exposed bedrock surface in the area of the NPD powerhouse looking north toward the Ottawa River. Figure 2.27 also shows that the exposed bedrock surface as flat-lying without obvious erosional and weathering depressions, and that shallow bedrock is fractured with a dominant fracturing orientation striking parallel to the Ottawa River (i.e., northwest-southeast) with moderate (~30º) dip to the northeast toward the Ottawa River. This dominant fracturing orientation is likely related to bedrock gneissosity and foliation.

Fractures showing the same orientation at CRL are interpreted as being developed following the planes of weakness generated by gneissosity and foliation and are predominantly closed fractures with reduced permeability.

Figure 2.28 shows the bedrock excavation during construction of the NPD powerhouse looking to the east. Figure 2.28 also shows the exposed northeast (left) and southeast (right) bedrock excavation faces. The northeast excavation face shows primarily subhorizontal fracturing, whereas the southeast wall shows both subhorizontal (likely sheeting joints) fracturing and moderately northeast dipping fracturing. Figure 2.28 indicates the presence of subhorizontal and northwest-southeast striking, northeast dipping fracturing at the NPDWF site.

Figure 2.29 shows similar fracturing to that interpreted from Figures 2.27 and 2.28. Figure 2.29-left, looking northeast, shows the northeast excavation face, with limited exposure of the southeast and northwest excavation faces. The northeast excavation face shows predominately subhorizontal fracturing and lithologic layering. The southeast excavation faces, as shown on Figures 2.28 and 2.29-left, show migmatitic or lithologic layering (i.e., light-coloured rock layers) that dip moderately to the northeast. Figure 2.29-right shows a close-up of subhorizontal sheeting joints and a northwest-southeast striking, moderately northeast dipping fracture zone exposed near the base of the southeast excavation face.

The northwest-southeast striking, moderately northeast dipping fracture zone shown on the right panel of Figure 2.29 is unlikely to be the cause of the bedrock low at BH/MW18-05 for several reasons. First, the apparent dip at about 35° to the northeast creates a rise of about 35 m from the NPD floor elevation of 110 mASL to reach the inferred position of the fracture zone in the bedrock low at BH/MW18-05 which is at about 110 mASL and about 50 m southwest of the NPD. To be responsible for the bedrock depression at BH/MW18-05, the dip of the fracture zone would have to be much less, closer to 5-6°.

Figure 2.27 Excavation of Bedrock Surface at NPD Powerhouse, Looking North

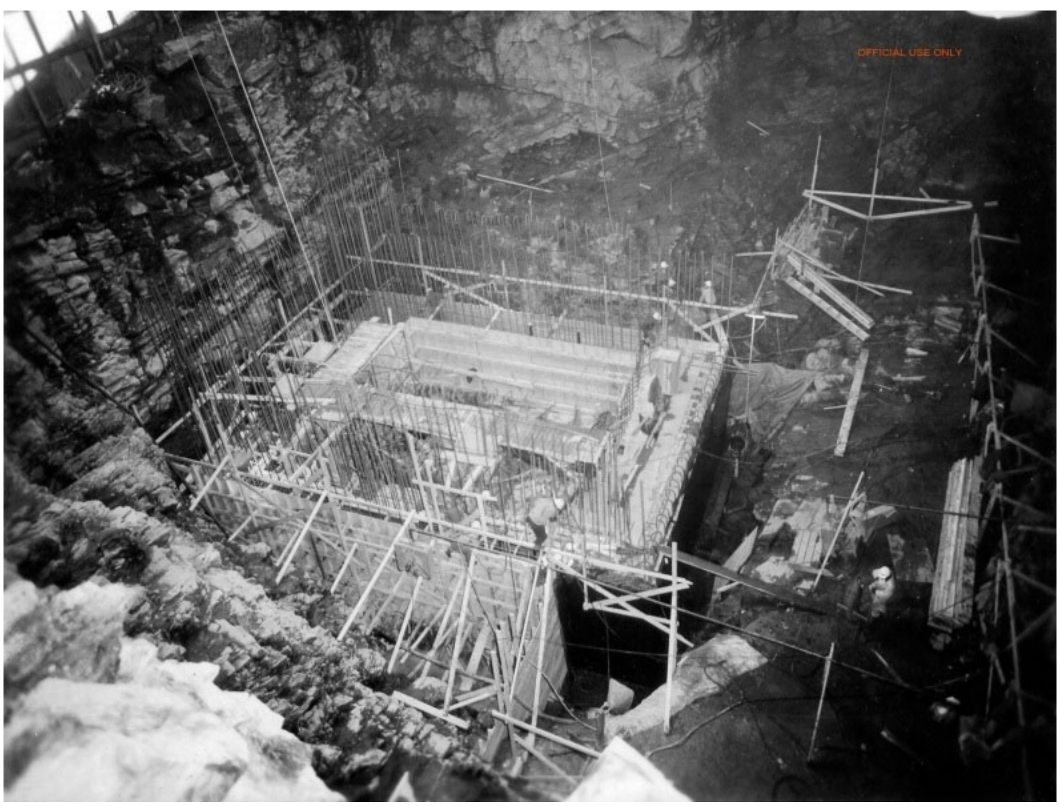


Figure 2.28 NPD Powerhouse Excavation, Looking East.

Figure 2.29 NPD Powerhouse Excavations: Left - Looking Northeast, Right – Looking Southeast

depression at BH/MW18-05, the dip of the fracture zone would have to be much less, closer to 5-6°. Second, such flat-lying structures are unlikely to create depressions in the bedrock surface – they are more likely to be created by subvertical structures. Third, the intensity of fracturing is moderate and unlikely to cause depressions in the bedrock surface. Fourth, subvertical fracturing evident in BH/MW18-05 is more likely to create the bedrock depression, although results of drilling of BH/MW18-09 and BH/MW18-10 suggest the bedrock depression may be isolated and not part of linear bedrock trough created by splays of the Mattawa Fault.

Figures 2.27 to 2.29 show that the bedrock at the NPD powerhouse excavations is sparsely to highly fractured with dominant northwest-southeast striking, moderately northeast-dipping fractures and subordinate subhorizontal sheeting fractures. These excavation photographs do not show the presence of an east-west striking, moderately south-dipping, 90 m-wide shear zone as interpreted from pre-excavation diamond drilling investigations.

Visual inspection of the excavation faces shown in Figures 2.28 and 2.29 as well as other excavation photographs not reproduced in this report suggest fracture frequencies of 5 to 30/m, equivalent to sparsely to highly fractured rock as defined at CRL based on detailed outcrop and core logging (see Section 4.4).

2.4.6.4 2019 Bedrock Outcrop Mapping

Geological mapping of bedrock outcrops on and near the NPD site was recently completed by Geofirma Engineering Ltd. (2019). Figure 2.30 shows the 13 locations of bedrock outcrops mapped in late 2018 as part of geoscientific characterization of the NPD site. Mappable bedrock outcrops were generally limited to bedrock exposures along road cuts of Highway 17 and Renfrew County Road 635 (Swisha Road) located along the southern and western limits of the NPD site.

Outcrops throughout the study area generally display weak to strong blocky weathering defined by 2-4 joint sets with spacing of centimetres to metres. Northwest- and perpendicular northeast-striking jointing sets typically dominate. Joint sets have spacing varying from decimetre to metre scale. In regions of highly focused jointing, spacing is centimetre scale. Figure 2.31 presents the contoured upper-hemisphere polar plot of all joints sets mapped in bedrock outcrops. Figure 2.31 shows the predominance of northwest-striking steeply southwest-dipping joints, northeast-striking vertical-dipping joints and north-south striking, shallow east dipping (i.e., subhorizontal sheeting) joints in bedrock outcrops. Minor north- and northwest-striking joints are also evident in bedrock outcrops.

Shallow-dipping gneissic foliation generally strikes north-south and east-west, with localized irregular folding and ductile deformation. Figure 2.32 presents the contoured upper-hemisphere polar plot of all gneissosity measurements mapped in bedrock outcrops. Figure 2.32 shows the predominant gneissosity as striking about north-south with a secondary orientation of subhorizontal. A minor gneissosity orientation of east-west is evident in Figure 2.32.

Figures 2.33 to 2.41 provide photo documentation of fault, shear and other structural features noted in bedrock outcrop mapping summarized in Appendix A of the Geoscientific Characterization of the NPD Site Report (Geofirma Engineering Ltd., 2019).

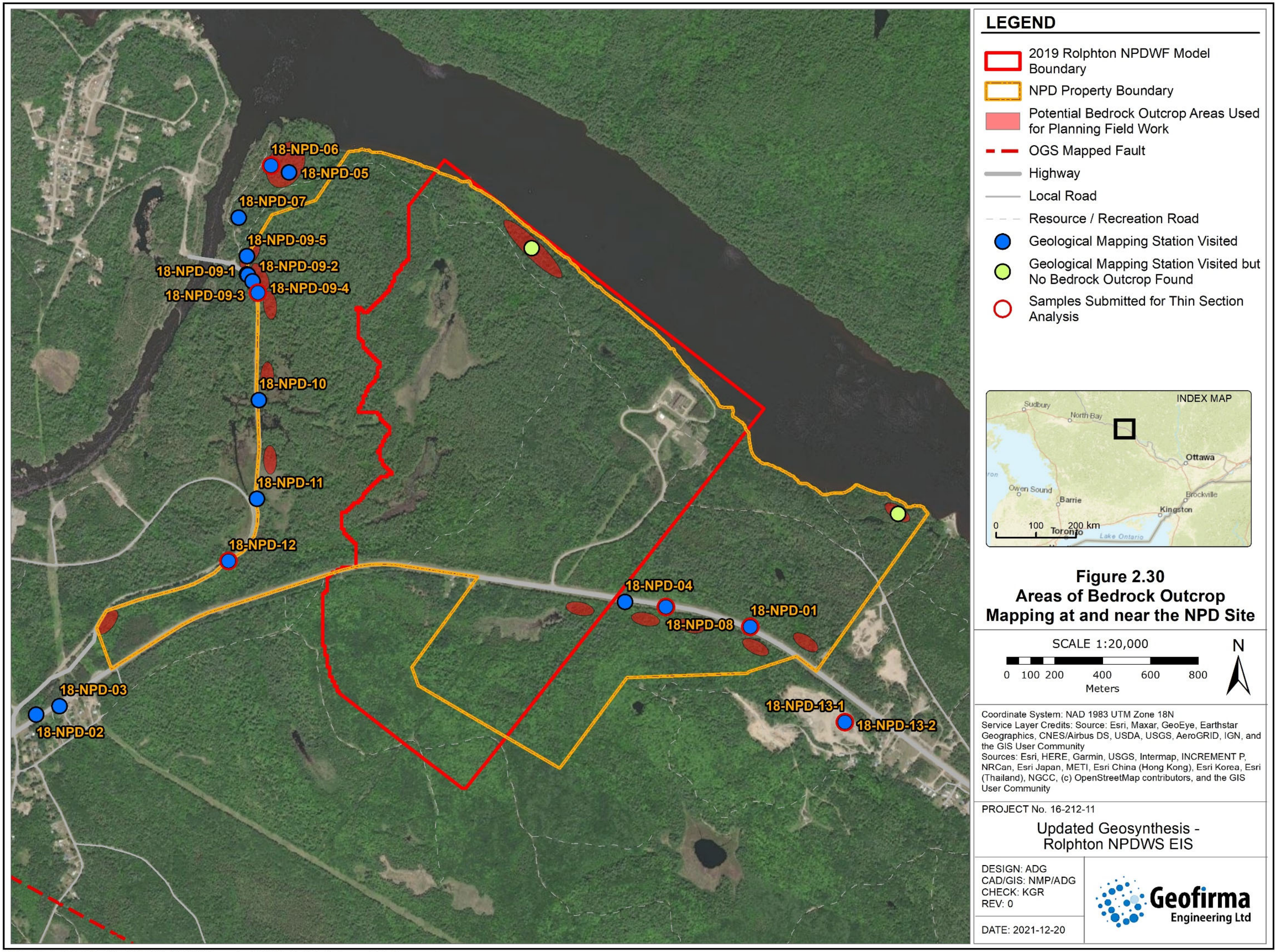


Figure 2.30
Areas of Bedrock Outcrop Mapping at and near the NPD Site

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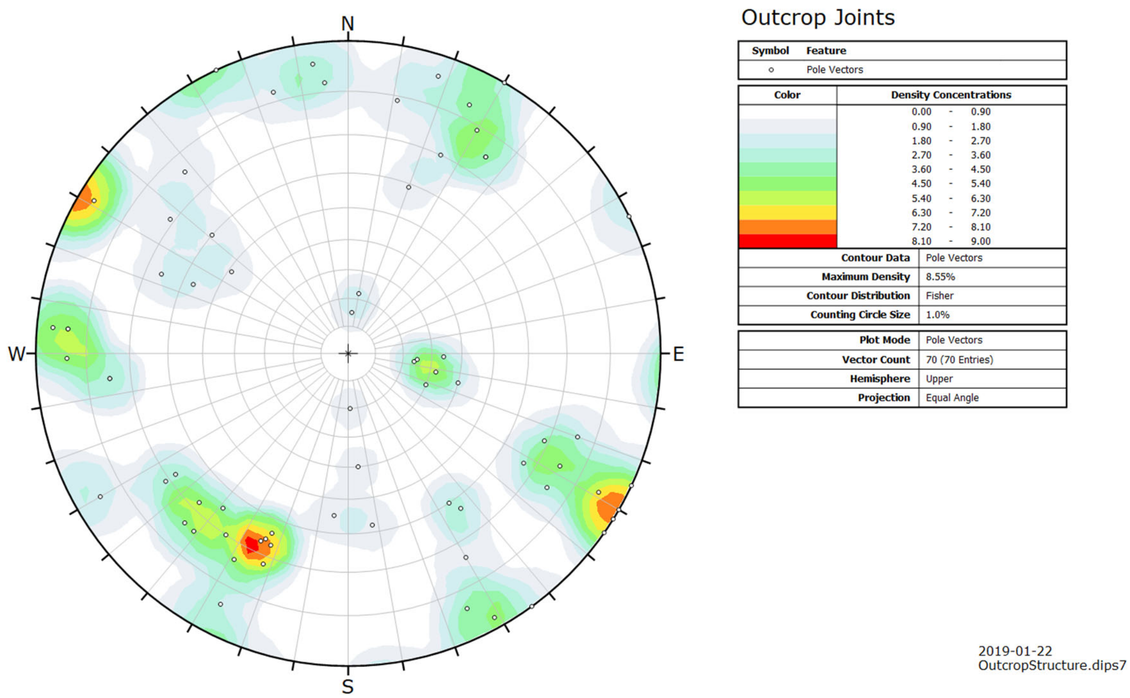


Figure 2.31 Contoured Upper-Hemisphere Polar Plot of Outcrop Jointing

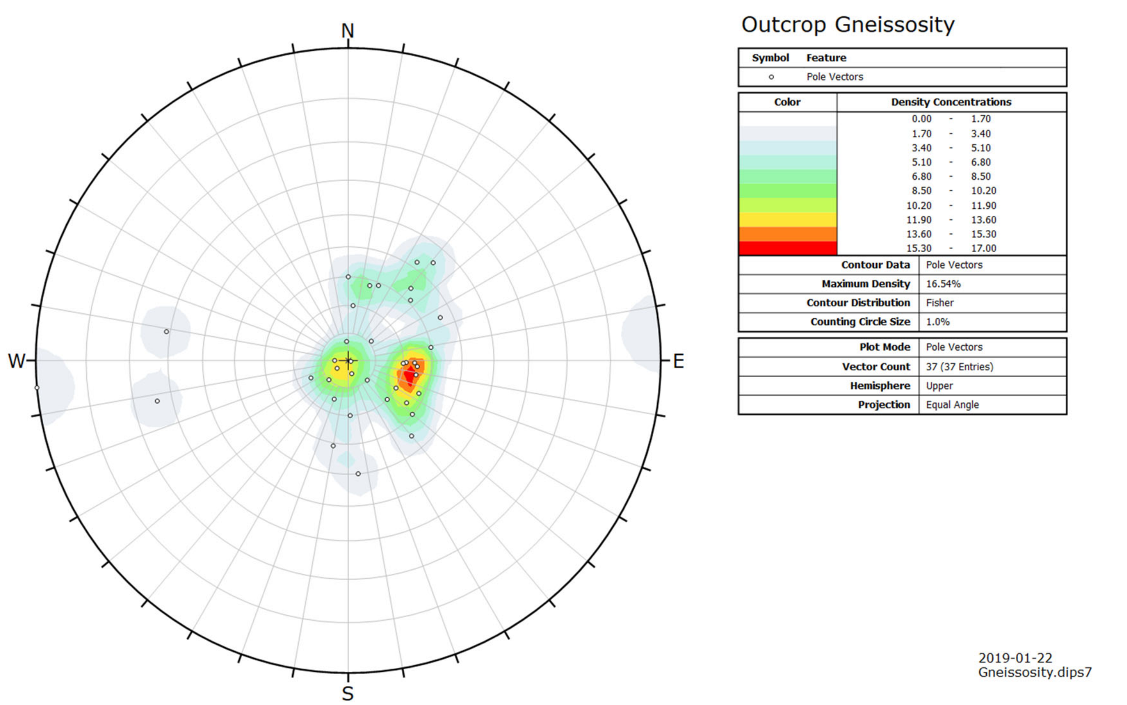


Figure 2.32 Contoured Upper-Hemisphere Polar Plot of Outcrop Gneissosity

Figures 2.33 and 2.34 show epidotization and chloritization of joint surfaces. Figure 2.35 is a photograph of a sheared fissile mylonitic fault layer. Figure 2.36 shows a potassic (K) feldspar augen with tails illustrating dextral (right-hand) shearing of bedrock. Drag-folding along a high angle fault (Figure 2.37) is visible in one outcrop (18-NPD-09.2) and is consistent with normal faulting. Figure 2.38 shows local low angle faulting visible as fine-grained mylonitic layers, 10-20 cm thick, that are parallel to or cross-cutting gneissic banding. Figure 2.39 portrays deformed white quartz veins at outcrop 18-NPD-12. Deformed gneissic bedrock with K-Feldspar and quartz augens and shear sense tails are evident at outcrop 18-NPD-13.2 in Figure 2.40. Figure 2.41-left shows a high-angle fault at the same mapping station as shown in Figure 2.37. Figure 2.41-right shows deformed mylonitic layers of K-Feldspar, biotite, plagioclase and quartz at the same outcrop shown in Figure 2.39.

Figure 2.33 Photo 119-5699 – Station 18-NPD-03, #1 Joint Set Showing Epidotization and Chloritization

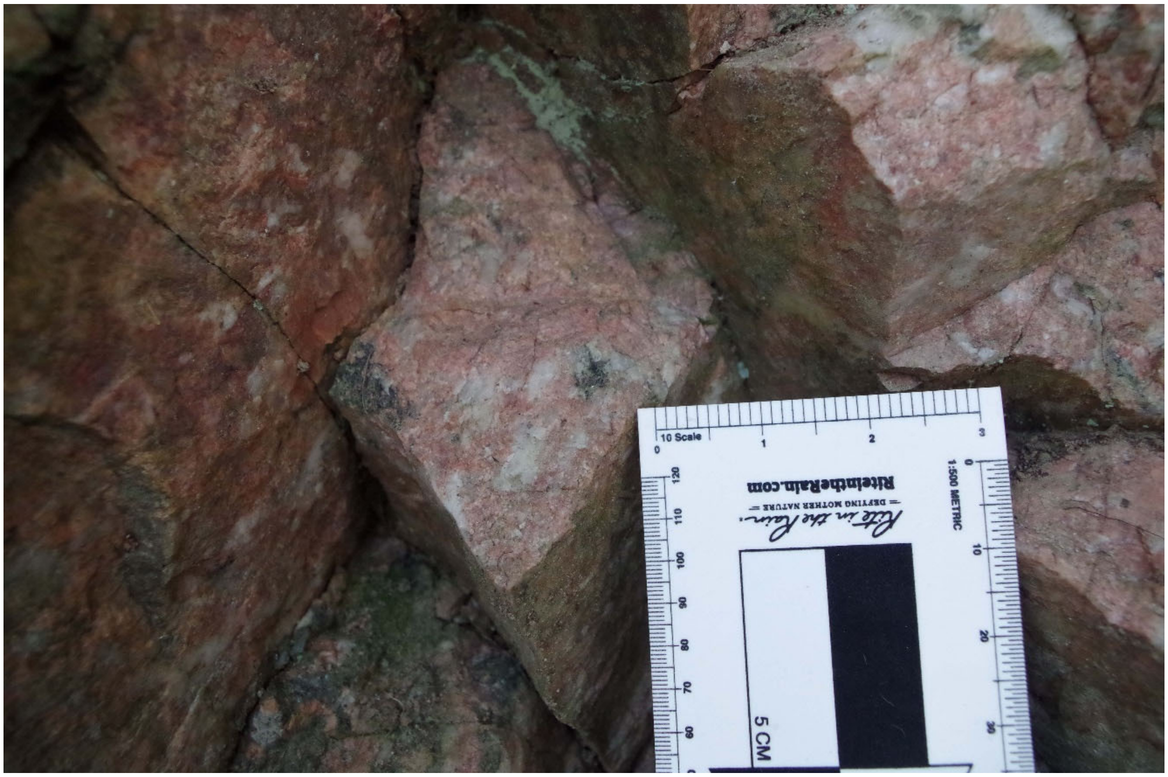


Figure 2.34 Photo 119-5700 – Station 18-NPD-03, Close-up of Local Chloritization of Biotite on Joint Surfaces

Figure 2.35 Photo 121-5784 – Station 18-NPD-09.1, Sheared Fissile Mylonitic Fault Layer

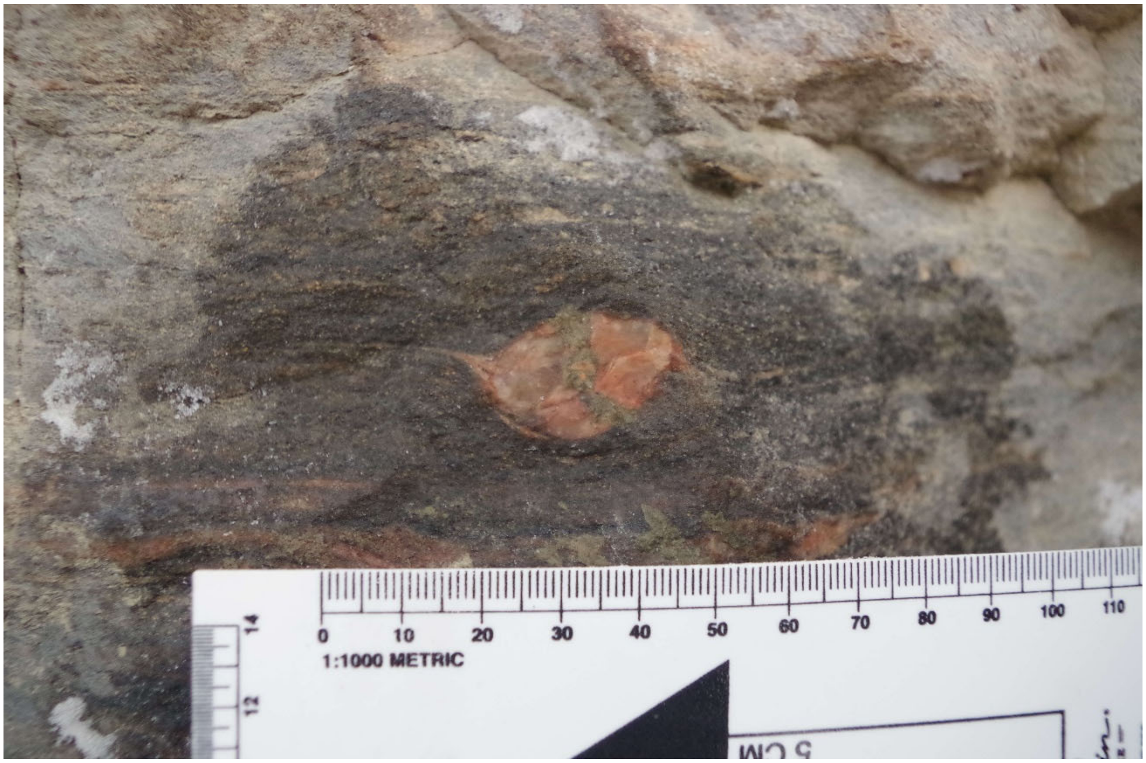


Figure 2.36 Photo 121-5803 – Station 18-NPD-09.2, Potassic Augen with Tails Showing Dextral (Right-Hand) Shearing

Figure 2.37 Photo 121-5809 – Station 18-NPD-09.2, Drag Folding Along a High-Angle Fault

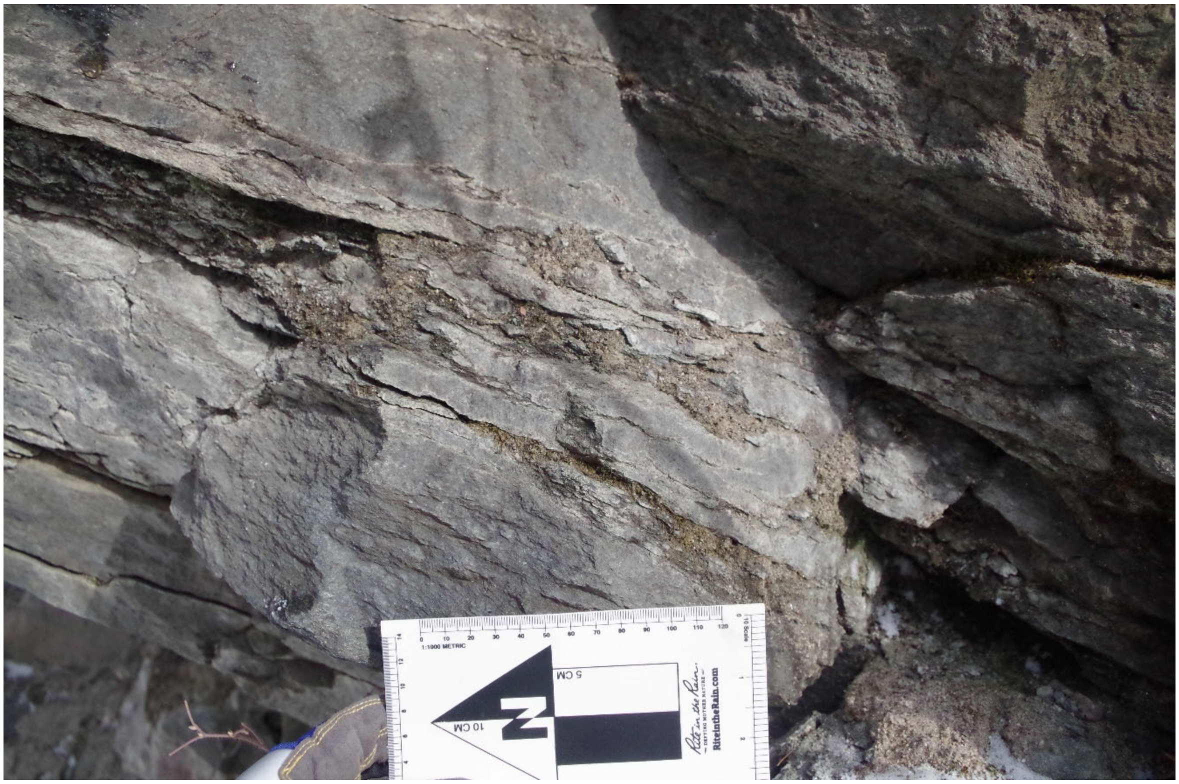


Figure 2.38 Photo 121-5851 – Station 18-NPD-09.4, Fissile Mylonitic Fault Layers Parallel to Foliation

Figure 2.39 Photo 122-5912 – Station 18-NPD-12, Deformed White Quartz Veins

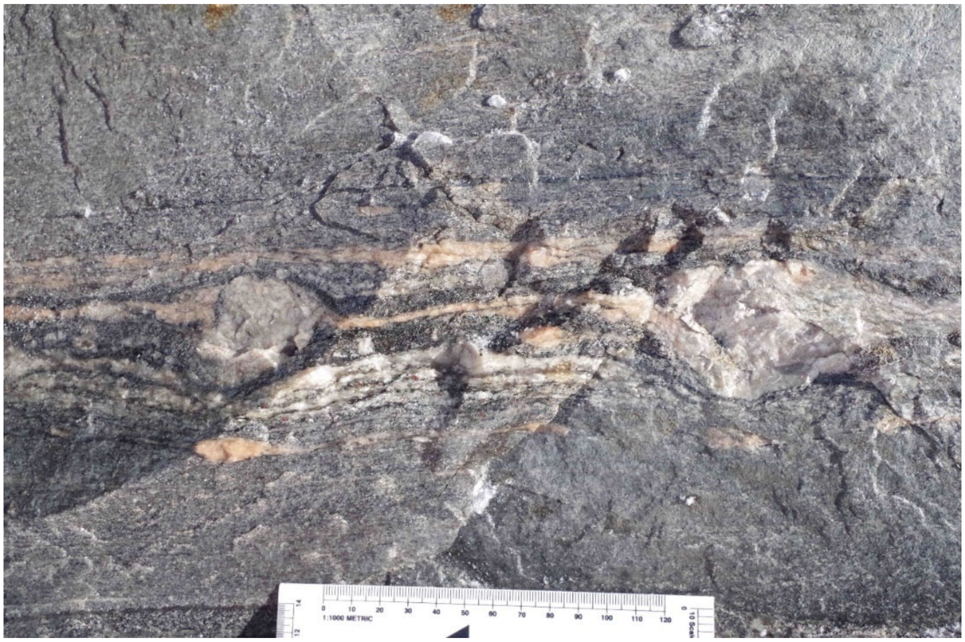


Figure 2.40 Photo 122-5937 – Station 18-NPD-13.2, K-Feldspar and Quartz Augens with Shear Sense Tails

Figure 2.41 Left - Photo 121-5813 – Station 18-NPD-09.2, High-Angle Fault; Right – Photo 122-5906 – Station 18-NPD-12, Deformed Mylonitic Layer of K-Feldspar, Biotite, Plagioclase and Quartz

2.4.6.5 2019 Shallow Bedrock Drilling and Coring

Structural measurements of shallow bedrock were made during bedrock coring and borehole acoustic televiewer (ATV) logging of boreholes BH18-05 to BH18-08 as part of geoscientific characterization of the NPD site (Geofirma Engineering Ltd., 2019). Such structural measurements include core recovery (%), rock quality designation (RQD in %), natural fracture frequency (fractures/m) and number of intensely fractured, rubble and breccia zones from logging of recovered core, and spacing and orientation of fractures from borehole ATV geophysical logging.

Table 2.2 summarizes the structural measurements obtained from logging of recovered core from boreholes BH18-05 to BH18-08 drilled off of the corners of the NPDWF (see Figure 2.4 for location of the shallow bedrock boreholes). Core recovery was very good, with average values per borehole ranging from 93% (BH18-06) to 98% (BH18-08) with an overall average of approximately 96% for all four boreholes. Minimum core run recovery in individual boreholes was as low as 33% in BH18-06 due to drilling equipment difficulties, and between 70-75% in BH18-05, BH18-07, and BH18-08.

Table 2.2 Summary of Shallow Bedrock Structural Measurements from Core Logging of BH18-05 to BH18-08

Structural Measurement	***BH18-05***	***BH18-06***	***BH18-07***	***BH18-08***	***Overall***
Core Recovery (%)					
Min	75.7	32.9	69.1	75.0	32.9
Max	100	100	100	100	100
Arithmetic Mean	97.3	93.0	95.3	98.1	95.9
Geometric Mean	97.1	91.6	95.0	98.0	95.3
Rock Quality Designation (RQD, %)					
Min	24.5	13.7	0.0	7.8	0.0
Max	100.0	93.9	100.0	100.0	100
Arithmetic Mean	83.0	66.0	58.7	69.4	69.3
Geometric Mean	80.2	60.6	53.9	60.5	63.1
Fracture Frequency (m^{-1})					
Min	0.0	1.0	1.0	1.0	0.0
Max	10.0	14.0	12.0	13.0	14
Arithmetic Mean	4.5	6.6	7.2	6.0	6.0
Geometric Mean	4.0	5.9	6.5	5.3	5.4
Number of Intensely Fractured, Rubble and Breccia Zones					
Number of Zones	13	16	22	19	70

The rock quality designation (RQD, % of recovered core with lengths greater than 10 cm) values were variable and ranged from less than 10% to 100%. Average values per borehole ranged from 59% (BH18-07) to 83% (BH18-05) with an overall average of approximately 69%, indicating fair to good rock quality conditions (Deere *et al*, 1967; ISRM, 1977).

The frequency of natural fractures was moderate, typically between 0 and 14 fractures/m. Average natural fracture frequency values per borehole ranged from 4.5 fractures/m (BH18-05) to 7.2 fractures/m (BH18-07), with an overall average of 6.0 fractures/m for all four boreholes. These natural fracture frequencies are very similar to and slightly better than the ranges of natural fracture frequencies inferred from inspection of NPD excavation faces at 5 to 30 fractures/m (see Section 2.4.6.3).

The bedrock structural data listed in Table 2.2 shows that overall rock quality and fracture spacing decrease with proximity to the Ottawa River. BH18-05 which is farthest from the Ottawa River shows the best rock quality, whereas boreholes BH18-07 and BH18-08 which are closest to the River show the poorest rock quality. BH18-06 which is located between BH18-05 and BH18-07/BH18-08 shows intermediate rock quality. Such decreasing rock quality with proximity to the Ottawa River is most likely due to borehole proximity to the major Mattawa Fault that defines the alignment of the Ottawa River.

Localized zones of low core recovery and RQD numbers are associated with zones of increased fracture frequency. Several zones of intense fracturing in the bedrock boreholes (e.g., at 50-53 m depth in BH18-05, 43-44 m depth in BH18-06, 41-43 m depth in BH18-07, and 22-23 m and 44-45 m depth in BH18-08) are associated with carbonate-healed/sealed subvertical fracture zones and brecciated zones.

Figures 2.42 to 2.46 show representative core photographs of the zones of intense fracturing encountered in BH18-05, BH18-07 and BH18-08. Such zones of intense fracturing, while apparent in individual boreholes as discrete bedrock structures, have not and likely cannot be mapped between individual boreholes given available data and site conditions. The low core recovery of 33% in BH/MW18-06 at about 24 m depth, based on ATV logs and core photos appears to be due to drilling difficulties (core loss from core barrel).

Figure 2.42 Calcite Infilled Subvertical Fractures, BH18-05, 50.2 to 50.7 mBGS

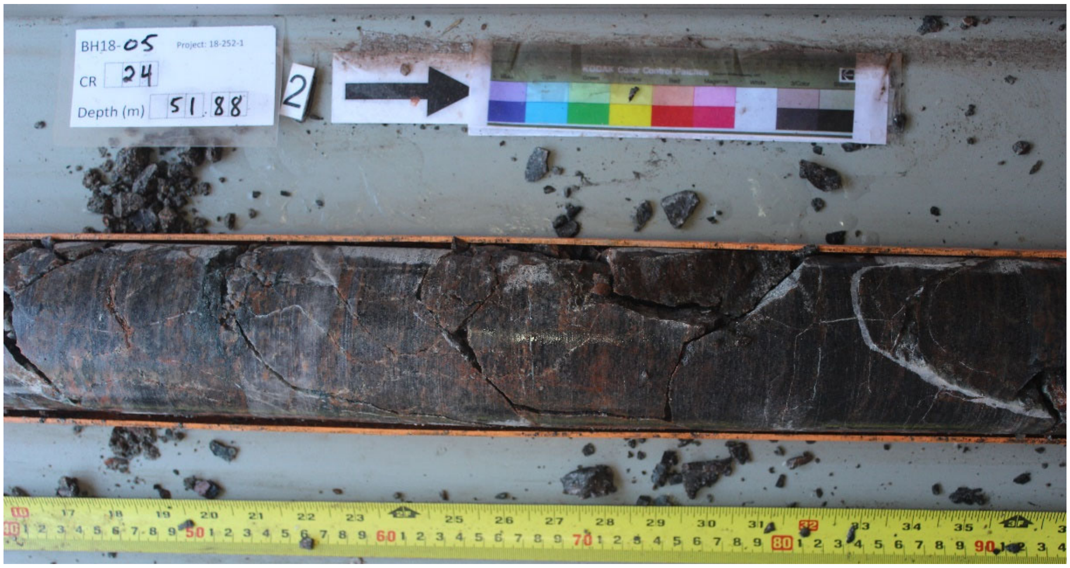


Figure 2.43 Calcite Infilled Subvertical Fractures and Breccia Zone, BH18-05, 52.3 to 52.8 mBGS

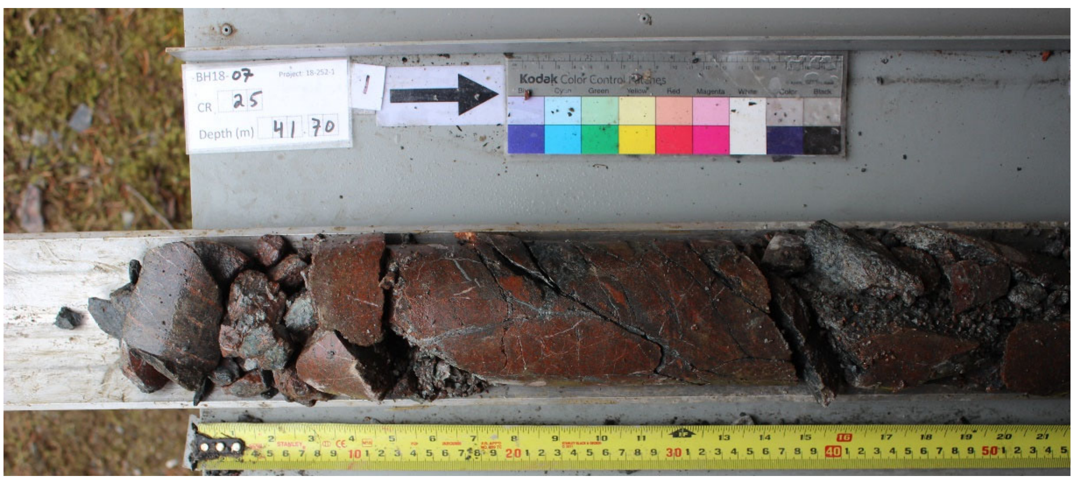


Figure 2.44 Rubble and Breccia Zone, BH18-07, 41.7 to 42.3 mBGS

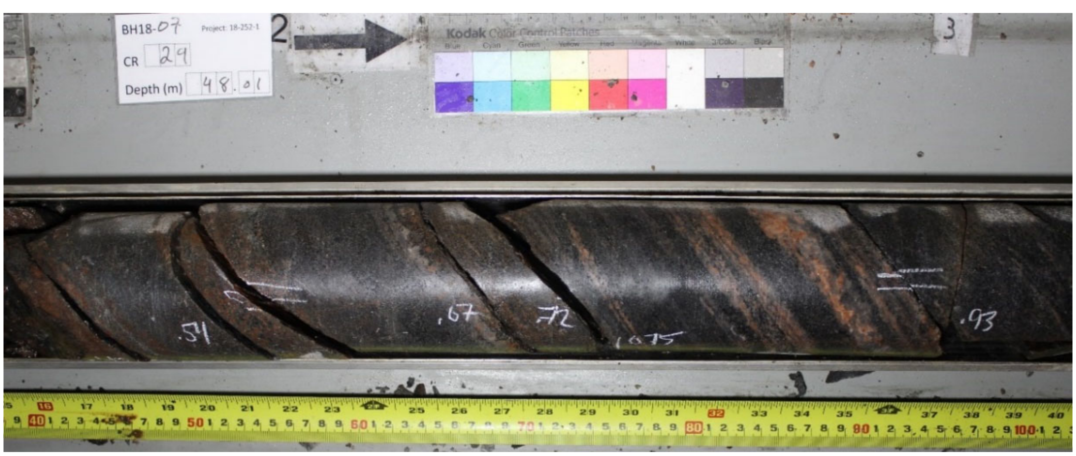


Figure 2.45 Foliation Shear Zone in Hornblende Gneiss, BH18-07, 48.4 to 49.0 mBGS

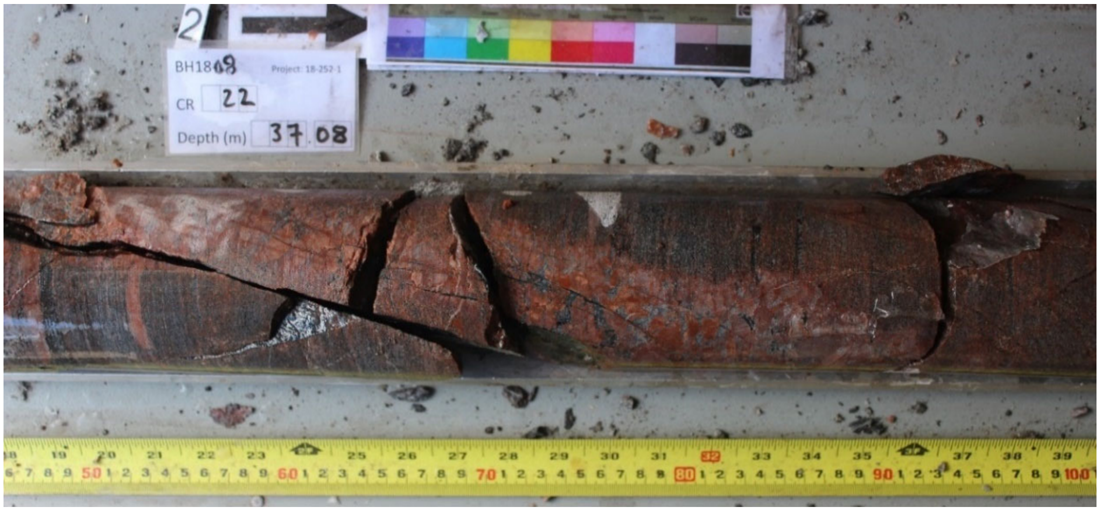


Figure 2.46 Fractured Contact of Subvertical Pegmatite Dyke, BH18-08, 37.5 to 38.1 mBGS

Figure 2.42 shows the presence of calcite-infilled subvertical fractures in dioritic gneiss at 50.2 to 50.7 mBGS in BH18-05. Figure 2.43 shows a similar occurrence of calcite-infilled subvertical fractures and a minor breccia zone in dioritic gneiss at 52.3 to 52.8 mBGS in BH18-05. Figure 2.44 illustrates a rubble and breccia zone in granitic gneiss at 41.7 to 42.3 m in BH18-07. Figure 2.45 shows a foliation shear zone in hornblende gneiss at 48.4 to 49.0 mBGS in BH18-07. Figure 2.46 portrays the fractured contact of a subvertical pegmatite dyke in dioritic gneiss at 37.5 to 38.1 mBGS in BH18-08.

Core photos and logs do not provide evidence of mylonitized, clay gouge or significant chemical alteration (e.g., argillization, chloritization, sericitization, etc.) zones that are characteristic of larger scale Grenville faults that would create air photo lineaments and topographic relief.

The orientation of nature fractures intersecting the walls of boreholes BH18-05 to BH18-08 were measured during borehole ATV geophysical logging surveys. Figures 2.47 to 2.50 show the contoured upper-hemisphere polar plot of borehole fractures in boreholes BH18-05 to BH18-08, respectively. Figure 2.51 shows the combined contoured upper-hemisphere polar plot for all borehole fractures.

All contouring in Figures 2.47 to 2.51 were created with Rockscience Inc. DIPS V7 software and includes Terzaghi (1965) sampling bias to a minimum intersection angle of 15º with the borehole axis. Inspection of Figures 2.47 to 2.50 shows that major fractures orientations are different in different boreholes. BH18-05 shows the predominant fracture orientation as east-west striking and south dipping; BH18-06 as northeast-southwest striking and moderate southeast dipping; BH18-07 as northwest-southeast striking and moderate southwest dipping; and BH18-08 as subhorizontal.

The combined four borehole plot of ATV fractures shows a predominant set that is east-west to eastsoutheast-westnorthwest striking and south-southwest dipping, and minor sets that are subhorizontal to and northeast-southwest striking and southeast dipping, and northwest-southeast striking and northeast-dipping. The east-southeast striking southwest dipping fracturing is most likely associated with the regional Mattawa Fault that defines the alignment of the Ottawa River.

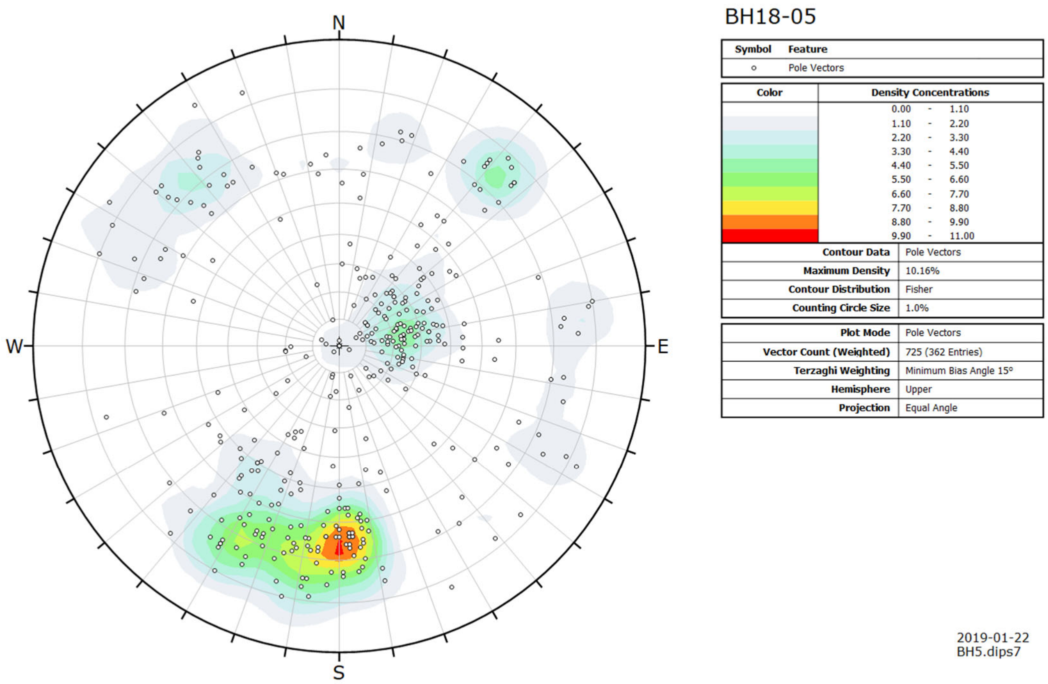


Figure 2.47 Contoured Upper-Hemisphere Polar Plot of Fractures in BH18-05 from ATV Logs

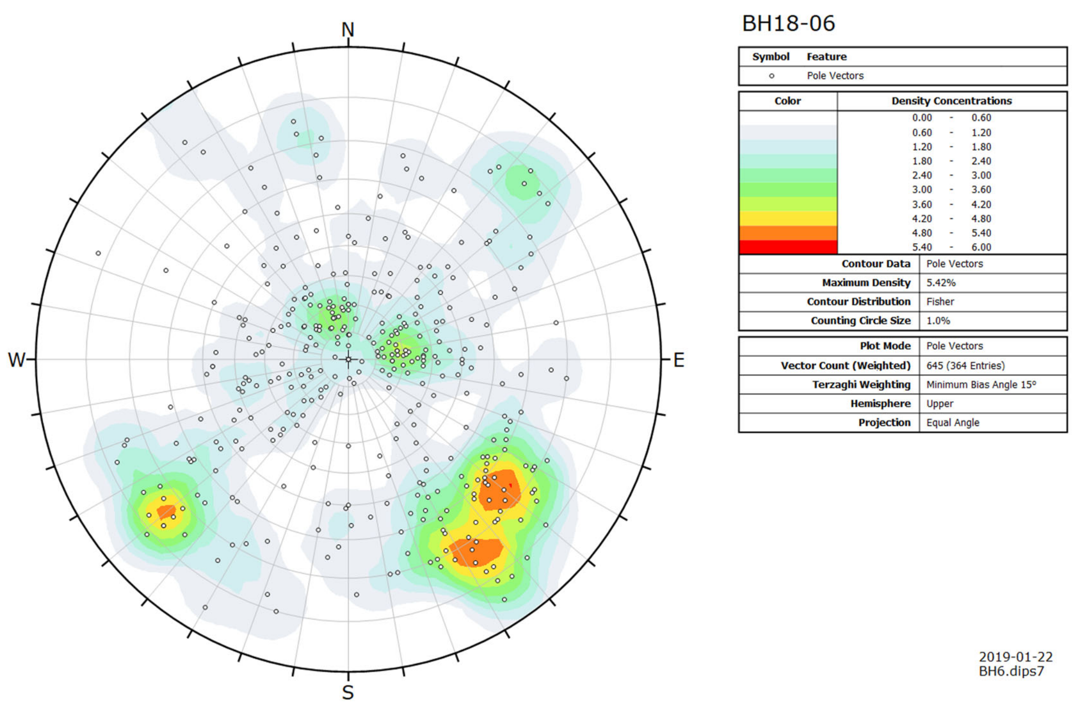


Figure 2.48 Contoured Upper-Hemisphere Polar Plot of Fractures in BH18-06 from ATV Logs

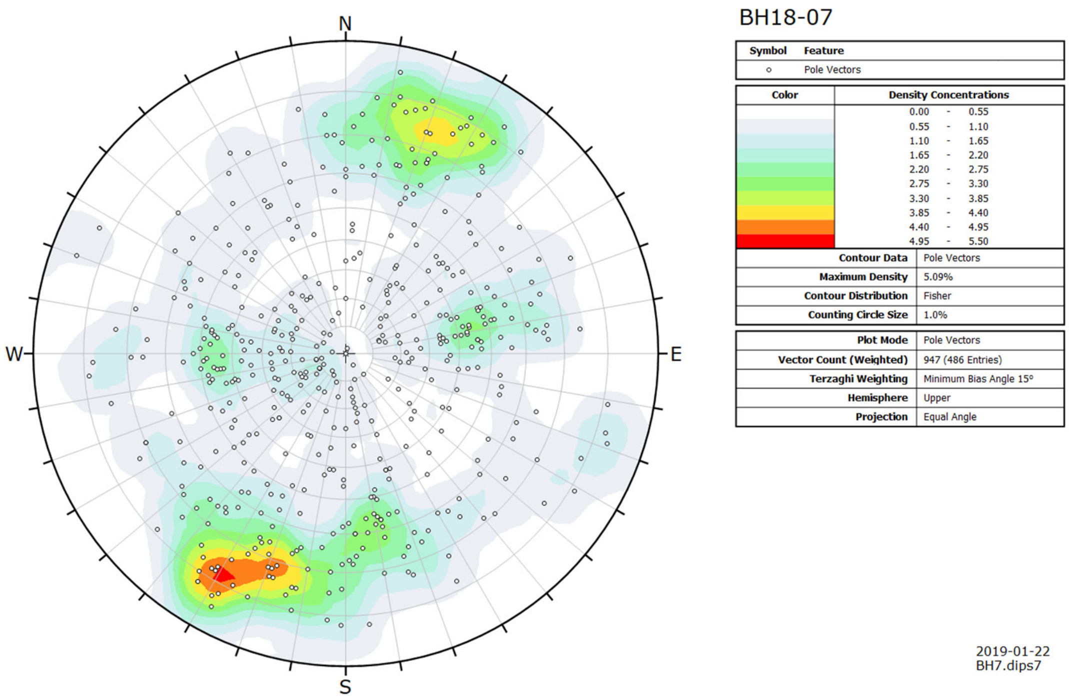


Figure 2.49 Contoured Upper-Hemisphere Polar Plot of Fractures in BH18-07 from ATV Logs

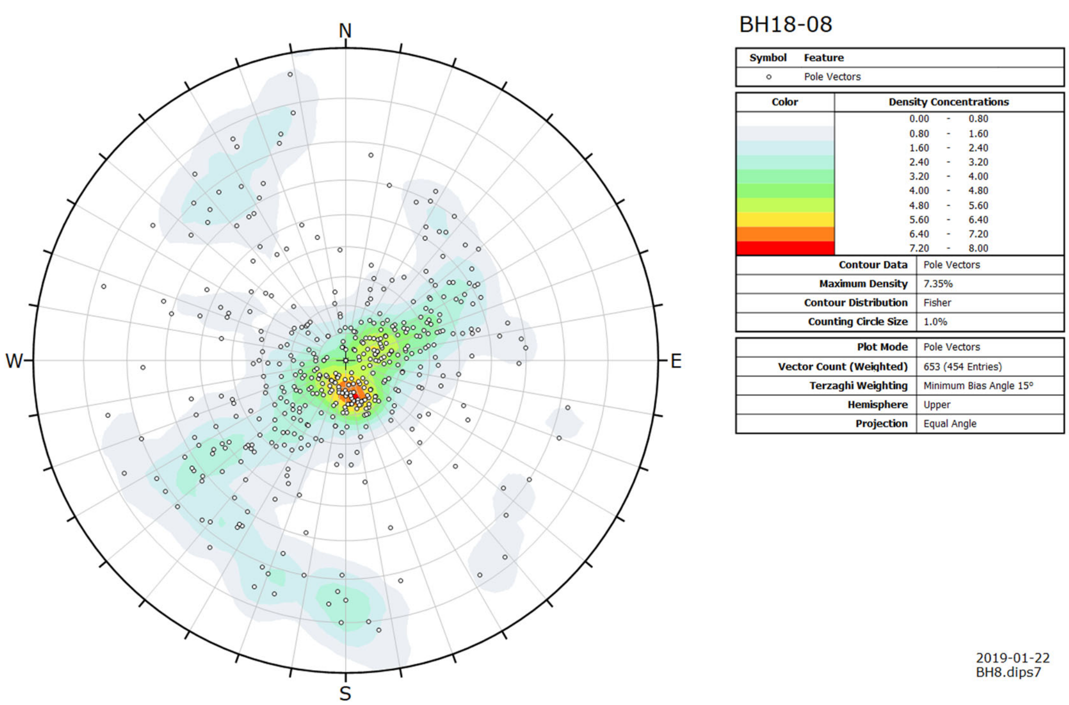


Figure 2.50 Contoured Upper-Hemisphere Polar Plot of Fractures in BH18-08 from ATV Logs

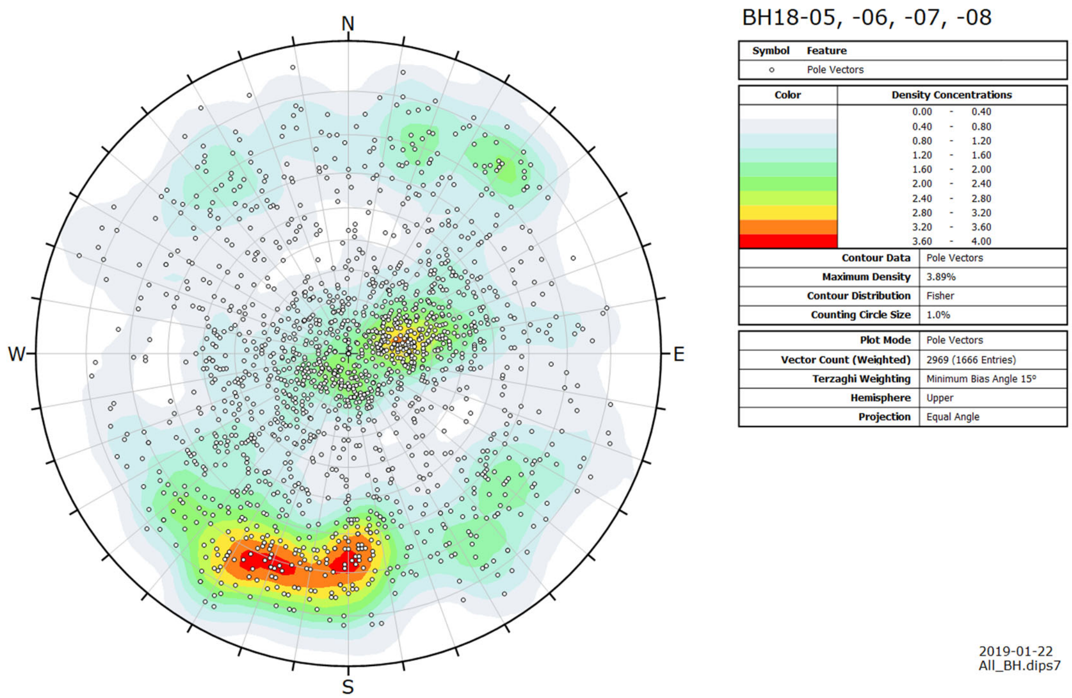


Figure 2.51 Contoured Upper-Hemisphere Polar Plot of Fractures in BH18-05 to BH18-08 from ATV Logs

2.4.6.6 Potential for Presence of Bedrock Faulting

There is little doubt that the shallow bedrock to depths of about 50 m below bedrock surface at the NPDWF site is fractured with metre-scale to sub-metre scale fracture zones, some brecciated/broken zones and subhorizontal sheeting fractures. It also likely that some of these fracture zones may be characterized as small-scale faults as evident in surface outcrop mapping. However, these small-scale mapped faults in outcrop as mylonite layers and sub-metre scale fractures/fracture zones are minor and do not create depressions in the outcrop bedrock surface. Consequently, similar minor faults may be present at the NPDWF site without creating bedrock surface depressions commonly associated with larger-scale Grenville faults. Given the proximity of the NPDWF site to the large-scale regional Mattawa Fault that defines the course of the Ottawa River it is not unreasonable to expect some fracturing and possibly minor faulting at the NPDWF site that relates to the Mattawa Fault. Similar observations are available from near-shore drilling of the bedrock at the Ottawa River at CRL site as part of the Geologic Waste Management Facility Project (McCrank, 2016a; 2016b).

Steeply dipping fractures and fracture zones in the bedrock at the NPDWF site that sub-parallel the Mattawa Fault, are most likely related to the Mattawa Fault. Review of core photos shows that several zones of intense fracturing in the bedrock boreholes (e.g., at 50-53 m depth in BH18-05, 43-44 m depth in BH18-06, 41-43 m depth in BH18-07, and 22-23 m and 44-45 m depth in BH18-08) are associated with carbonate-healed/sealed subvertical fracture zones and brecciated zones. Core photos and logs do not provide evidence of mylonitized, clay gouge or significant chemical alteration (e.g., argillization, chloritization, sericitization, etc.) zones that are characteristic of larger scale Grenville faults that would create air photo lineaments and topographic relief. Core photos of these intensely fractured zones in

BH18-05 (Figures 2.42 and 2.43) and BH18-07 (Figures 2.44 and 2.45) illustrate described poor quality core conditions. Some of the noted zones of intense fracturing show increases in bedrock hydraulic conductivity, but others do not. The highest K interval (K=6.6E-06 m/s) occurs at depths of 35.0-40.2 mBGS in BH18-08 and is associated with the subvertical open sheared contact of a pegmatite dyke (Figure 2.46), a small rubble zone and subhorizontal fracturing.

The depression in the bedrock surface at BH/MW18-05 as shown on Figures 2.5 and 2.6 might be related to subvertical fracturing that sub-parallels the Mattawa Fault, however, the available data do not allow for a definitive conclusion on the cause of the depression. The drilling of boreholes BH/MW18-09 and BH/MW18-10 that were completed along strike and normal to the suspected Mattawa Fault-related bedrock depression both yielded higher and similar bedrock surface elevations suggesting that the bedrock depression at BH/MW18-05 was isolated and not part of a NW-SE trending linear fault depression in the bedrock surface. Based on the isolated nature of this feature, the geomechanical description of the NPDWF rock mass (high strength intact rock that is moderately fractured with fair to good rock mass quality), the small scale of logged bedrock structures, and considering that bedrock fractures have been already incorporated in the groundwater flow model as an equivalent porous media (EPM), the impact of this feature on the NPD project closure is expected to be negligible.

2.4.6.7 Summary

The available data on fracture occurrence and orientation at the NPD site indicate a primary fracturing orientation of northwest-southeast strike with both southwest and northeast dips, and secondary fracturing orientation of north-south strike and subhorizontal dip to the east. These facture orientations are generally evident in the lineament study, NPD bedrock excavations, outcrop mapping and ATV logging of BH18-05 to BH18-08. Borehole natural fracture frequency and RQD measurements indicate shallow bedrock that is moderately fractured and of fair to good rock quality, with an observed increase in fracturing and decrease in RQD with proximity to the Ottawa River. The available data on fracture occurrence do not indicate the presence of major fault or shear zone in the bedrock of the NPDWF. This characterization of the bedrock indicates that the bedrock can be considered competent and unlikely to be adversely affected by local and regional seismic activity.

The structural features observed in the four bedrock boreholes completed to depths of 50 m below bedrock surface show numerous small-scale structures of open fractures, subvertical fractured dyke contacts, minor foliation shear zones, metre to sub-metre scale fracture zones and minor rubble zones that are consistent with the geomechanical description of the NPDWF rock mass as high strength intact rock that is moderately fractured with fair to good rock mass quality. The scale of logged bedrock structures is not of sufficient size or unique character to allow mapping of the structures between the four bedrock boreholes and hence to construct a discrete 3-D fracture network structural model or groundwater flow model of the NPDWF rock mass. Instead, the small scale, high frequency and wide range of fracture orientations (see polar plots of Figures 2.47 to 2.51) detected in bedrock supports an aggregated or bulk rock mass description of bedrock structural features for use in descriptive geological, hydrogeological and geomechanical models of the NPDWF site. For groundwater flow models this means use of an equivalent porous media (EPM) isotropic representation of the rock mass K. The small scale of the bedrock structures is consistent with the lack of air photo lineaments and OGS-mapped faults at the NPDWF site.

2.4.7 NPD Site Lithology

2.4.7.1 Historical Mapping and Core Logging

Lithology of the NPD bedrock was historically identified by Hydro-Electric Power Commission of Ontario (1956) and summarized by Canadian General Electric Company Ltd. (1962) based on inspection of recovered core from both adjacent and on-site diamond drilling programs. These reports identify the bedrock at the NPD site as quartz feldspar hornblende gneiss, or as hornblende biotite gneiss with quartzofeldspathic layering. This site bedrock lithology is consistent with historical local mapping of bedrock outcrops by Lumbers (1976) and Ontario Geological Survey (2011), and mapping of the bedrock at the adjacent Rapides des Joachims power development.

2.4.7.2 Bedrock Outcrop Mapping

Lithology of bedrock at the NPD site has recently been identified based on geological mapping of 13 bedrock outcrops (see Figure 2.30 for outcrop mapping locations) and logging of recovered core from BH18-04 to BH18-08 as part of geoscientific site characterization work (Geofirma Engineering Ltd., 2019).

Table 2.3 summarizes the bedrock mapping stations with UTM coordinates, main lithology observed at each location, sample identification numbers and outcrop photo numbers. Figures 2.52 to 2.55 show examples of field photographs of bedrock outcrops. Appendix A of the Geoscientific Characterization of the NPD Site Report (Geofirma Engineering Ltd., 2019) provides additional information on outcrop structural measurements including orientation and spacing of main joint sets, and orientation of gneissic foliation, dykes/veins and other structural features including lithological contacts, mylonites and faulting.

The lithology of the mapped outcrops around the NPD site is interpreted as the following three dominant groups, in order of decreasing abundance:

1) Granitic to Quartz-Monzonitic Gneiss;
2) Biotite Hornblende Garnet Augen Gneiss;
3) Gabbroic Gneiss.

These three bedrock lithology descriptions for the NPD site are consistent with historical geological interpretations based on inspection of recovered core from diamond drilling and with local mapping of bedrock outcrops by Lumbers (1976).

Outcrops around the NPD property are dominated by granitic to quartz-monzonitic augen gneiss, with weak to moderate banding defined by biotite +/- hornblende. The relative mineralogical proportions are potassic feldspar > plagioclase > biotite > +/- hornblende > quartz. Augens are primarily composed of coarse-grained potassic feldspar, locally contain quartz, and are 1-4 cm in diameter. Figures 2.52, 2.53 and 2.54 show field photographs of outcrops of Lithology 1. The second most abundant lithology is a biotite +/- hornblende garnet augen gneiss, with strong gneissic banding defined by quartzofeldspathic layers. Garnet porphyroblasts (0.1 to 1 cm) are abundant in this lithology. The relative mineralogical proportions are plagioclase > potassic feldspar > biotite > garnet > hornblende > quartz. Figure 2.55 shows a field photograph of Lithology 2.

Table 2.3 Summary of Results of Bedrock Outcrop Mapping

Outcrop ID	Outcrop Location (UTM) Zone 18T	Lithology	Photo Numbers	Rock Sample ID
18-NPD-01	295178m E, 5117279m W	Biotite granitic gneiss	119-5664 to 119-5670	18-NPD-01-A01
18-NPD-02	292194m E, 5116910m W	Litho A and B: Biotite granitic gneiss (lithologies distinguished by strength of foliation)	119-5671 to 119-5692	18-NPD-02-A01 18-NPD-02-B01 18-NPD-02-B02 18-NPD-02-B03 18-NPD-02-B04
18-NPD-03	292291m E, 5116946m W	Litho A: Biotite rich granitic gneiss Litho B: Potassic feldspar pegmatitic intrusion	119-5693 to 119-5716	18-NPD-03-A01 18-NPD-03-B01
18-NPD-04	294655m E, 5117384m W	Biotite garnet augen gneiss with quartzofeldspathic banding	119-5717 to 119-5726	18-NPD-04-A01
18-NPD-05	307501m E, 5108175m W	Litho A: Biotite garnet augen gneiss with quartzofeldspathic banding Litho B: Potassic feldspar pegmatitic intrusion	120-5727 to 120-5739	18-NPD-05-A01 18-NPD-05-A02 18-NPD-05-B01
18-NPD-06	293175m E, 5119216m W to 293220m E, 5119206m W	Biotite garnet augen gneiss with quartzofeldspathic banding	120-5740 to 120-5751	18-NPD-06-A01
18-NPD-07	293040m E, 5118997m W	Biotite garnet granitic gneiss	120-5752 to 120-5760	18-NPD-07-A01
18-NPD-08	294825m E, 5117362m W	Biotite granitic gneiss	120-5761 to 120-5777	18-NPD-08-A01
18-NPD-09.1	293075m E, 5118759m W	Litho A: Granitic augen gneiss	121-5778 to 121-5789	18-NPD-09.1-A01
18-NPD-09.2	293079m E, 5118756m W	Granitic augen gneiss	121-5800 to 121-5813	None
18-NPD-09.3	293098m E, 5118730m W	Granitic augen gneiss	121-5814 to 121-5833	None
18-NPD-09.4	293120m E, 5118682m W	Litho B: Gabbroic gneiss Litho C: Mylonite	121-5834 to 121-5865	18-NPD-09.4-B01 18-NPD-09.4-C01
18-NPD-10	293124m E, 5118231m W	Granitic gneiss	121-5866 to 121-5883	18-NPD-10-A01
18-NPD-11	293116m E, 5117816m W	Quartz monzonitic gneiss	121-5866 to 121-5883	18-NPD-10-A01
18-NPD-12	292997m E, 5117555m W	Hornblende granitic augen gneiss	122-5893 to 122-5919	18-NPD-12-A01 18-NPD-12-A02
18-NPD-13.1	295573m E, 5116879m W	Biotite hornblende granitic augen gneiss	122-5920 to 122-5933	None
18-NPD-13.2	295573m E, 5116879m W	Biotite hornblende granitic augen gneiss	122-5934 to 122-5941	18-NPD-13.2-A01

Figure 2.52 Photo 119-5684 – Station18-NPD-02 – Biotite Granitic Gneiss

Figure 2.53 Photo 120-5869 – Station 18-NPD-08 – Jointing in Biotite Granitic Gneiss

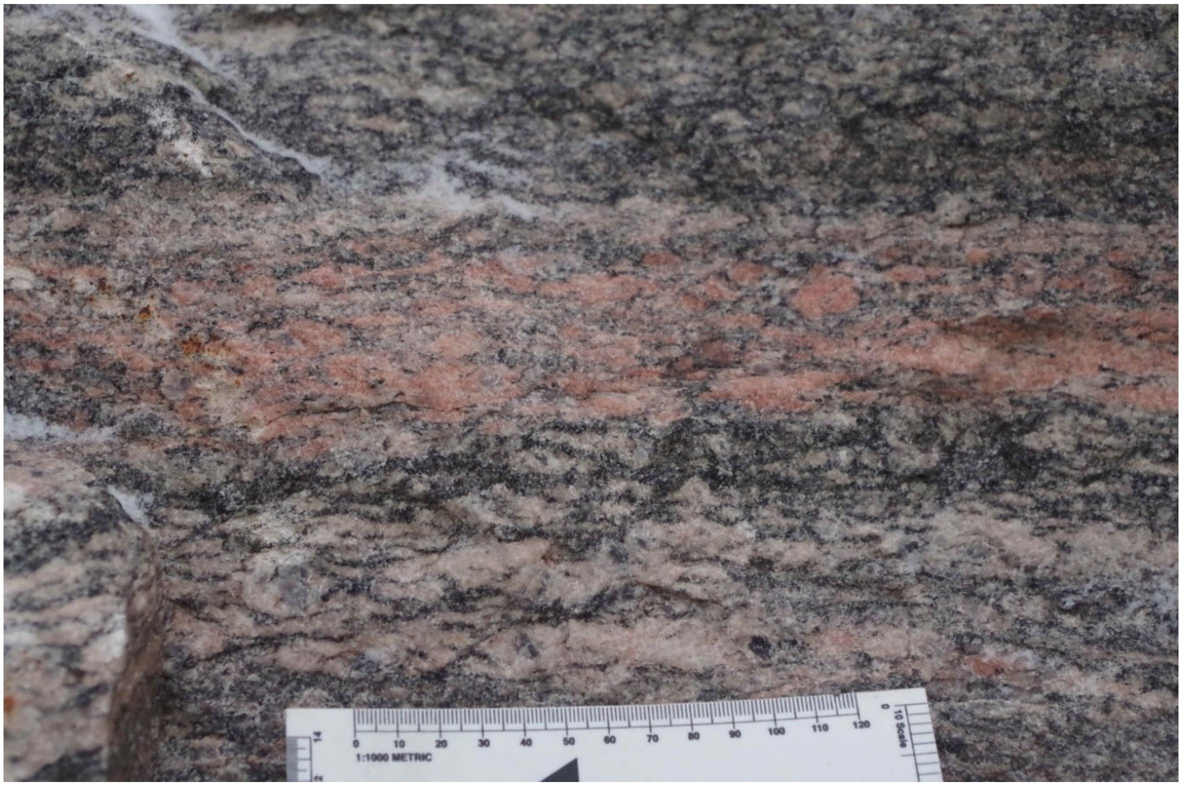


Figure 2.54 Photo 121-5887 – Station 18-NPD-12 – Quartzofeldspathic Banding in Hornblende Granitic Gneiss

Figure 2.55 Photo 122-5937 – Station 18-NPD-13.2 – Augenitic Hornblende Biotite Gneiss

The third lithology present at the NPD site is gabbroic gneiss interlayered with Lithology 1. The relative mineralogical proportions are biotite > hornblende > potassic feldspar > plagioclase > quartz.

Centimeter scale potassic (K) feldspar dykes are commonly observed to cross-cut foliation and are highly deformed. Additionally, this lithology occurs as sub-vertical metre scale pegmatite dykes that cross-cut outcrops. The relative mineralogy is potassic feldspar >> plagioclase > quartz. A thin (~5 cm) gabbroic sill is visible in one outcrop (Station 18-NPD-05), parallel to gneissic foliation.

2.4.7.3 2019 Shallow Bedrock Drilling and Coring

The lithology of shallow bedrock in the immediate vicinity of the NPDWF was determined from field logging of recovered core from boreholes BH18-05 to BH18-08 drilled to total depths of 55.28 to 69.01 mBGS or about 50 m below depth to competent bedrock. The lithology of the recovered core from these boreholes is summarized on borehole logs provided in Appendix D of the Geoscientific Characterization of the NPD Site Report (Geofirma Engineering Ltd, 2019). Figures 2.56 to 2.60 show representative core photographs of major bedrock lithologies encountered during the 2019 shallow bedrock drilling and core program.

Borehole logs for BH18-05 to BH18-08 show the bedrock is principally an interlayered sequence of metre-scale bands of granitic gneiss (Figure 2.56) and hornblende gneiss (Figure 2.57), with minor bands of dioritic gneiss (Figure 2.58) and hornblende K-feldspar gneiss (Figure 2.59). The granite gneiss and hornblende gneiss are present in about equal amounts in BH18-05, BH18-07 and BH18-08. Hornblende gneiss is more abundant than granitic gneiss in BH18-06. Metre-scale to sub-metre-scale pegmatite dykes (Figure 2.60) intrude the gneissic rock sequence in all boreholes. Sub-metre-scale diabase dykes (Figure 2.60) intersect the gneissic rocks only in BH18-07 and BH18-08 beside the Ottawa River and closest to the Mattawa Fault.

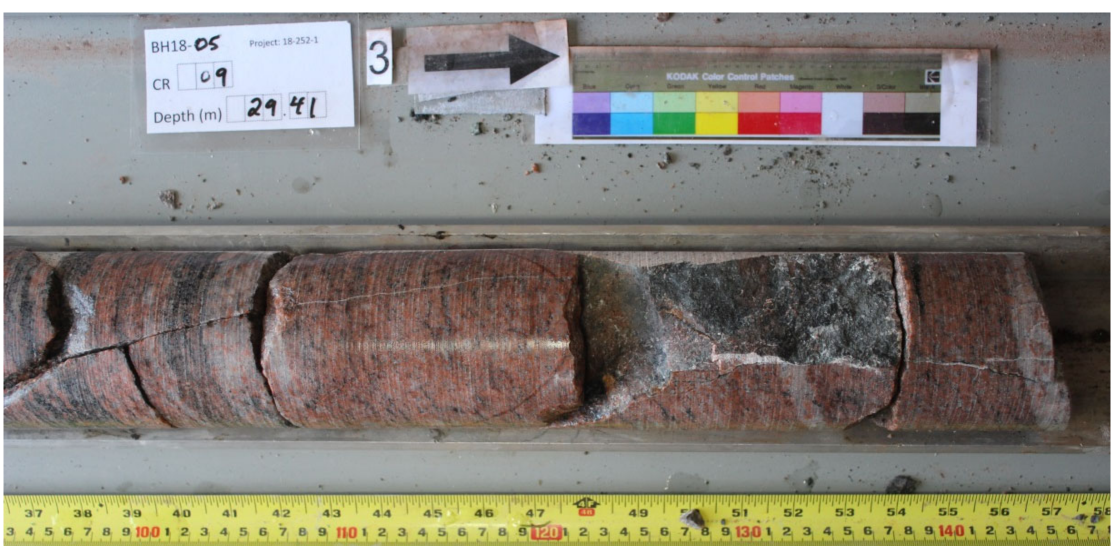


Figure 2.56 Granitic Gneiss at Depth of 30.6 mBGS in BH18-05

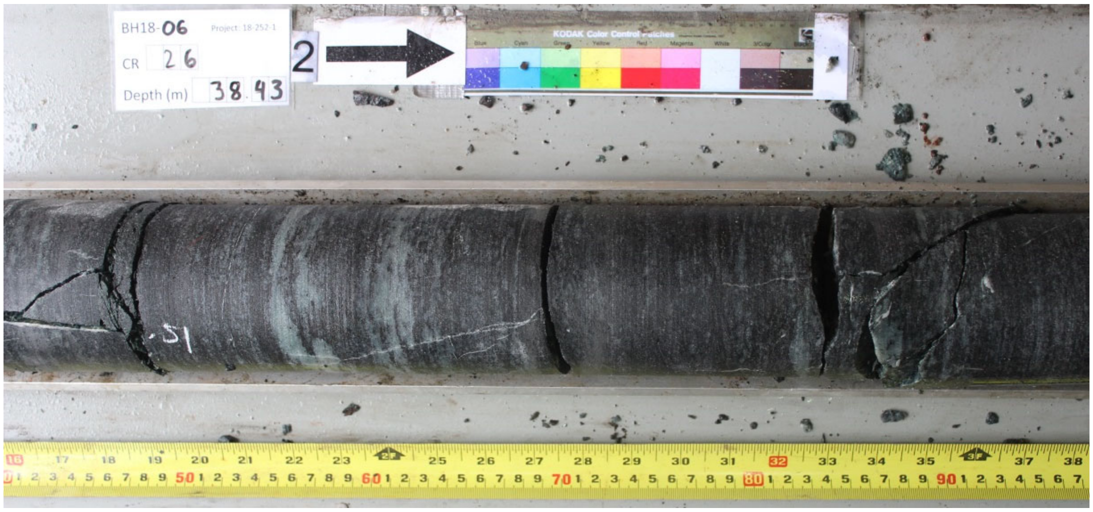


Figure 2.57 Hornblende Gneiss at Depth of 39.1 mBGS in BH18-06

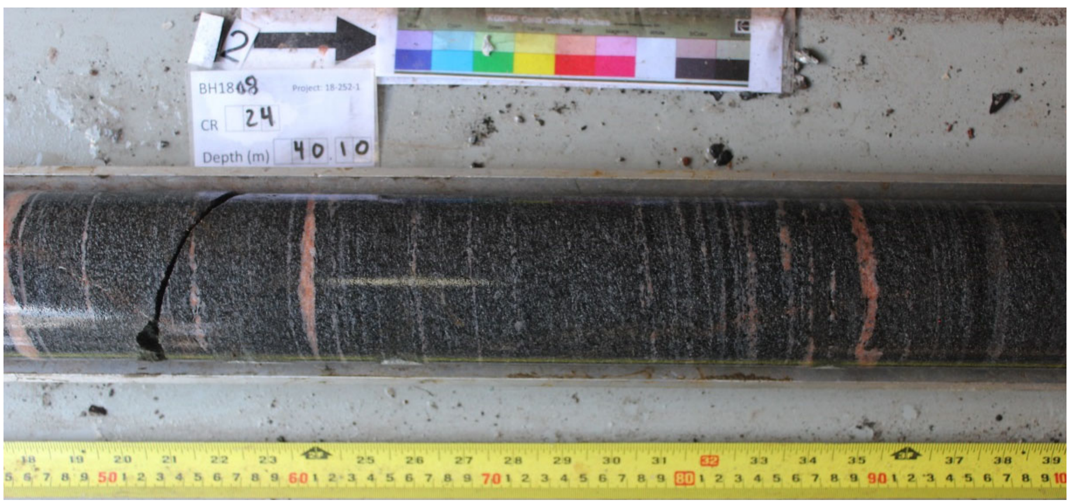


Figure 2.58 Dioritic Gneiss at Depth of 40.8 mBGS in BH18-08

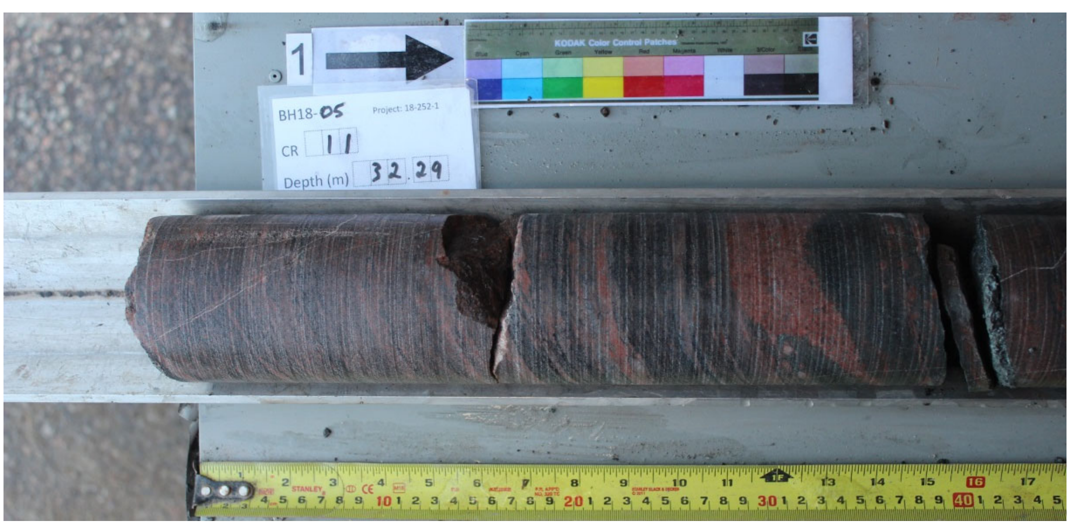


Figure 2.59 Hornblende K-Feldspar Gneiss at Depth of 32.4 mBGS in BH18-05

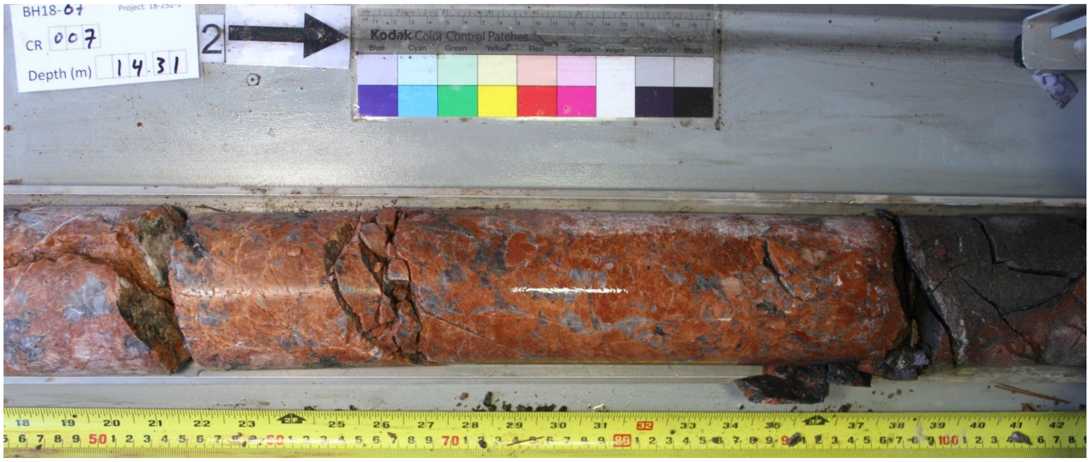


Figure 2.60 Pegmatite Dyke Overlying Diabase Dyke in BH18-07, Contact at 15.3 mBGS

2.4.8 NPD Site Petrology and Lithogeochemistry

Information on petrology and lithogeochemistry of bedrock at the NPD site is inferred from examination of core recovered from recent and historical on-site diamond drilling, from recent and historical mapping of outcrops in the vicinity of the site and from petrographic and lithogeochemical analyses of NPD site outcrop and borehole core samples and of similar rock types found at the CRL site.

2.4.8.1 Historical Investigations

Lumbers (1976) mapping of proximate outcrops east and southwest of the NPDWF site (see Figure 2.15) identifies the following relative bedrock mineralogy:

- Map Unit 1a - Biotite Gneiss: plagioclase>quartz>K-feldspar>biotite;
- Map Unit 5b – Hornblende Gneiss: plagioclase>quartz>amphibolite>biotite>garnet.

Chernis and Hamilton (1989), Raven Beck Environmental Ltd. (1994a), Thivierge (2011) and McCrank (2016a, 2016b) summarize the petrology and lithogeochemistry of CRL bedrock. Review of these reports suggests the following equivalence of bedrock units at the CRL property to those mapped by Lumbers (1976) and Hydro-Electric Power Commission of Ontario (1956):

- Lumbers Biotite Gneiss ~ Migmatitic Quartzofeldspathic Gneiss (Map Unit 1) of Raven Beck Environmental Ltd (1994a) and Quartzofeldspathic Gneiss (Map Unit 1) of Thivierge (2011) and McCrank (2016a, 2016b).
- Lumbers Hornblende Gneiss ~ Meta-Quartz Monzodiorite, Monzodiorite and Quartz Diorite (Map Unit 4) of Raven Beck Environmental Ltd (1994a) and Dioritic and Amphibolitic Gneiss (Map Unit 2) of Thivierge (2011) and McCrank (2016a, 2016b).

Based on these equivalencies, Table 2.4 summarizes the inferred mineralogy and lithogeochemistry of the biotite gneiss and hornblende gneiss rock present at the NPD site. Based on Table 2.4, the mapped biotite and hornblende gneiss bedrock units are lithologically similar and, according to the Streckeisen

(1976) (quartz – alkali (K) feldspar – plagioclase feldspar – feldspathoid) double ternary classification system, are likely quartz-monzonite to quartz-monzodiorite rocks with plagioclase feldspar dominant over K-feldspar and mafic minerals, and quartz present at less than 20%.

Table 2.4 Summary of Inferred Major Mineralogy and Lithogeochemistry of Bedrock at NPD Site from CRL Work

Lumbers (1976) Map Unit and Rock Type	*Major Mineralogy from Petrographic Thin-Section Analyses (%)*	*Lithogeochemistry as Major Oxides (weight %)*
1a - Biotite Gneiss	Plagioclase: 25-40% K-Feldspar: 15-30% Quartz: 15-30% Biotite: 10-20% Hornblende: 5-10% Garnet: 0-5%	SiO_2: 45-55% Na_2O: 2.6-3.7% Al_2O_3: 15-18% K_2O: 2.6-5.7% Fe_2O_3: 3-8% TiO_2: 0.4-0.9% MnO: 0.04-0.12% P_2O_5: 0.1-0.2% MgO: 0.7-2.7% CaO: 1.9-4.0%
5b - Hornblende Gneiss	Plagioclase: 50-60% K-Feldspar: 5-20% Quartz: 10-20% Biotite: 10-15% Hornblende: 10-15% Garnet: 0-2%	SiO_2: 55-60% Na_2O: 3.8-4.2% Al_2O_3: 17-19% K_2O: 3.6-5.0% Fe_2O_3: 1.1-2.3% TiO_2: 0.7-1.2% MnO: 0.11-0.19% P_2O_5: 0.2-0.4% MgO: 1.1-1.5% CaO: 4.6-5.1%

2.4.8.2 2019 Investigations

Twenty rock samples consisting of six outcrop samples and 14 core samples were submitted to SGS Canada Inc. for high-definition mineralogical characterization using QEMSCAN (quantitative evaluation of materials by scanning electron microscopy), optical mineralogy, and XRD (X-ray diffraction) analysis. One polished thin section (PTS) was prepared from each sample on a marked area defined by Geofirma. The PTSs were used for the QEMSCAN analysis for the optical mineralogy. All PTSs were examined with reflected and transmitted light microscopy. The off cuts from the PTS's were pulverized and submitted for qualitative XRD analysis. The purpose of this test program was to determine the overall mineral assemblage and textural characteristics of the samples to assist in identification of bedrock lithologies at the NPD site.

The results of mineralogical characterization work are summarized in Appendix J of the Geoscientific Characterization of the NPD Site Report (Geofirma Engineering Ltd., 2019) and in a separate laboratory analysis report (SGS Canada Inc., 2019). Table 2.5 summarizes the field identification and SGS Canada Inc. laboratory mineralogical and petrographic characterization of the 20 rock samples. In interpreting the results provided on Table 2.5 and the comparison of Table 2.5 data with data from Section 2.4.8.1 and Table 2.4, it is important to consider the scale of the different measurements from large outcrops to hand specimens/core samples to small polished thin sections/XRD samples on which most of the laboratory mineralogical testing was performed. Given the natural variability of mineralogy over these different measurement scales and the difficulty of selecting rock sample areas for preparation of polished thin sections and XRD work that are representative of outcrop and hand specimens/core samples, only approximate similarity in mineralogical identification and lithological naming should be expected.

Table 2.5 Summary of 2019 Field and Laboratory Identification of Mineralogy and Petrology at NPD Site

Sample ID	Field Rock Description	Qualitative XRD Mineralogy	QEMSCAN Modal Mineralogy (%)	SGS Rock Name
Bedrock Outcrop				
18-NPD-01-A01	Biotite granitic gneiss	Plag>Qtz>Kspar.Mica~Magh	Plag(63.2), Biot(18.6), Qtz(8.8), Kspar(4.1)	Quartz Diorite
18-NPD-06-A01	Biotite garnet augen gneiss with quartzo-feldspathic banding	Qtz>Plag>Mica>Kspar~Magh	Plag(38.4), Qtz(22.1), Biot(17.7), Garnet(16.8)	Garnet Gneiss
18-NPD-08-A01	Biotite granitic gneiss	Qtz~Plag.>Kspar>Mica~Pyrx	Plag(36.9), Qtz(35.2), Kspar(22.4), Biot(6.3)	Granitic Gneiss
18-NPD-09.4-B01	Gabbroic gneiss	Plag>Qtz>Pyrx~Mica~Magh~Kspar	Plag(57.4), Qtz(17.8), Kspar(7.8), Amph(6.5), Biot(6.3)	Clinopyroxene/Amphibole-bearing Gneiss
18-NPD-12-A01	Hornblende granitic augen gneiss	Qtz~Epdt>Kspar>Pyrr	Epdt(45.2), Kspar(28.3), Qtz(12.9), Amph(0.8)	Granodiorite
18-NPD-13.2-A01	Biotite hornblende granitic augen gneiss	Qtz~Plag>>Kspar~Mica~Magh	Plag(49.4), Qtz(26.7), Kspar(15.3), Biot(12.2)	Granite
Borehole Core				
BH18-05-27.85	Hornblende gneiss	Plag>Qtz>Amph~Mica~Kspar	Plag(76.3), Biot(12.2), Amph(5.4), Qtz(2.6)	Monzonite
BH18-05-31.66	Hornblende Kspar gneiss	Qtz>Kspar~Plag	Plag(35.1), Kspar(31.5), Qtz(30.4), Biot(0.2)	Granite
BH18-05-49.31	Granitic gneiss	Qtz~Plag>>Mica~Kspar~Magh	Plag(59.7), Biot(14.1), Kspar(12.3), Qtz(12.0)	Felsic Gneiss/ Quartz Monzodiorite
BH18-05-68.90	Granitic gneiss	Plag>Qtz~Kspar>Mica~Ept	Plag(49.3), Qtz(24.2), Kspar(17.2), Biot(7.5)	Granodiorite
BH18-06-14.75	Hornblende gneiss	Plag>Qtz>Mica~Magh~Amph	Plag(79.4), Biot(5.9), Amph(5.5), Qtz(3.1)	Amphibole-bearing Monzonite

Sample ID	Field Rock Description	Qualitative XRD Mineralogy	QEMSCAN Modal Mineralogy (%)	SGS Rock Name
BH18-06-27.26	Hornblende gneiss	Plag>Mica>Kspar~Amph~Qtz	Plag(41.8), Biot(15.4), Amph(11.1), Qtz(7.8)	Amphibole Diorite/Gneiss
BH18-06-49.31	Granitic gneiss	Qtz>Kspar~Plag>Mica~Pyrx	Kspar(42.3), Qtz(30.1), Plag(20.4), Biot(2.3)	Granite
BH18-07-11.41	Hornblende gneiss	Qtz~Kspar>Plag>Pyrx	Plag(28.2), Biot (21.8), Kspar(13.0), Clays(11.5), Chlorites(10.1), Qtz(9.1)	Chlorite Gneiss
BH18-07-15.02	Pegmatite	Plag~Qtz>>Kspar~Mica	Qtz(45.1), Kspar(33.2), Plag(9.6), Biot(7.5)	Granite
BH18-07-39.13	Granitic gneiss	Plag~Qtz>>Kspar	Plag(69.8), Qtz(11.9), Kspar(5.0), Chlorites(3.9), Amph(2.5)	Altered Quartz Diorite
BH18-07-50.08	Hornblende gneiss	Plag~Qtz>Amph>Kspar~Mica	Plag(47.9), Amph(18.0), Biot(16.1), Qtz(11.8), Kspar(1.0)	Amphibole-Biotite Gneiss
BH18-08-13.01	Hornblende gneiss	Amph~Plag>Mica~Qtz	Plag(55.4), Amph(24.9), Qtz(10.5), Biot(4.0), Kspar(1.1)	Amphibole Gneiss
BH18-08-40.59	Dioritic gneiss	Plag>Amph~Qtz~Mica>Kspar	Plag(39.3), Amph(31.5), Biot(15.2), Qtz(6.7), Kspar(1.8)	Amphibole-Biotite Gneiss
BH18-08-54.62	Hornblende gneiss	Plag>Amph~Qtz~Mica>Kspar	Plag(42.5), Amph(29.0), Qtz(11.7), Biot(11.0), Chlorites (0.2), Epdt(0.2)	Amphibolite
Plag=plagioclase, Qtz=quartz, Kspar=potassic(K)feldspar, Biot=biotite, Amph=amphibole, Pyrx=pyroxene, Magh=maghemite, Epdt=epidote, Pyrr=pyrrhotite				

2.4.8.3 Summary

Recognizing that the mineral amphibole used in SGS Canada Inc. mineral identification is a synonym for hornblende, the lithological names listed in Table 2.5 are essentially the same as those outlined for the NPD site and surrounding area in the Geosynthesis Report (Arcadis Canada Inc., 2018a). The lithologies listed in Table 2.5 are entirely consistent with the summary rock description of migmatitic biotite gneiss provided in the Geosynthesis Report and earlier OGS preliminary mapping by Lumbers (1976) as well as current bedrock outcrop mapping described in Section 2.4.6.4 of this report.

The plagioclase, K-feldspar (alkali feldspar) and quartz modal mineral percentages plotted on a Streckeisen (1976) ternary plot are shown in Figure 2.61 and indicate the dominant lithologies in both 2019 outcrop and borehole core samples vary from granite/granodiorite to quartz monzodiorite to quartz diorite to diorite/gabbro. This Streckeisen ternary plot is remarkably similar to plots for the Chalk River Laboratories bedrock presented by Chernis and Hamilton (1989), Raven Beck Environmental Ltd. (1994a), Thivierge (2011) and McCrank (2016a, 2016b), indicating a general similarity in mineralogies and lithologies at the NPD and CRL sites.

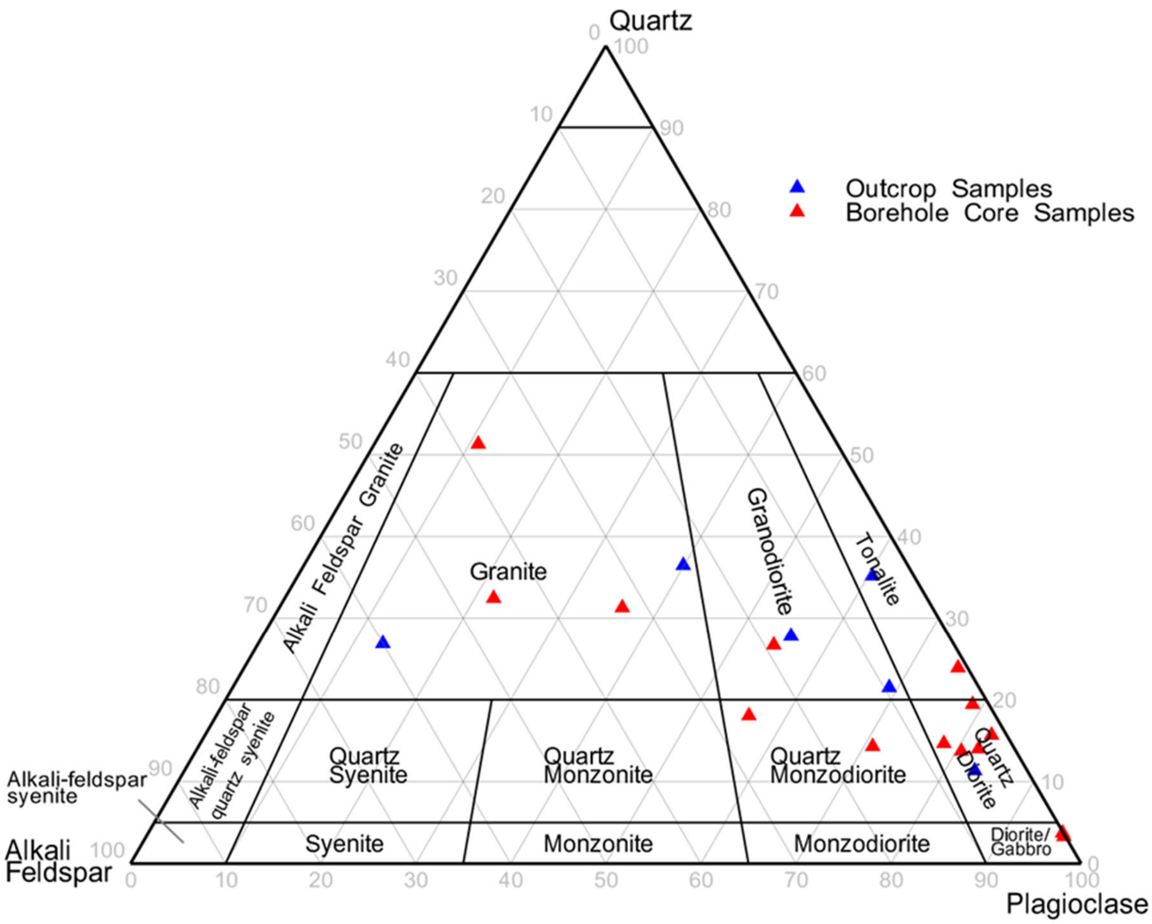


Figure 2.61 Ternary Streckeisen Plot of Major Modal Mineralogy of NPD Outcrop and Borehole Core Samples from 2019 Investigations

2.5 Economic Geology

Economic geology in the area of the NPD site is assessed based on review of Ontario Ministry of Northern Development and Mines (2018), Ontario Ministry of Natural Resources (2006) and Ontario Geological Survey (2014) databases of mines, mining claims, mineral resources and pits and quarries. Figure 2.62 shows the location of all mineral occurrences, mining claims, mines and pits and quarries in the area surrounding the NPD site.

2.5.1 Mining Claims

Figure 2.62 shows there is one active mining claim, for gneiss and granite building stone, located 12 km west of the NPDWF site at Mackey, Ontario. Figure 2.62 also shows a past-producing silica sand and feldspar mine located north of Mackey on the Ottawa River, also about 12 km west of the NPDWF site. There are also two discretionary mineral occurrences for anorthosite and graphite located 13 km southwest and 28 km southeast, respectively, of the NPDWF site.

2.5.2 Pits and Quarries

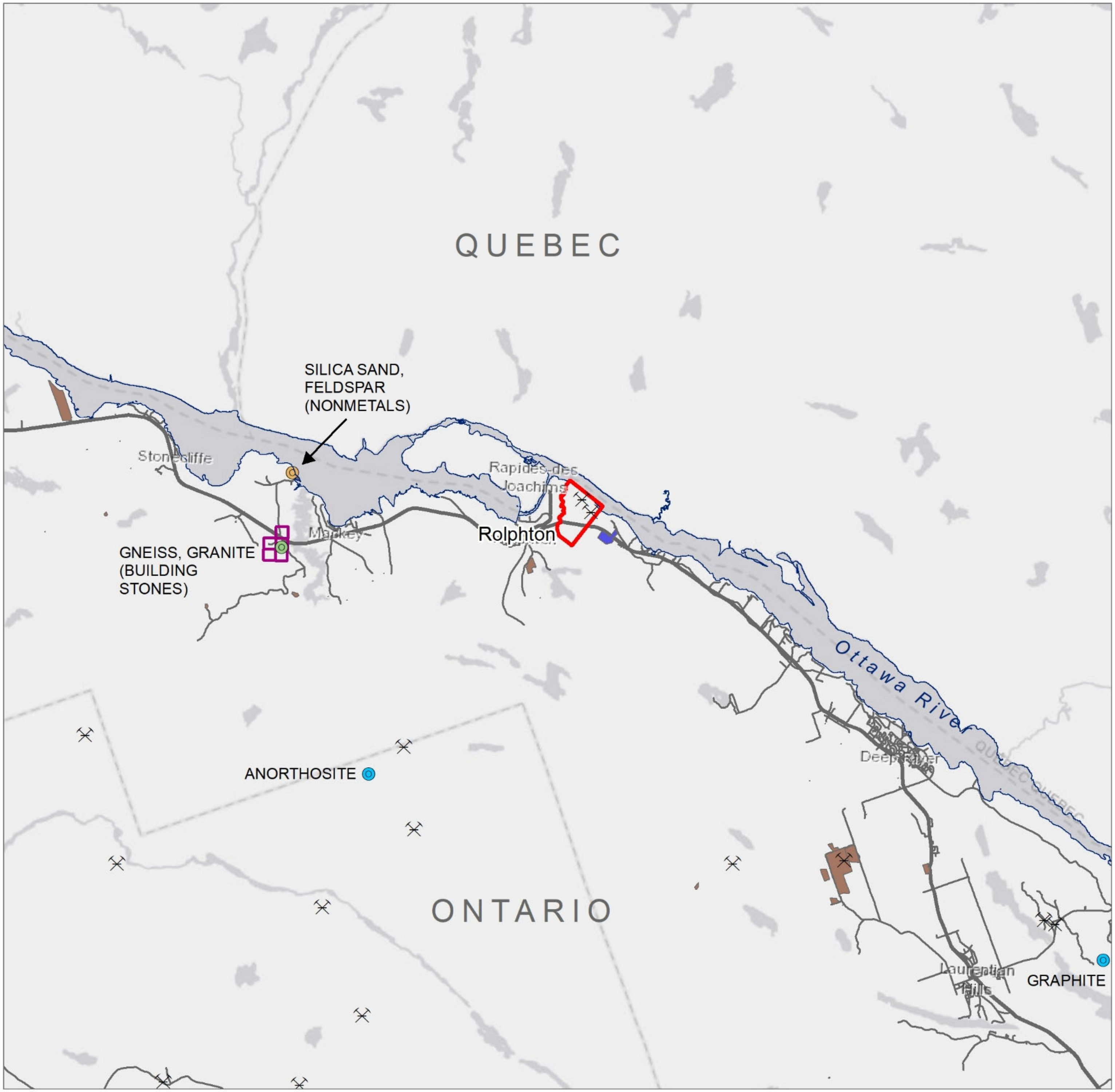
Figure 2.62 shows that several pits and/or quarries are located in the immediate vicinity with two former aggregate pits located on the NPD site. Several pits and quarries, all identified as aggregate sites, are located southeast, south and southwest of the NPDWF site.

2.6 Descriptive Geological Framework

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 framework for the NPDWF site and surrounding area. The descriptive geological framework of the NPDWF site includes the following key elements and information:

1. The NPDWF site is located on the northeast-facing slope of a former glacial and current fluvial spillway of the Ottawa River. The elevation of the ground surface drops from 164 mASL near Highway 17, to 128 mASL at the NPD buildings, to 111 mASL at the Ottawa River. In the immediate area of the NPDWF buildings and structures, the post-glacial fluvial sand and gravel deposits of the spillway are mixed with sand and gravel fill to form the surficial overburden and directly overlay bedrock. Elsewhere the fluvial sand and gravel deposits overlay silty sand to sand, gravel and cobble and boulder glacial till. The upper metre or so of glacial till unit is locally washed by fluvial wave action resulting in removal of silt and development of material similar to the overlying fluvial sand and gravel deposits.

2. Overburden thickness at the NPD site ranges from about 2 m near the Ottawa River up to about 15-18 m southwest of the NPDWF and thinning to 5 to 7 m near Highway 17. Overburden thickness adjacent to the NPDWF building averages 5 to 6 m. Overburden thickness northwest and southeast of the NPDWF is interpreted to average about 10 to 15 m based on available borehole data and OGS (2010) and Gadd (1963a) overburden mapping. The noteworthy bedrock high at MW18-06 creates an overburden thickness of about 3.0 m and limits the southeastward



LEGEND

- 2019 Rolphton NPDWF Model Boundary
- Highway
- Local Road
- Ottawa River Outline
- Active Claim
- Pit and Quarry (MNR, 2006)
- Pit (MNR, 2006)
- Pit and Quarry (OGS, 2010)
- Developed Mineral Prospect With Reserves
- Discretionary Mineral Occurrence
- Past Producing Mine Without Reserves

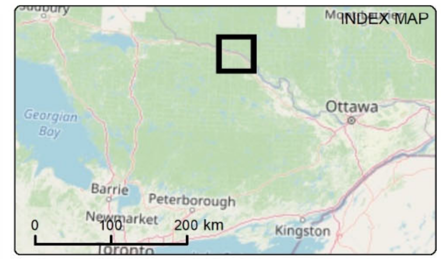


Figure 2.62
Economic Geology

SCALE 1:225,000
0 1 2 4 6 8
Kilometers
N

Coordinate System: NAD 1983 UTM Zone 18N
Source:
Basemap: LIO, MNR
Claims: Ministry of Northern Development and Mines, April 2018
Mineral Inventory: Mineral Deposit Inventory, 2014
Aggregate: LIO, Aggregate_Site_Authorized, 2013; MRD128-REV, OGS, 2010
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

PROJECT No. 16-212

Updated Geosynthesis -
Rolphton NPDWF EIS

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR
REV: 0

DATE: 2021-11-12

Geofirma Engineering Ltd

D:\Data\Project\ChalkRiver\Map\16-212-11_NPDWF_Geosynthesis\2021\16-212_Fig2_62_Economic.mxd extent of the fluvial sand and gravel unit from the area of the NPDWF. Overburden thickness northwest of the NPDWF thins to zero where bedrock is exposed in the northwest part of the NPD site. Near and southwest of Highway 17 the glacial till is the surficial overburden.

3. Bedrock at and in the local and regional area of the NPD site is Precambrian Canadian Shield. Historical regional mapping of the Precambrian bedrock places the NPD site within the lithostructural Opeongo Domain of the Algonquin (Lac Dumoine) Terrane of the Central Gneiss Belt, of the Grenville Province of the Canadian Shield. The Central Gneiss Belt consists mainly of upper amphibolite and local granulite facies, quartzofeldspathic gneisses chiefly of igneous origin (orthogneiss) with subordinate paragneisses (sedimentary origin). Local bedrock geology in the vicinity of the NPDWF site is mapped by OGS as layered biotite gneisses and migmatites of uncertain protolith with minor amphibolite mafic gneiss. Similar bedrock lithology as light and dark hornblende biotite gneiss with relative mineralogical composition of plagioclase>quartz> hornblende~biotite occurs at the adjacent Des Joachims hydroelectric power site.

   Mapping of bedrock outcrops as part of Geoscientific Characterization of the NPD Site (Geofirma Engineering Ltd, 2019) identify NPD bedrock geology as interlayered granitic to monzonitic gneiss and biotite hornblende gneiss with minor gabbroic gneiss. Core logging of shallow bedrock boreholes completed as part of the same 2019 investigations show the subsurface bedrock is principally an interlayered sequence of metre-scale bands of granitic gneiss and hornblende gneiss, with minor bands of dioritic gneiss and hornblende K-feldspar gneiss. Metre-scale to sub-metre-scale pegmatite dykes and occasional diabase dykes intrude the gneissic rock sequence. Although these bedrock descriptions appear different, they are all consistent with the best overall description of the bedrock rock type at the NPD site as migmatitic biotite gneiss. The inferred mineralogy based on available rock descriptions and 2019 petrographic work completed on both NPD outcrop and borehole core samples is plagioclase>quartz>K-feldspar>amphibolite~biotite. Based on Streckeisen ternary plot, the dominant lithologies at the NPD site vary from granite/granodiorite to quartz monzodiorite to quartz diorite to diorite/gabbro.

4. Regional and local structural geology of the NPD site is dominated by the major regional structural feature of the Mattawa Fault that defines the course of the Ottawa River and the northern limit of the regional Ottawa-Bonnechere graben system. The Ottawa-Bonnechere graben system runs from Montreal to Lake Timiskaming, displays a rift valley morphology and is about 60 km wide and 700 km long. In the area of the NPDWF, the graben trends west-northwesterly with the major, steeply southwest-dipping, Mattawa Fault defining the northeast margin of the graben. The graben probably developed as a plume-generated failed rift related to the opening of the proto-Atlantic (Iapetus) Ocean. The graben system is characterized by a network of faults and lineaments that strike east-west and northwest-southeast. This fault system developed after the peak of Grenville metamorphism (1180 to 1030 million years ago) and has been active intermittently since that time, with nodes of activity about 575, 450-420, and 190-170 million years ago.

5. Results of a lineament mapping study completed over a 20 km by 20 km area centred on the NPDWF site, show that major brittle structures as faults oriented east-southeast – west-northwest (120-140º azimuth) are located north of the site, along the Ottawa River and south of the site in line with a series of small lakes including Colton Lake, Tee Lake, Lower/Upper Pergeon Lake (from northwest

to southeast). A series of less well-defined east-southeast – west-northwest, north-south and east-west trending lineaments are located within close proximity to the site; however, there is no evidence to suggest that any of these lineaments extend to or within the NPD or NPDWF site boundaries.

6. Historical regional, local and site geoscientific information indicates the potential occurrence of the following structural features in the bedrock of the NPDWF site: east-west striking, moderate south dipping, 90 m-wide shear zone, fractures and minor shear zones associated with northwest-southeast striking, moderate (~30º) northeast dipping gneissosity and foliation, and subhorizontal sheeting joints. Contoured pre-excavation bedrock surfaces and excavation photographs do not indicate the presence of an east-west striking, moderately south-dipping, 90 m-wide shear zone as interpreted from pre-excavation diamond drilling investigations. Historical photographs also show that the bedrock at the NPD powerhouse excavations is sparsely to highly fractured (visually estimated frequencies of 5-30 fractures/m) with dominant northwest-southeast striking, moderately northeast-dipping fractures and subordinate subhorizontal sheeting fractures.

7. 2019 outcrop mapping of the NPD site and shallow bedrock drilling (BH18-05 to BH18-08) in the vicinity of the NPDWF provide important information on the geological structural characteristics of the bedrock at the NPD site. These data on fracture occurrence and orientation at the NPD site indicate primary fracturing orientation of northwest-southeast strike with both southwest and northeast dips, and secondary fracturing orientation of north-south strike and subhorizontal dip to the east. These on-site facture orientations from 2019 investigations are generally evident in the lineament study and NPD bedrock excavations.

   Borehole natural fracture frequency and RQD measurements indicate the shallow bedrock to 50 m depth below top of competent bedrock is moderately fractured and of fair to good rock quality. The 2019 geological structural data from the four shallow bedrock boreholes indicate the occasional presence of metre-scale and sub-metre scale fracture zones, some brecciated/broken zones, minor foliation shear zones and subhorizontal sheeting fractures.

   The relatively high average core recoveries (e.g., 93.0 to 98.1%) and RQDs (58.7 to 83.0%) and moderate average fracture frequencies (4.5 to 7.2 fractures/m from core logging and 362 to 486 fractures/borehole from ATV logging) for each of the four shallow bedrock boreholes is consistent with the conclusion that the structures are predominately small scale and numerous. Given this large number of small-scale structures, interpretation and presentation of such data is practically limited to summary presentations on a per borehole basis. Such presentations show that overall rock quality and fracture spacing decrease with proximity to the Ottawa River and the Mattawa Fault consistent with expectations. Development of discrete 3-D models of minor fault and fracture occurrence in the bedrock of the NPDWF site is impractical and not possible with existing data.

   The small scale, high frequency and wide range of fracture orientations detected in bedrock supports an aggregated or bulk rock mass description of bedrock structural features for use in descriptive geological, hydrogeological and geomechanical models of the NPDWF site. For groundwater flow models, this means use of an equivalent porous media (EPM) spatially-variable, isotropic representation of the rock mass K.

It is also likely that some of the logged fracture zones may be characterized as small-scale faults as evident in surface outcrop mapping. Note, these mapped faults in outcrop as mylonite layers and sub-meter scale fractures/fracture zones are minor and do not create depressions in the bedrock surface. Consequently, similar minor faults may be present at the NPDWF site without creating bedrock surface depressions commonly associated with larger-scale Grenville faults. Given the proximity of the NPDWF site to the large-scale regional Mattawa Fault that defines the course of the Ottawa River, it is not unreasonable to expect some fracturing and possibly minor faulting at the NPDWF site that relates to the Mattawa Fault. However, the 2019 shallow bedrock investigations show no evidence of a 90 m-wide, east-west striking, south-dipping shear zone or similar major structural features in the vicinity of the NPDWF.

8. Economic geological resources in the vicinity of the NPD site include mining and aggregate pits and quarries. There is one active mining claim, for gneiss and granite building stone, located 12 km west of the NPDWF site at Mackey, Ontario and a past-producing silica sand and feldspar mine located north of Mackey on the Ottawa River. There are also two discretionary mineral occurrences for anorthosite, and graphite located 13 km southwest and 28 km southeast, respectively of the NPDWF site. Several aggregate pits and/or quarries are located in the immediate vicinity with two former aggregate pits located on the NPD site.

3 HYDROGEOLOGICAL FRAMEWORK

3.1 Introduction

The regional and site hydrogeological framework for the NPDWF site is described based on historical and 2019 local investigation and site characterization work completed at and in the vicinity of the NPD site and at the CRL site, review of MECP water well records, and review of the scientific literature.

Extrapolations of hydrogeological data from the CRL site to the NPDWF site are appropriate given the similarity of overburden and bedrock geological and hydrogeological setting at both sites, and the acknowledgment that bedrock hydrogeological properties are largely independent of lithology, being mostly dependent on fracture presence and opening.

2019 hydrogeological investigations of the NPD site were completed as part of Geoscientific Characterization of the NPD Site (Geofirma Engineering Ltd., 2019). These investigations focused on hydrogeological characterization of the till overburden upgradient of the NPDWF and of the shallow bedrock to depths of 50 m below competent bedrock surface in the vicinity of the NPDWF.

3.2 Conceptualization of Groundwater Flow Systems in Canadian Shield Terrain

Raven Beck Environmental Ltd. (1994b) provides an overview of the conceptualization of groundwater flow systems in Canadian Shield terrain based on review of scientific literature and detailed work completed at the CRL property that is applicable to the area of the NPDWF site.

Groundwater flow systems in the sediments and bedrock at CRL and similar locations in the Canadian Shield can be broadly categorized into regional, intermediate and local systems in accordance with definitions originally proposed by Toth (1963, 1972). Regional groundwater flow systems in such terrain exist in deep bedrock and will be bounded by major topographic highs and lows and influenced by geological conditions. Geological conditions will strongly influence the development of regional, intermediate and local groundwater flow systems in the Canadian Shield. Major short circuiting of flow systems in Shield bedrock will occur due to presence of permeable fracture zones, faults and shear zones, and possibly due to rock permeability changes due to diabase dykes.

The Ottawa River is a regional topographic low and groundwater discharge area. Regional topographic highs exist beyond the CRL and NPD properties to the southwest and likely extend to the highlands of Algonquin Park. Regional groundwater flow will occur within the deep bedrock (>150 m deep) on the NPDWF site with direct discharge to the Ottawa River via upward flow along the geological structure associated with the Mattawa Fault below the Ottawa River.

Local groundwater flow systems, and to a lesser degree intermediate groundwater flow systems are influenced by recharge rates, topography and geology. Local groundwater flow systems are recharged on topographic highs created by bedrock ridges, flow laterally within overburden and shallow bedrock and discharge to local wetlands, bogs, streams and lakes. The vast majority of infiltration that recharges groundwater flows within permeable sandy deposits. Flow also occurs within shallow bedrock likely to depths of about 30 to 50 m; however, these flow rates are typically a small percentage of flow rates in the overlying sandy deposits. Local groundwater flow systems within the permeable sandy overburden will be the dominant groundwater system at the NPDWF site. These local groundwater flow systems will likely be recharged near Highway 17 and will discharge along the ground slope extending northeast to the Ottawa River and directly to the Ottawa River.

Intermediate groundwater flow systems will exist between the regional and local groundwater flow systems described above. Intermediate groundwater flow systems will likely exist at the NPDWF site between topographic highs located southwest of Highway 17 near Tee Lake with discharge to the Mattawa Fault and the Ottawa River. These intermediate flow systems will likely extend to depths of about 50 to 150 m based on available groundwater chemistry data and the elevation changes between bedrock near Tee Lake and the Ottawa River (~ 100 m).

3.3 Hydrogeological Investigations of NPD Site

3.3.1 Historical Investigations

Forty-five wells were historically drilled at the NPD site for various site investigations. NPD-1 through NPD-14 were drilled as part of AECL hydrogeologic investigations of Landfills 1 and 2 (Killey and Munch, 1988; 1989). Wells MT-1 through MT-10 were drilled by MacLarentech Inc. (1990) for site characterization purposes. BH 06-01 through BH-16-01 were drilled by J.D Paterson and Associates (2002) (BH-14-01 through BH-16-01 are dry), and BH16-01 through BH16-04 were drilled by Golder Associates Ltd. (2017b) for hydraulic conductivity (K) testing.

Table 3.1 (from Calder, 2018) summarizes the results of all historical on-site hydraulic testing of overburden and bedrock units at the NPD site. Hydraulic conductivities were measured by Killey and Munch (1988) and Golder Associates Ltd. (2017a, 2017b).

Table 3.1 Summary of Historical Measurements of Hydraulic Conductivities at NPD Site

Hydrogeologic Unit Tested	*Borehole ID*	*Hydraulic Conductivity (m/s)*
Killey and Munch (1988)		
Sand and Gravel	NPD-1	7.0E-06
Coarse Sand	NPD-4	4.0E-05 (minimum)
Silty Sand and Gravel	NPD-7	6.0E-07 (order of magnitude estimate)
Glacial Till	NPD-5	8.2E-08
Golder Associates Ltd. (2017a, 2017b) Winter 2017		
Sand	MT-5	7.0E-04
Sand / Shallow Bedrock	BH12-01	1.0E-03
Sand	BH16-01	5.0E-04
Shallow Bedrock	BH16-02A	3.0E-08
Shallow Bedrock	BH16-02B	3.0E-09
Golder Associates Ltd. (2017a, 2017b) Spring 2017		
Fill	BH16-03	1.0E-06
Glacial Till / Shallow Bedrock	MT-8	2.0E-05
Sand	MT-5	2.0E-04
Sand / Shallow Bedrock	BH7-01	1.0E-04

Hydrogeologic Unit Tested	***Borehole ID***	***Hydraulic Conductivity (m/s)***
Sand / Shallow Bedrock	BH9-01	3.0E-07
Sand / Shallow Bedrock	BH11-01	3.0E-05
Sand / Shallow Bedrock	BH12-01	2.0E-04
Sand / Shallow Bedrock	BH13-01	1.0E-05
Sand	BH16-01	5.0E-05
Shallow Bedrock	BH16-02B	1.0E-09

Figures 3.1 and 3.2 show the depth of historical measured hydraulic conductivities and the plan spatial variability of hydraulic conductivity of the sand overburden unit at the NPD site.

All measurements that span both sand and shallow bedrock are assumed to be reflective of the higher sand conductivity, and the hydraulic conductivity values for these boreholes as given in Table 3.1 were corrected to represent only the sand. Hydraulic conductivity measured in the fill is low and represents a small interval at the bottom of the borehole (BH16-03). The glacial till measurement by Golder Associates Ltd. (2017a, 2017b) is at MT-8, where the borehole overburden description is bouldery sandy till described as native till used as fill (MacLarentech Inc., 1990). There is considerable heterogeneity in the fluvial sand and gravels with no particular spatial pattern apparent (Calder, 2018) as evident in Figure 3.2.

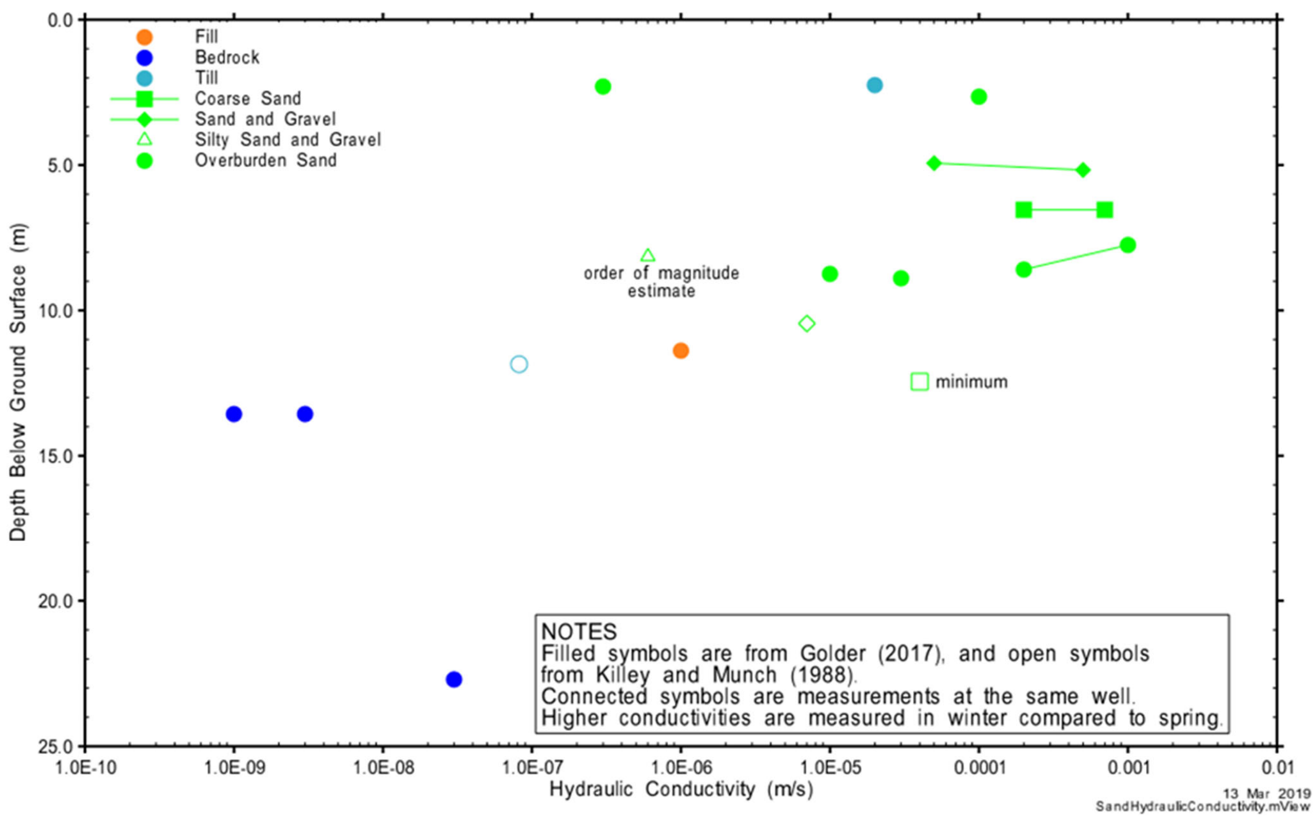


Figure 3.1 Depth of Historical Measurements of Hydraulic Conductivities at NPD Site

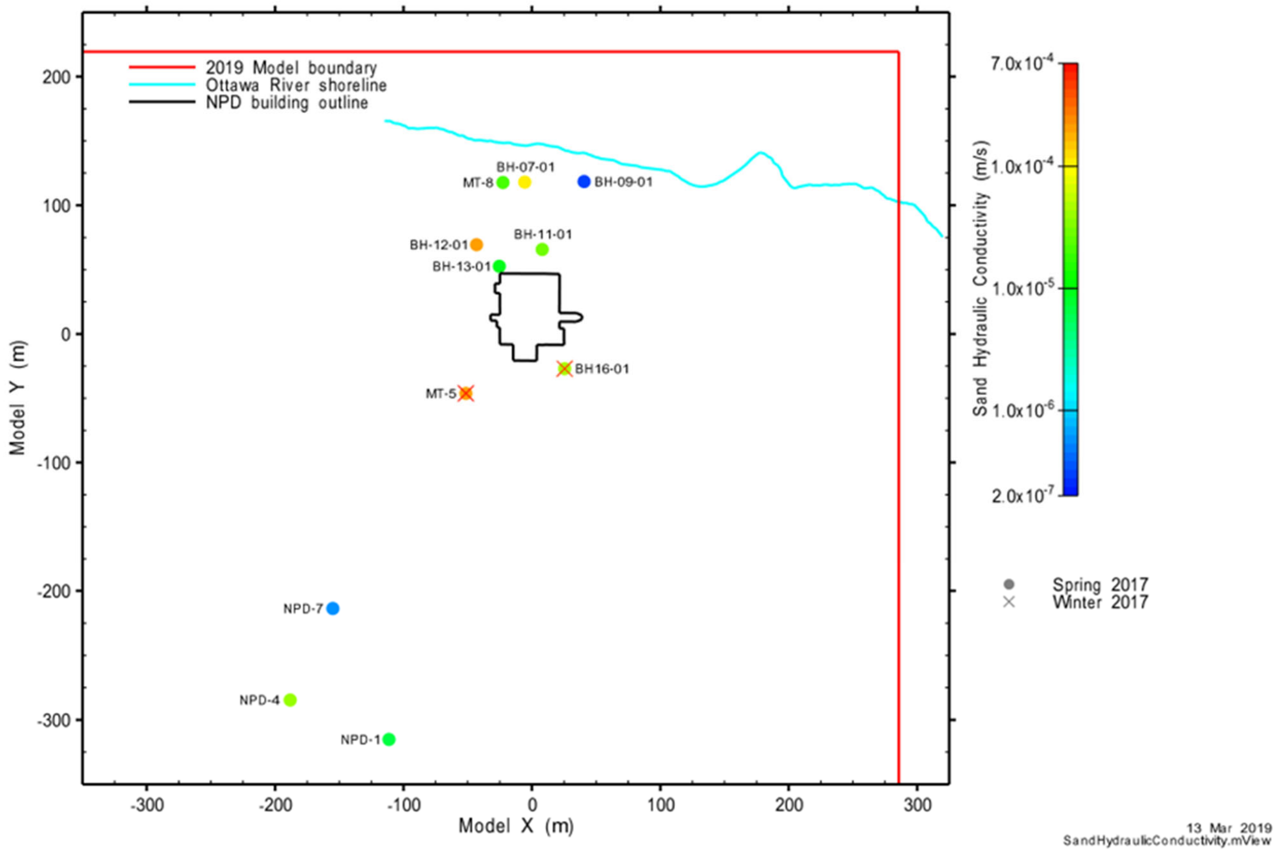


Figure 3.2 Plan Spatial Distribution of Sand Hydraulic Conductivity at the NPD Site

3.3.2 2019 Investigations

Methodology and results of 2019 hydraulic conductivity measurements of the basal till and shallow bedrock at the NPD site are described by Geofirma Engineering Ltd. (2019). Hydraulic conductivities were measured in the basal till at monitoring wells MW18-01 to MW18-04, MW18-09 and MW18-10 using slug tests. Continuous profiles of hydraulic conductivity in shallow bedrock were measured at BH18-05 to BH18-08 using straddle-packer, constant-pressure injection tests. Straddle-packer tests were configured with real-time downhole pressure measurement within the test interval and flowrate measurement at ground surface. Figure 2.4 shows the locations of the tested boreholes and monitoring wells. Figures 2.5 and 2.6 show the depth of the overburden monitoring well screens.

All hydraulic tests were analyzed for hydraulic properties using nSights (n-dimensional Statistical Inverse Graphical Hydraulic Test Simulator) software. nSights is state of the art hydraulic test analysis software originally developed by Geofirma staff for Sandia National Laboratory as part of the Waste Isolation Pilot Plant to analyze well-tests in complex formations subject to non-ideal test conditions.

Table 3.2 summarizes the results of the 2019 hydraulic testing of the basal till overburden. Table 3.2 lists the monitoring well, depth of monitoring well interval tested, the stratigraphy of the tested interval and the hydraulic conductivity of the interval. Table 3.2 shows two groupings of hydraulic conductivity: 6.6E-09 to 7.6E-08 m/s for silt to cobble till, and 1.1E-05 to 2.5E-05 for boulder till.

Table 3.2 Summary of 2019 Hydraulic Conductivities in Basal Till

Monitoring Well	*Depth of Sandpack Interval (mBGS)*	*Stratigraphy of Interval*	*Hydraulic Conductivity (m/s)*
MW18-01	5.49 - 9.14	Silt to Cobble Till	7.6E-8
MW18-02	9.41 – 12.8	Silt to Cobble Till	3.2E-8
MW18-03	8.63 – 12.34	Silt to Cobble Till and Boulder Till	6.6E-9
MW18-04	8.93 – 12.56	Silt to Cobble Till	3.2E-8
MW18-09	15.24 – 20.42	Boulder Till	1.1E-5
MW18-10	11.89 – 15.54	Boulder Till	2.5E-5

Table 3.3 summarizes the hydraulic properties of hydraulic conductivity (K), specific storage and hydraulic head determined from individual 2019 straddle-packer testing of the shallow bedrock near the NPDWF. Figure 3.3 shows the comparative profiles of hydraulic conductivity of the shallow bedrock plotted against test interval elevation on a log scale. Table 3.4 summarizes interpreted statistics of hydraulic conductivities measured in each borehole.

Table 3.3 and Figure 3.3 show the interpreted hydraulic conductivities of the shallow bedrock based on 5.16 m test interval lengths range from 2.8E-09 to 6.6E-06 m/s. Table 3.3 shows the interpreted specific storages from the straddle-packer tests range from 6.8E-10 to 2.0E-05 m^{-1} with most values at 1.0E-08 to 1.0E-07 m^{-1}. The hydraulic conductivity-weighted mean specific storage values for individual boreholes range from 2.9E-07 to 5.4E-06 m^{-1}, with an overall average value of 1.2E-06 m^{-1}. Interpreted hydraulic heads from the straddle-packer tests are strongly influenced by the open borehole water level elevations measured in each borehole during hydraulic testing. However, notwithstanding this bias, the interpreted hydraulic heads from the straddle-packer testing show both upward and downward hydraulic heads in each borehole. The upward hydraulic heads in BH18-06 are the most noteworthy.

Inspection of Figure 3.3 hydraulic conductivity profiles and borehole core logs and ATV logs given in Appendices D and E of the Geoscientific Characterization of the NPD Site Report (Geofirma Engineering Ltd., 2019) shows that the majority of intervals with elevated hydraulic conductivity (~> 1.0E-06 m/s) correlate with specific horizontal and vertical open fractures and metre- and sub-metre scale fracture zones. Based on this observed correlation, Table 3.4 presents calculations of geometric mean K values for each bedrock borehole with and without elevated K intervals.

Table 3.4 shows that the geometric mean K of shallow bedrock both with and without permeable fractures and fracture zones increases with proximity to the Ottawa River. Hydraulic conductivity correlations with depth in individual boreholes are not apparent. With permeable fracture zones the geometric mean K ranges from 3.9E-08 m/s at BH18-05 to 1.1E-06 m/s at BH18-08. Without permeable fracture zones the geometric mean K ranges from 8.1E-09 m/s at BH18-05 to 3.5E-07 m/s at BH18-09. The geometric mean of the 12 permeable fracture zones considered in Table 3.4 was 2.2E-06 m/s. The overall geometric mean K of shallow bedrock from 2019 testing is 1.7E-07 m/s with permeable fracture zones and 5.1E-08 m/s without permeable fracture zones.

Table 3.3 Summary of Hydraulic Conductivity, Specific Storage and Hydraulic Head Data from 2019 Straddle-Packer Testing

Borehole	Test Zone Top (mBTOC)	Test Zone Bottom (mBTOC)	Hydraulic Conductivity (m/s)	Specific Storage (m^{-1})	Hydraulic Head (mASL)
BH18-05	24.00	29.16	6.0E-07	2.0E-05	125.69
	29.16	34.32	1.3E-06	1.2E-10	125.77
	33.12	38.28	2.2E-08	7.0E-07	125.43
	38.28	43.44	4.6E-09	1.8E-08	124.86
	43.44	48.60	9.7E-09	3.2E-06	124.04
	48.60	53.76	1.0E-06	1.1E-07	125.95
	53.76	58.92	2.8E-09	1.2E-07	125.35
	58.92	64.08	8.5E-09	7.3E-06	124.06
	62.88	68.04	1.2E-08	6.3E-06	124.45
BH18-06	9.01	14.17	2.3E-08	1.3E-05	128.69
	14.17	19.33	4.7E-08	1.6E-07	122.92
	19.83	24.99	1.5E-07	1.2E-08	123.19
	25.69	30.85	2.5E-08	1.7E-08	123.32
	31.35	36.51	2.2E-08	1.0E-08	123.01
	36.81	41.97	4.4E-08	1.5E-08	123.01
	40.77	45.93	3.6E-06	4.8E-07	126.12
	44.73	49.89	3.1E-06	6.8E-10	124.45
	48.59	53.75	8.3E-08	5.8E-09	124.36
BH18-07	6.00	10.04	2.3E-06	8.5E-06	111.13
	10.54	15.70	4.5E-08	6.5E-09	116.32
	16.00	21.16	2.5E-07	1.8E-06	111.91
	21.66	26.82	2.1E-07	4.2E-09	112.16
	27.32	32.48	2.8E-08	4.6E-09	112.12
	33.58	38.74	1.1E-08	4.9E-07	115.71
	39.24	44.40	1.2E-07	1.8E-05	111.86
	44.90	50.06	2.7E-08	1.5E-07	111.60
	50.56	55.72	1.2E-06	3.8E-07	111.87
BH18-08	5.75	10.11	2.0E-06	4.1E-07	110.93
	10.61	15.77	5.3E-06	6.9E-07	109.92
	14.37	19.53	4.8E-06	5.7E-07	115.33
	19.83	24.99	2.8E-07	2.6E-08	111.98
	24.69	29.85	6.0E-07	4.5E-08	112.38
	29.85	35.01	2.6E-07	4.7E-09	112.28
	35.01	40.17	6.6E-06	1.5E-08	112.13
	40.17	45.33	2.3E-07	8.5E-09	112.08
	45.33	50.49	5.5E-07	9.6E-10	112.34
	49.79	54.95	1.6E-06	1.6E-08	112.07

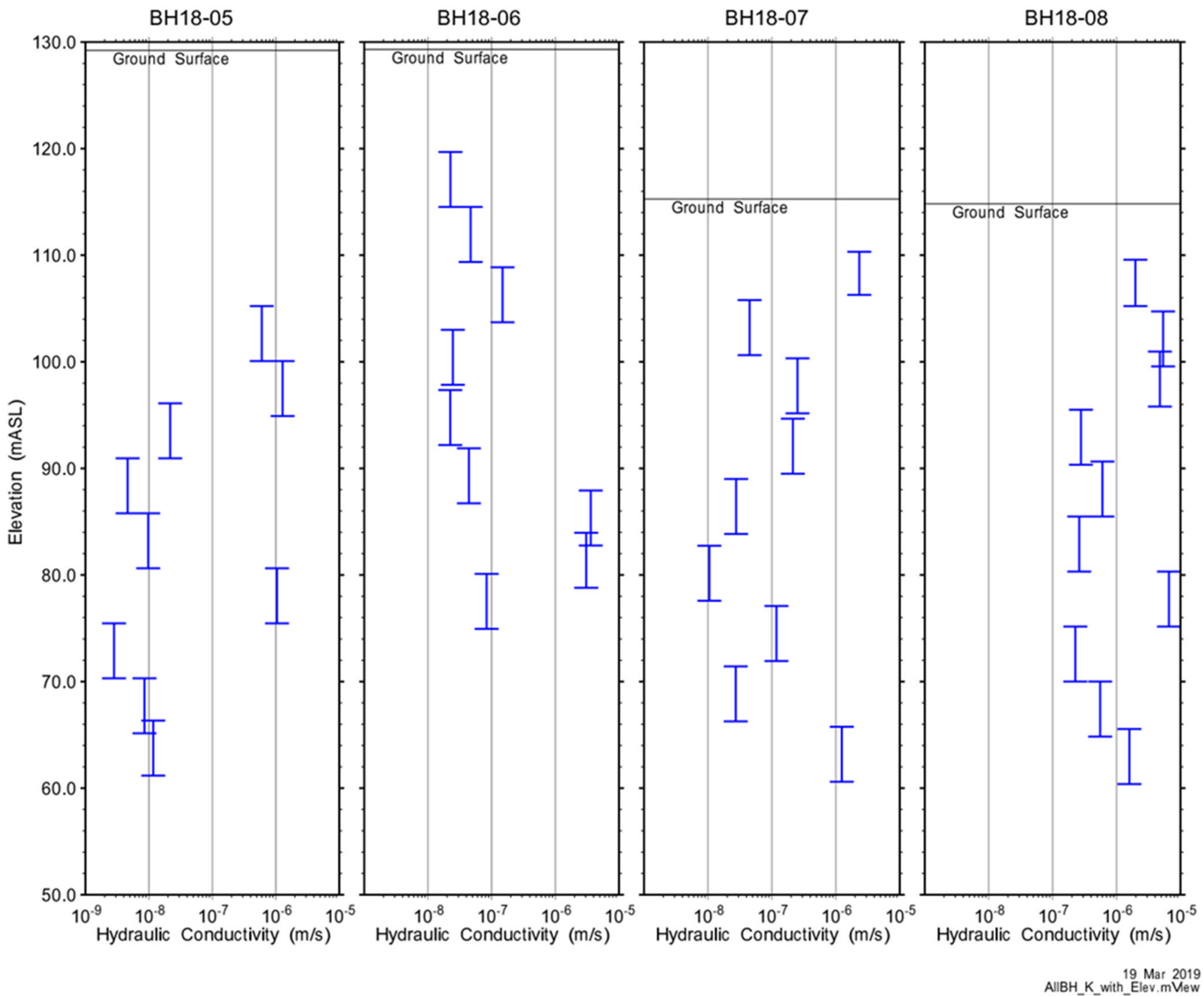


Figure 3.3 Elevation Profiles of Hydraulic Conductivity in Shallow Bedrock from 2019 Straddle-Packer Testing

Table 3.4 Summary of Interpreted Statistics of Hydraulic Conductivity in Shallow Bedrock

Borehole	***Geometric Mean of Borehole***	***No. of Permeable Zones (Depth in BH)***	***Geometric Mean of Borehole Minus Permeable Zones***
BH18-05	3.9E-08	3 (Shallow, Middle)	8.1E-09
BH18-06	1.4E-07	2 (Deep)	4.3E-08
BH18-07	1.2E-07	2 (Shallow, Deep)	5.7E-08
BH18-08	1.1E-06	5 (Shallow, Middle, Deep)	3.5E-07
Overall	1.7E-07	12 (Shallow to Deep)	5.1E-08

3.4 Hydrostratigraphic Units

The available geological and hydrogeological data for the NPD site supplemented by similar regional information from the CRL property and surrounding area, indicate that the hydrogeology of the NPDWF site is conveniently described with reference to five hydrostratigraphic units. A hydrostratigraphic unit is a geological unit that possesses similar hydrogeological properties over a suitably large scale to useful in hydrogeological interpretation including modeling.

The five hydrostratigraphic units at the NPDWF site are:

- Sand and gravel fill unit,
- Fluvial sand and gravel unit,
- Silt to cobble glacial till unit,
- Boulder glacial till unit, and
- Shallow bedrock unit.

The occurrence, thickness, hydraulic conductivity, porosity and specific storage of these hydrostratigraphic units are described in the following sections. The distribution of these five hydrostratigraphic units at the NPD site is shown on cross sections A-A' and B-B' in Figures 2.5 and 2.6.

3.4.1 Sand and Gravel Fill Unit

Sand and gravel fill unit including reworked fluvial deposits is the youngest hydrostratigraphic unit. It is present near the NPD buildings and in the area northeast of the buildings that were subject to excavation for construction of water intake and discharge lines and tile drainage lines between the buildings and the Ottawa River. The fill above the bedrock used at the NPD was described by MacLarentech Inc. (1990) as bouldery sand, similar to the sand overburden found at the site, but with a more consistent size of gravel and boulders and the presence of debris such as excavated rock and construction rubble. Fill thickness at the NPD site is variable ranging from about 2 m near the Ottawa River to about 5-6 m adjacent to the NPDWF building.

A single measurement of the hydraulic conductivity of the fill of 1.0E-06 m/s is low compared to the values of sand and till (see Table 3.1). The measurement is for a small interval at the bottom of the borehole and is expected to represent the lower end of the range of potential values. Based on 2018 base case groundwater model calibration, the best estimate for hydraulic conductivity of the sand and gravel fill hydrostratigraphic unit was 1.3E-04 m/s increased from an initial estimate of 5.0E-06 m/s (Calder, 2018). Lacking other information, the sand and gravel fill is assumed to be isotropic with porosity of 0.3 and specific storage of 1.0E-05 m^{-1}.

3.4.2 Fluvial Sand and Gravel Unit

The fluvial sand and gravel unit is the most widespread permeable overburden unit at the NPD site and is the youngest hydrostratigraphic unit consisting of native material. It represents the older alluvial deposits of OGS (2010) as well as the fluvial gravel unit of Gadd (1963a). MacLarentech Inc. (1990)

describes the overburden near the NPD facility to be predominantly sand, divided into four classifications of sand with various amounts of gravel, boulders and trace amounts of silt. The thickness of this hydrostratigraphic unit averages 5 m to 10 m at the NPD site. As noted in Section 2.3.2 and as shown on Figures 2.5 and 2.6, the fluvial sand and gravel unit extends southwest from NPDWF toward Highway 17 (to about BH18-02), northwest to at least Landfill 2 (NPD-14) but is limited to the southeast of NPDWF by the bedrock high at BH18-06.

Based on hydraulic conductivity measurements (Table 3.1), the fluvial sand and gravel unit is heterogeneous, with a wide range of conductivity and no particular spatial pattern (Figure 3.2). The fluvial sand and gravel is represented by a single homogenous hydrostratigraphic unit. Based on a cumulative distribution function of the fluvial sand and gravel hydraulic conductivity (Figure 3.4), the horizontal hydraulic conductivity of the fluvial sand and gravel is expected to be near 4.0E-04 m/s, with a range of 2.0E-07 to 1.0E-03 m/s. These hydraulic conductivities are greater than those reported for the CRL property (2.0E-05 to 2.0E-04 m/s - Raven Beck Environmental Ltd., 1994b), reflecting the increased grain size at the NPDWF site due to fluvial erosion. The fluvial sand and gravel unit is also assumed to be anisotropic. Similar deposits at CRL have an anisotropic ratio (horizontal/vertical) between 2 to 10 depending on the degree of silt lamination (Raven Beck Environmental Ltd., 1994b). Fluvial sand and gravel porosity is assumed the same as CRL at 0.4. This is consistent with previous estimates by Killey and Munch (1988) of sand and gravel porosity of between 0.3 and 0.4. Specific storage for fluvial sand and gravel is assumed as 1.0E-05 m^{-1}.

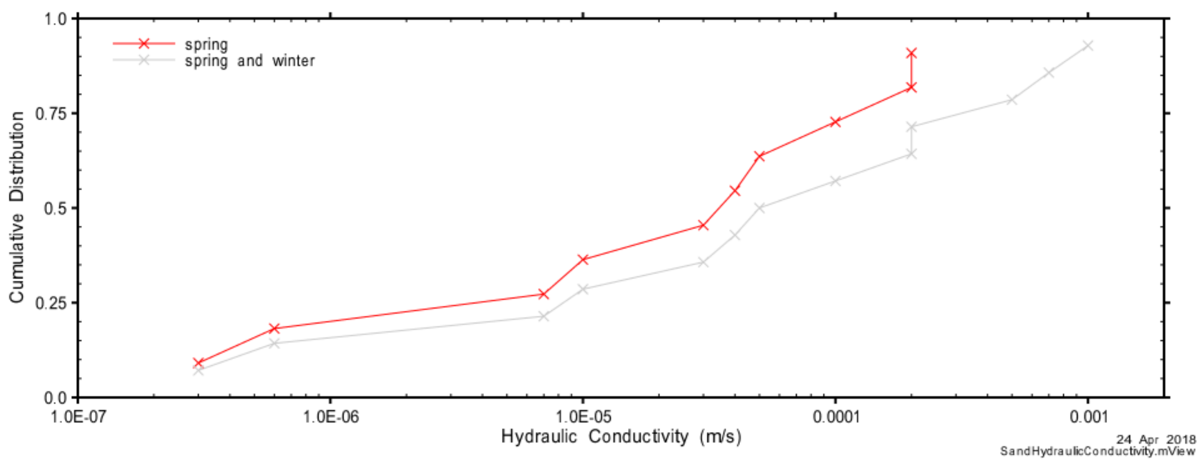


Figure 3.4 Cumulative Distribution of Measured Hydraulic Conductivity of Fluvial Sand and Gravel Unit

Based on 2018 base case groundwater model calibration, the best estimate for hydraulic conductivity of the fluvial sand and gravel hydrostratigraphic unit was 3.5E-04 m/s with an anisotropy ratio of 10 (Calder, 2018).

3.4.3 Silt to Cobble Glacial Till Unit

The silt to cobble glacial till hydrostratigraphic unit is the most widespread overburden hydrostratigraphic unit at the NPD site. It represents the shield-derived silt to cobble till of OGS (2010) and the silty sandy glacial till unit of Gadd (1963a). It is found at ground surface near Highway 17 and at depth below the fluvial sand and gravel hydrostratigraphic unit northeast of Highway 17 on the NPD site. The upper metre or so of the silt to cobble glacial till unit has been locally subject to fluvial erosion by wave action resulting in a texture and likely hydraulic conductivity similar to the overlying fluvial sand and gravel unit.

Based on 2019 investigations (see Figures 2.5 and 2.6), the thickness of the silt to cobble glacial till unit ranges from 0 to 2 m near the NPDWF up to 5 to 10 m northwest and southeast of the NPDWF. Based on 2019 investigations, nearby bedrock exposures and earlier pre-construction drilling (Hydro-Electric Power Commission of Ontario, 1956), the silt to cobble glacial till unit is about 5 m thick southwest of the NPDWF below the fluvial sand and gravel unit and up to about 10 m thick near Highway 17.

Only two hydraulic conductivity measurements were historically available for silt to cobble glacial till at the NPD site (Table 3.1) – 8.0E-08 m/s at NPD-5, representing till underlying fluvial sand and gravel, and $2x10^{-5}$ m/s at MT-8, representing till used as fill. Glacial till at the CRL property ranges between 2.0E-05 and 6.0E-07 m/s (Scheier and Killey, 2009), with an average of 3.0E-07 m/s (Raven Beck Environmental Ltd., 1994b).

2019 hydraulic testing of silt to cobble glacial till (see Table 3.2) indicates a K range of 6.6E-09 to 7.6E-08 m/s upslope from the NPDWF at MW18-01 to MW18-04, much lower than historical values measured closer to NPDWF. Additionally, during rotary drilling of BH18-09 an approximate metre-wide zone of major water loss was encountered at a depth of 15.2 mBGS within the silt to cobble till unit. Based on the steady state rate of water loss during drilling (51 L/min, Geofirma Engineering Ltd., 2019) and approximate applied head as about 50% of the depth to water table (i.e., ~5.0 m, Geofirma Engineering Ltd., 2019), the estimated K for this permeable 1 m thick horizon in the silt to cobble glacial till is about 2.0E-04 m/s. This high K horizon in the silt to cobble till is at an elevation of 119.7 to 120.7 mASL and is likely a glacial-fluvial washed beach deposit.

These historical and 2019 K data suggest two sets of K values are necessary to represent silt to cobble glacial till. Testing completed at NPD-5 and MW18-01 to MW18-04 indicate geometric mean K of 3.3E-08 m/s that is considered representative of silty sand member southwest of MW18-03 and MW18-04. A K value range of 2.0E-05 to 2.0E-04 m/s is used as the best estimates of hydraulic conductivity for the sand to cobble till member in the vicinity of the NPDWF. Both of these K estimates are assumed to be isotropic.

Porosity of the glacial till at the CRL property has been estimated at 0.3 (Raven Beck Environmental Ltd., 1994b) and is assumed to be representative of silt to cobble glacial till at the NPD site. Specific storage of 1.0E-05 m^{-1} was assumed for silt to cobble glacial till at the NPDWF site, the same as values assumed for all overburden materials.

3.4.4 Boulder Glacial Till Unit

The boulder glacial till unit is the oldest overburden unit at the NPD site and locally directly overlies competent bedrock in areas of bedrock depression. It consists of metre-size boulders with granular matrix material and underlies silt to cobble glacial till and fluvial sand and gravel where the silt to cobble till is absent (see geological cross sections in Figures 2.5 and 2.6). It is found northwest and southwest of the NPDWF based on intersections with BH18-03, BH18-05, BH18-09 and BH18-10 with thicknesses of 2 to 5 m. It is likely equivalent to the "boulder pavement" of Killey and Munch (1988) with noted composition of 2 m size boulders.

Hydraulic testing of the boulder glacial till is limited to 2019 testing of MW18-09 and MW18-10 located southwest of the NPDWF. Based on Table 3.2, these slug tests yield hydraulic conductivities of 1.1E-05 m/s (MW18-09) and 2.5E-05 m/s (MW18-10) indicating a geometric mean K for the boulder glacial till unit of 1.7E-05 m/s. Additionally, during rotary drilling of BH18-10 an approximate 0.6 m wide zone of major water loss was encountered at a depth of 14.9 to 15.5 mBGS within the bottom of the boulder till unit. Based on the steady state rate of water loss during drilling (60 L/min, Geofirma Engineering Ltd., 2019) and approximate applied head as about 50% of the depth to water table (i.e., ~2.70 m, Geofirma Engineering Ltd., 2019), the estimated K for this permeable 0.6 m thick horizon in the boulder glacial till is about 1.7E-03 m/s. This high K horizon in the boulder till is at an elevation of 114.1 to 115.1 mASL and is likely a basal gravel layer found on top of bedrock.

These 2019 K data suggest a K value of 1.7E-05 m/s be used as the best estimate of hydraulic conductivity for the boulder till, recognizing the potential for inclusion of sub-metre thick higher K gravel and cobble layers with K up to 1.7E-03 m/s. The boulder till is assumed to be isotropic with respect to K.

Porosity of the glacial till at the CRL property has been estimated at 0.3 (Raven Beck Environmental Ltd., 1994b) and is assumed to be representative of boulder glacial till at the NPD site. Specific storage of 1.0E-05 m^{-1} was assumed for boulder glacial till at the NPDWF site, the same as values assumed for all overburden materials.

3.4.5 Shallow Bedrock Unit

The shallow bedrock hydrostratigraphic unit at bedrock depths of 0 to 50 m below competent bedrock surface is the only bedrock unit considered for the NPDWF site based on the relatively shallow excavations completed for construction of the NPD (about 18 m into rock) and the assumption that essentially all of the local groundwater flow in bedrock will occur in the upper 50 m of bedrock. Deeper groundwater flows in intermediate and regional flow systems are likely present at the NPD and NPDWF sites, but these flows are likely to be much smaller, are unlikely to interact with the NPDWF and will likely directly discharge to the Ottawa River via the Mattawa Fault.

Historical data on the hydraulic properties of shallow bedrock at the NPDWF site were limited and largely inferred from detailed measurements made at the CRL property (Arcadis Canada Inc. 2018a). Two field measurements of bedrock hydraulic conductivity were obtained near the south corner of the NPDWF building at Golder Associates Ltd. (2017a) boreholes BH16-02A and BH16-02B. Shallow measurements (12-15 m depth) of 1.0E-09 and 3.0E-09 m/s and a deeper measurement (21-24 m depth) of 3.0E-08 m/s were obtained.

Straddle-packer hydraulic testing of bedrock to depths of about 50 m below competent bedrock surface significantly improved the database and understanding of the hydraulic properties of the shallow bedrock at the NPD site. Based on the 37 tests completed in the four shallow bedrock boreholes BH18-05 to BH18-08, the overall geometric mean horizontal K is 1.7E-07 m/s based on a range of measurements of 2.8E-09 to 6.6E-06 m/s. As the hydraulic conductivity of intact bedrock is several orders of magnitude lower than the lowest K value measured from straddle-packer testing, all of the reported K values from testing of BH18-05 to BH18-08 are attributed to the presence of fractures, either as individual discontinuities or as part of small fracture zones. As noted in Section 3.3.2, the majority of intervals with elevated hydraulic conductivity (i.e., >~ 1.0E-06 m/s) correlate with specific subhorizontal and subvertical open fractures and metre- and sub-metre-scale fracture zones. The highest K interval (K=6.6E-06 m/s) occurs at depths of 35.0 to 40.2 mBGS in BH18-08 and is associated with the subvertical open sheared contact of a pegmatite dyke (see Figure 2.46), a small rubble zone and subhorizontal fracturing. The overall geometric mean K of shallow bedrock from 2019 testing is 5.1E-08 m/s without permeable fracture/rubble zones.

Review of borehole RQD, fracture frequency and K data presented in Sections 2.4.6.5 and 3.3.2 shows that there is an increase in shallow bedrock K and fracture frequency and a decrease in RQD with proximity to the Ottawa River. This spatial trend most likely reflects attendant fracturing related to the regional Mattawa Fault that defines the course of the Ottawa River. Geometric mean K for boreholes BH18-05 and BH18-06 located southwest of the NPDWF is 7.3E-08 m/s. Geometric mean K for boreholes BH18-07 and BH18-08 drilled adjacent to the Ottawa River is higher at 3.6E-07 m/s.

Review of the measured fracture frequency data (see Figures 2.27 to 2.29 and Table 2.2) and fracture orientation data in shallow bedrock (see Figures 2.33 to 2.37) indicate moderately fractured bedrock with a variety of fracture orientations from subhorizontal to subvertical that characterize the shallow bedrock. These fracture frequency and orientation data suggest that the hydraulic conductivity of the shallow bedrock rock mass is most likely isotropic.

Analysis of the straddle-packer injection tests also allowed quantification of specific storage parameters for the shallow bedrock. Based on Table 3.3, specific storage values for shallow bedrock range from 6.8E-10 to 2.0E-05 m^{-1} with most values between 1.0E-08 and 1.0E-06 m^{-1}. The hydraulic conductivity-weighted mean specific storage values for individual boreholes range from 2.9E-07 to 5.4E-06 m^{-1}, with an overall average value of 1.2E-06 m^{-1} for the shallow bedrock unit.

Given the similar lithological and structural geological settings at the NPDWF and CRL sites it is useful to interpret the bedrock hydraulic conductivity data for the NPDWF site with the extensive bedrock hydraulic conductivity dataset available for the CRL site for similar depth ranges. Raven Beck Environment Ltd., (1994b) provides a summary of the hydraulic properties of the shallow bedrock without major faults or shear zones to depths of 50 m based on 371 straddle-packer hydraulic testing results in 37 bedrock boreholes. Based on these testing programs, hydraulic conductivity at CRL in the depth range of 0 to 50 m covers an extraordinarily wide range of 3.0E-12 to 4.0E04 m/s, with an overall geometric mean of 6.0E-08 m/s, and a porosity of 0.005. Most of the shallow bedrock measurements (i.e., 340, with geometric mean of 2.0E-09 m/s) are from Raven (1986) as shown in Figure 3.5 for a rock mass without obvious major structural features such as faults and shear zones. The higher rock mass hydraulic conductivities shown in Figure 3.5 are from a subhorizontal sheeting joint or small fracture zone detected as depths of 33 to 50 m over distance of greater than 200 m at the CRL site.

The best initial estimates of hydraulic conductivity in shallow bedrock at the NPD site are 7.3E-08 m/s near BH18-05, BH18-06 and the NPDWF, and 3.6E-07 m/s near BH18-07, BH18-08 and below the Ottawa River. These values, which are based on 2019 straddle-packer testing, are comparable to but greater than best initial estimates recommended in the initial 2018 Geosynthesis Report (Arcadis

Canada Inc., 2018a) for bedrock lacking faults, shear zones and large sheeting joints at 1.0E-08 m/s. Allowing for the presence of permeable subhorizontal sheeting joints and sub-vertical fracturing near the Ottawa River, the recommended best initial estimates of shallow bedrock K are consistent with 2018 recommendations.

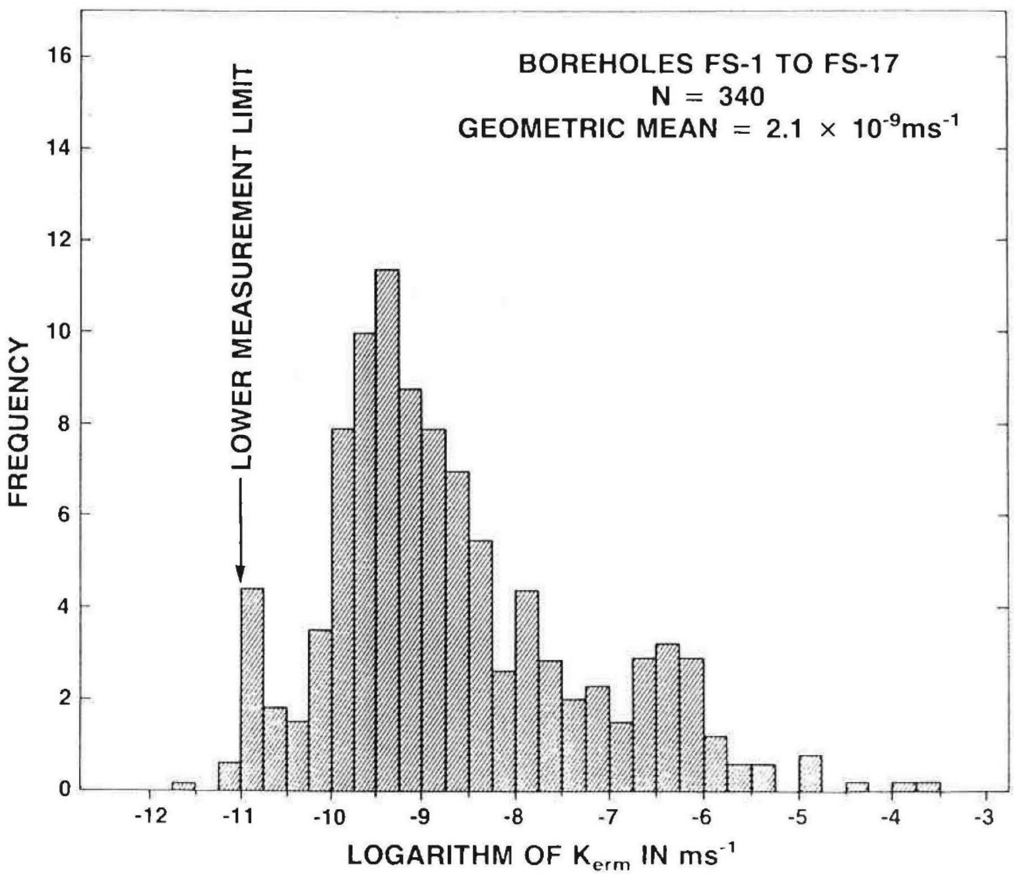


Figure 3.5 Distribution of Common Logarithm of Rock Mass Hydraulic Conductivity in Upper 50 m at CRL (from Raven, 1986)

A specific storage value of 1.2E-06 m^{-1} is recommended for shallow bedrock at the NPD site based on 2019 hydraulic testing. Best estimate of shallow bedrock porosity, which is entirely due to fractures, is 0.005 based on Raven Beck Environmental Ltd. (1994b).

In summary, ubiquitous minor structural features that are not mappable between bedrock boreholes create horizontal hydraulic conductivity in the bedrock that varies over the relatively small range of 3.0E-09 to 6.6E-06 m/s with K and fracturing increasing with proximity to the Ottawa River. The 2019 final groundwater model calibration which is based on average bedrock structural and hydraulic properties uses bedrock K estimates that are essentially the same as the best estimates from straddle-packer testing completed as part of 2018 site characterization work. This is an important direct use of structural and hydraulic conductivity data in site model development.

3.5 Hydrogeochemistry and Groundwater Quality

3.5.1 Overburden

3.5.1.1 Historical Sampling and Testing

Killey (2014), Golder Associates Ltd. (2017b) and McVeigh (2018) provide a detailed summary of historical groundwater quality for the shallow (typically <12 mBGS) overburden at the NPD site, including groundwater quality in the vicinity of Landfill 1, Landfill 2 and the reactor buildings or NPD Station (see Figure 3.6).

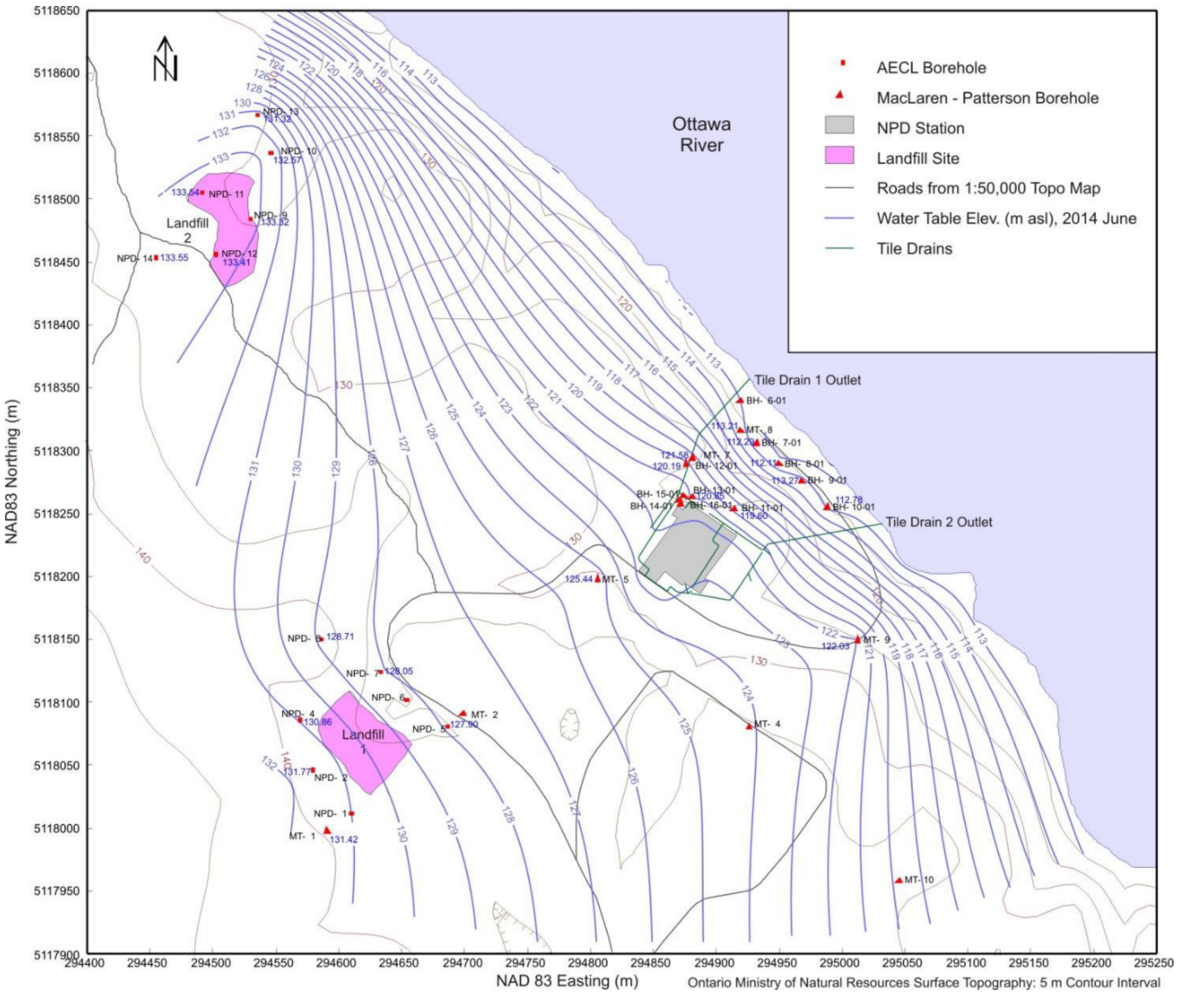


Figure 3.6 Historical Groundwater Monitoring Locations and Water Table Elevations at the NPDWF Site

Killey (2014) reports on field geochemical measurements, major ion and trace element chemistry, radiological parameters (tritium, total beta and gross alpha) and conventional contaminants (PHCs, VOCs, PAHs and base-neutral extractables). Golder Associates Ltd. (2017b) reports on sampling of overburden groundwater for field geochemical measurements and PHC/BTEX and PAH contaminants. McVeigh (2018) summarizes radionuclide groundwater quality from 2017 sampling of 24 overburden monitoring wells from background locations, Landfill 1, Landfill 2, NPDWF and Ottawa River shoreline.

Earlier work by Killey and Munch (1988, 1989) describe similar major ion and radiological chemistry for Landfills 1 and 2. Earlier work by MacLarentech Inc. (1990) summarizes major ion and trace element chemistry for the NPD site including the areas of Landfill 1 and reactor buildings.

Based on McVeigh (2018), Killey (2014), Killey and Munch (1988, 1989) and MacLarentech Inc. (1990), shallow overburden groundwater is dilute (total dissolved solids [TDS] of 100 to 200 mg/L), Ca-HCO_3 type with Na-Cl/SO_4 as subordinate major ions. The NaCl signature likely reflects road salting of upgradient Highway 17 and NPD site roads. The overburden groundwater is moderately oxidizing as evident by low iron concentrations (about 10 to 100 µg/L) and for Landfill 2 Eh of 200 to 530 mV.

Historical (2014) tritium, gross alpha activity and gross beta activity in overburden groundwater are low with no exceedances of Health Canada drinking water quality guidelines or screening levels. Radionuclide concentrations from 2017 sampling (McVeigh, 2018) did not exceed maximum acceptable concentrations for drinking water. Tritium concentrations in 1988 and 1989 in the area of Landfills 1 and 2 were typically 100 to 1000 Bq/L. Tritium concentrations in 2014 at the NPD site were typically <30 to 85 Bq/L. Tritium levels in 2017 ranged from 7.6 Bq/L (background) to 9.3 Bq/L (Landfill 1), 16.3 Bq/L (Landfill 2), 63.7 Bq/L (NPDWF) and 65.6 Bq/L (Ottawa River shoreline). Tritium levels in overburden groundwater likely reflect local washout of tritiated water vapour that is periodically vented to the atmosphere from the NPD station (Killey, 2014).

3.5.1.2 2019 Sampling and Testing

Geofirma Engineering Ltd. (2019) describes the sampling and testing of deeper (~12 to 20 mBGS) NPD overburden groundwater as part of geoscientific characterization of the NPD site. This 2019 groundwater sampling and testing focused on characterization of field parameters, major ions, trace metals, tritium, gross alpha activity and gross beta activity in overburden groundwater at MW18-09 and MW18-10. Figure 2.4 shows the location of these two overburden wells whose well screens intersect silt to cobble till and boulder till, respectively. The results of these overburden groundwater analyses are presented in Table 3.5 together with analyses of shallow bedrock groundwater, tile drain and Ottawa River water.

Table 3.5 shows that the relatively deep overburden groundwater at MW18-09 and MW18-10 is dilute (total dissolved solids [TDS] of 210 and 545 mg/L), Na-HCO_3 type with Ca-Cl/SO_4 as subordinate major ions. The elevated TDS and NaCl/SO_4 signature relative to historical overburden groundwater analyses likely reflects road salting of upgradient Highway 17 and NPD site roads (NaCl), deeper sampling intervals and influence of shallow bedrock groundwater (SO_4). Compared to historical overburden groundwater, the 2019 overburden groundwater is slightly less oxidizing as evident by slightly higher iron concentrations (81.5 and 168 µg/L) and Eh of 343 and 332 mV (Geofirma Engineering Ltd., 2019).

Tritium concentrations measured in 2019 at MW18-09 and MW18-10 are comparable to historical sampling of overburden at the NPD site with concentrations of <100 Bq/L reported for both monitoring wells. Gross alpha activity and gross beta activity were 1.1 Bq/L and 0.59 Bq/L, respectively at MW18-09, and 0.25 Bq/L and 0.32 Bq/L, respectively at MW18-10. These activities are slightly higher than values reported for shallower overburden (Killey, 2014). The reported gross alpha activity at MW19-09 (1.1 Bq/L) slightly exceeds Health Canada screening level of 0.5 Bq/L.

Table 3.5 Summary of Analytical Results of 2019 Sampling of Deep Overburden Groundwater, Shallow Bedrock Groundwater, Tile Drain and Ottawa River Water

Interval (Depth mBGS)	Cond (µS/cm)	TDS (mg/L)	DOC (mg/L)	Cl (mg/L)	HCO_3 (mg/L)	SO_4 (mg/L)	Ca (mg/L)	Na (mg/L)	Mg (mg/L)	K (mg/L)	^3H (Bq/L)	Grs α (Bq/L)	Grs β (Bq/L)
Deep Overburden Groundwater													
MW18-09 (15.2-20.4)	432	545	19	25	92	82	17.8	48.2	4.7	2.2	<100	1.1	0.59
MW18-10 (11.9-15.5)	194	210	5.4	22	66	40	9.7	32.5	3.8	2.4	<100	0.25	0.32
Shallow Bedrock Groundwater													
MW18-05-P2 (26.2-29.2)	732	805	16	30	197	160	10.0	126	0.9	1.6	1000	0.91	0.69
MW18-05-P3 (32.2-34.4)	313	175	4.0	3.4	141	30	14.8	36	1.9	1.0	1350	0.11	<0.10
MW18-05-P5 (49.2-53.7)	201	145	1.6	2.1	154	18	13.6	32.8	2.0	1.6	990	0.21	<0.10
MW18-05-P6 (59.2-62.9)	428	280	5.0	8.0	180	56	10.5	70.1	1.2	1.6	640	0.21	<0.10
MW18-06-P1 (9.3-11.8)	467	310	23	41	130	110	13.9	77.7	1.8	4.4	<100	0.30	0.38
MW18-06-P2 (15.3-18.3)	662	540	21	38	125	88	12.7	101	1.5	4.6	950	1.50	0.98
MW18-06-P4 (29.5-31.5)	826	635	23	79	128	250	23.8	144	3.2	2.6	1320	1.50	0.34
MW18-06-P6 (42.0-43.3)	783	925	31	110	143	340	16.5	226	1.5	2.3	930	3.60	3.70
MW18-07-P1 (4.7-9.4)	459	275	2.8	7.0	262	59	54.9	15.4	14.3	2.9	<100	0.14	0.24
MW18-07-P2 (12.4-14.8)	542	330	7.0	11	246	96	52.5	38.6	12.8	2.1	190	0.37	0.33
MW18-07-P6 (40.2-43.9)	559	320	17	40	133	80	14.6	97.0	2.4	1.5	170	0.14	0.13
MW18-07-P7 (48.9-51.8)	582	420	15	23	139	150	7.7	114	1.0	1.0	<100	0.26	0.22
MW18-08-P1 (4.2-7.9)	203	310	21	33	128	55	13.0	57.9	3.2	2.9	<100	1.40	0.61
MW18-08-P3 (13.4-14.9)	288	310	21	33	128	55	13.0	57.9	3.2	2.9	<100	1.40	0.61
MW18-08-P4 (19.9-22.4)	421	285	17	28	134	72	14.5	71.5	3.2	2.4	<100	0.62	0.33
MW18-08-P6 (41.9-44.9)	246	280	5.0	11	141	42	4.7	54.2	0.8	0.8	<100	0.36	0.33
Tile Drain and Ottawa River Water													
Tile Drain	196	120	1.3	35	34	6.9	8.9	18.6	3.1	1.8	<100	<0.1	0.14
Ottawa River	NM	55	19	2.1	33	1.8	6.3	2.2	1.8	0.63	<100	<0.1	<0.1

Cond=Conductivity, TDS=total dissolved solids, DOC=dissolved organic carbon, Cl=chloride, HCO_3=bicarbonate, SO_4=sulphate, Ca=calcium, Na=sodium, Mg=magnesium, K=potassium, ^3H=tritium, Grs α=gross alpha, Grs β=gross beta, NM=not measured

3.5.2 Shallow Bedrock

3.5.2.1 Historical Sampling and Testing

There is no historical testing of groundwater quality in shallow bedrock at the NPD or NPDWF sites. Lacking such data, information from the CRL property was used to infer likely hydrogeochemistry of shallow (0-50 m deep) bedrock at the NPDWF site (Arcadis Canada Inc., 2018a).

McCrank (2016b) provides information on the major ion chemistry and isotope concentrations of shallow (i.e., 35 m deep) bedrock at the CRL property from recent site characterization completed in support of a proposed Geological Waste Management Facility. Johnston and Flavelle (1985) describe field geochemical measurements and the major ion and trace element chemistry for the 50 m deep bedrock site at CRL investigated by Raven (1986).

Based on McCrank (2016b) and Johnston and Flavelle (1985), shallow bedrock groundwater at NPD was inferred to be dilute (TDS of 200 to 420 mg/L), Ca-HCO_3 type with Na-Cl/SO_4 as subordinate major ions. The shallow bedrock groundwater at NPD based on CRL data was expected to be moderately oxidizing to reducing as evident by moderate iron concentrations (about <50 to 700 µg/L) and Eh of 90 to 450 mV. Average tritium concentrations in shallow bedrock at CRL were elevated above background levels at about 78 Bq/L reflecting on-site tritium sources, similar to the NPDWF site.

3.5.2.2 2019 Sampling and Testing

Results of 2019 sampling and testing of shallow bedrock groundwater are given in Table 3.5. Sampling of shallow bedrock groundwater was completed from installed CMT™ (continuous multi-channel tubing) multilevel groundwater monitoring systems. Four of the seven CMT monitoring intervals in MW18-05 to MW18-08 were sampled following well development and purging. The four sampled intervals were selected to provide depth coverage in the shallow bedrock and high permeability fractured zones in each borehole. This 2019 groundwater sampling and testing focused on characterization of field parameters, major ions, trace metals, tritium, gross alpha activity and gross beta activity of shallow bedrock groundwater. Additionally, four CMT intervals (MW18-07-P5, MW18-08-P2, MW18-08-P3 and MW18-08-P6) located downgradient of the NPDWF that showed elevated gamma readings in borehole geophysical logging were analyzed for radionuclides. No radionuclides were detected above reporting detection limits of 0.1 to 5 Bq/L.

Table 3.5 shows that shallow bedrock groundwater at the NPD site in proximity to the NPDWF is dilute (TDS of ~200 to 925 mg/L), predominantly Na-HCO_3 type with Ca-Cl/SO_4 as subordinate major ions. Locally near MW18-06-P4, MW18-06-P6 and MW18-07-P7 the shallow bedrock groundwater is Na-SO_4 type with Ca-Cl/HCO_3 as subordinate major ions. Near MW18-07-P1 and MW18-07-P2 the shallow bedrock groundwater is Ca-HCO_3 type with Na/Mg-Cl/SO_4 as subordinate major ions. Compared to inferences from CRL data, the 2019 shallow bedrock groundwater at NPD is slightly more oxidizing as evident by lower iron concentrations (<5 to 35 µg/L) and Eh of 321 to 412 mV (Geofirma Engineering Ltd., 2019).

Relatively elevated tritium concentrations of 650 to 1350 Bq/L are reported near MW18-05 and MW18-06 upgradient of the NPDWF. Downgradient of the NPDWF at MW18-07 and MW18-08 tritium concentrations are lower at <100 to 190 Bq/L. Gross alpha and gross beta activities in shallow bedrock range from 0.11 to 3.6 Bq/L and <0.10 to 3.7 Bq/L, respectively. The cause of the elevated tritium concentrations in shallow bedrock upgradient of the NPDWF is not known.

The relatively wide range of shallow bedrock groundwater chemistries suggests that some CMT monitoring intervals are influenced to some degree by residual drilling water used for bedrock coring which was mostly Ottawa River water. Given the very dilute chemistry in Ottawa River water (see Table 3.5), the reported 2019 chemistry of many of the shallow bedrock monitoring intervals may be underestimated. Subsequent groundwater sampling of the shallow bedrock is necessary to confirm this suggestion and representativeness of the 2019 data for shallow bedrock groundwater.

3.5.3 NPD Tile Drain and Ottawa River Water

NPD tile drain water chemistry is reported by Killey and Munch (1988), MacLarentech Inc. (1990), Killey (2014) and by Geofirma Engineering Ltd. (2019). MacLarentech Inc. report on major ion and trace element chemistry of tile drain water and Killey (2014) and Geofirma Engineering Ltd. (2019) report on geochemical field measurements, major ion and trace element chemistry, and radiological parameters (tritium, gross alpha activity, gross beta activity) of the tile drain water. Geofirma Engineering Ltd., (2019) reports on similar measurements for Ottawa River water immediately north of BH18-07.

The major ion and trace element chemistry and radiological chemistry of the tile drain water, as reported by MacLarentech Inc. (1990), Killey (2014) and Geofirma Engineering Ltd. (2019), indicate the tile drain water is very dilute (TDS of 100 to 130 mg/L) Na/Ca-HCO_3 type with Cl/SO_4 as subordinate major ions. The NaCl signature in tile drain water likely reflects road salting of upgradient Highway 17 and NPD site roads. The tile drain water is oxidizing as evident by low iron concentrations (about 3 to 30 µg/L) and Eh of 374 mV. Tritium concentrations in tile drain water range from 50 Bq/L (2014) to <100 Bq/L (2019). Gross alpha and beta activities in tile drain water in 2014 and 2019 were low and stable at <0.21 and <0.10 Bq/L, and 0.25 and 0.14 Bq/L, respectively. These tile drain chemistries indicate that shallow overburden groundwater as reported by Killey and Munch (1988), MacLarentech Inc. (1990) and Killey (2014) is the likely source of water to the tile drains. Killey and Munch (1988) made similar arguments on the source of tile drain water based on 1988 tritium data.

To further assess the likely sources of groundwater to the tile drains, the major ion chemistries of overburden and shallow bedrock groundwater and tile drain and Ottawa River samples are plotted on ternary Piper diagrams in Figure 3.7. Piper diagrams provide a simple and common basis for graphically illustrating the hydrogeochemical facies of different water types based on plotting water chemistries as percentages of total milliequivalents per liter (Freeze and Cherry, 1979). Such normalized plotting largely overcomes issues associated with dilution of groundwater samples by low TDS drilling fluids as is suspected for some of the shallow bedrock groundwater samples.

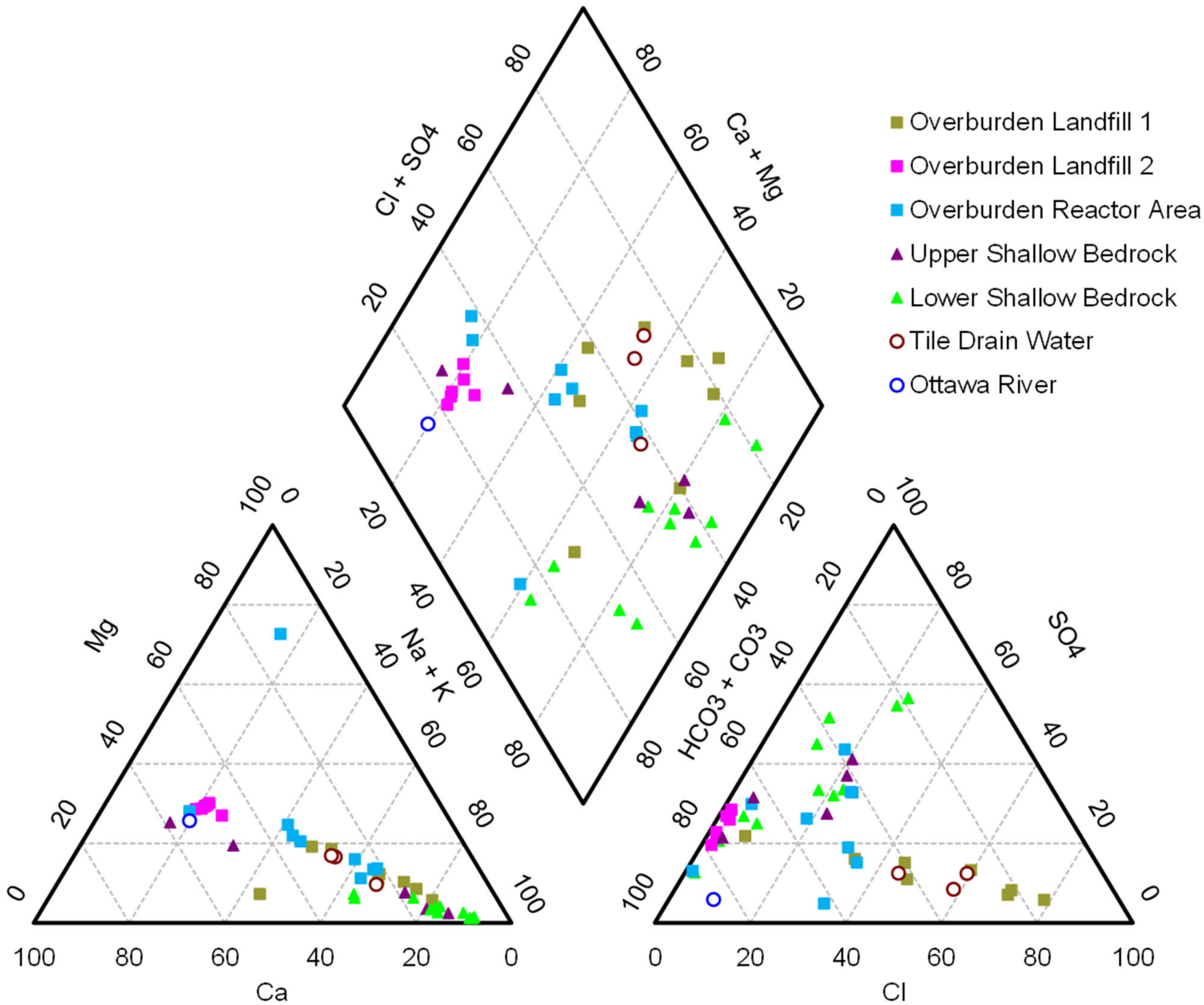


Figure 3.7 Piper Diagram of Major Ion Chemistry of Groundwater and Water Types at the NPD Site

For these plots alkalinities are assumed as carbonate alkalinities and alkalinities as $CaCO_3$ were converted to a common basis as HCO_3. Figure 3.7 identifies the following groundwater and water types based on sampling locations:

1. Overburden Groundwater – Landfill 1 Area,
2. Overburden Groundwater – Landfill 2 Area,
3. Overburden Groundwater – Reactor (NPDWF) Area,
4. Upper Shallow Bedrock (upper 20 m of bedrock),
5. Lower Shallow Bedrock (lower 30 m of bedrock),
6. Tile Drain Water, and
7. Ottawa River Water.

Figure 3.7 shows separate clustering of overburden groundwater and shallow bedrock groundwater especially on the combined diamond plot. Based on the proximity of different water types to the tile drain water, Figure 3.7 suggests that groundwater from the area of Landfill 1 and the reactor area are most likely the sources of water to the tile drains. This is entirely reasonable as these two groundwater types are in close proximity to the tile drains or are clearly upgradient of the tile drains. Figure 3.7 also shows that upper and lower shallow bedrock groundwater and Ottawa River water are not sources of water to the tile drains.

3.5.4 Uncertainties

There is uncertainty in the hydrogeochemistry and groundwater quality of shallow bedrock due to limited sampling, sampling purging constraints and the likely presence of residual drilling fluid contamination in some lower permeability bedrock sampling intervals.

Groundwater in shallow bedrock accessed by CMT™ completions in BH/MW18-05 to BH/MW18-08 was only sampled once as part of geoscientific characterization work in December 2018 to January 2019. Given the nature of the CMT installations and the restrictions on groundwater purging rates prior to sampling, Section 3.5.2.2 indicates that some of CMT monitoring intervals are influenced by residual drilling water (Ottawa River water) and hence the 2018/2019 groundwater quality results for bedrock may be underestimated. Follow-on groundwater sampling of the shallow bedrock was recommended to confirm this suggestion and the representativeness of the 2018/2019 data for shallow bedrock groundwater from the CMT completions. This recommendation is the principal means by which this hydrogeochemical uncertainty can be mitigated.

Uncertainty in shallow bedrock hydrogeochemistry does not likely pose an adverse effect to closure and post-closure phases because, although there is some uncertainty in shallow bedrock groundwater chemistry, that uncertainty will have a negligible effect on the rate and location of groundwater discharges from the NPDWF to the adjacent Ottawa River. Minor changes in shallow groundwater chemistry will not change the fact that shallow bedrock groundwater from the NPDWF will discharge to the Ottawa River immediately northeast of the NPDWF with relatively short transit time. This uncertainty relates entirely to the completeness of site characterization work and not to the fate of overburden groundwater discharge from the NPDWF to the Ottawa River.

3.6 Local Groundwater Flow Systems

3.6.1 Groundwater Depths and Elevations

Groundwater elevations in overburden prior to building excavation were reported at 128.6 m (422 ft.) (Hydro Electric Power Commission of Ontario, 1961), and given ground surface elevations, this value must be representative of the upgradient side of the building. Ground surface slopes sharply down northeast of the building towards the Ottawa River, with Ottawa River elevations at approximately 111 mASL.

Historical and recent water levels measured primarily in sand and gravel fill unit and fluvial sand and gravel unit, and to a lesser degree the glacial till unit and shallow bedrock unit (exclusive of CMT data) are illustrated against well ground surface elevation in Figure 3.8. Generally, winter water level measurements are lower than spring and summer measurements of water levels. The variation in water levels can be considerable, a maximum of 3.4 m and an average of 1.3 m difference, excluding bedrock wells. Where the same wells are measured, the April 2017 water levels generally correspond well to the June 2014 water levels with differences less than 0.5 m, with the exception of well MT-5. At well MT-5, June 2014 measures a water level 1.5 m higher than in 2017, and the 2017 water level measurements are more generally consistent with previous water levels measured by MacLarentech Inc. (1990). Figure 3.8 indicates depths to groundwater ranging from several m to over 10 m.

Water levels measured in January 2019 (Geofirma Engineering Ltd., 2019) provide additional information on water levels and elevations in the glacial till units and shallow bedrock. These 2019 and historical data as shown on Figures 2.5 and 2.6 show that groundwater levels are typically within the fluvial sand and gravel unit in the vicinity of NPDWF and within the overlying silt to cobble glacial till unit southwest, northwest and southeast of NPD, a few metres above the bedrock surface (Killey and Munch, 1988; 1989; Golder Associates Ltd., 2017b). Water levels within the shallow bedrock are typically within 1 to 2 m of overburden water levels. The groundwater table is subdued reflection of the bedrock surface topography (Figure 8-1 of MacLarentech Inc., 1990).

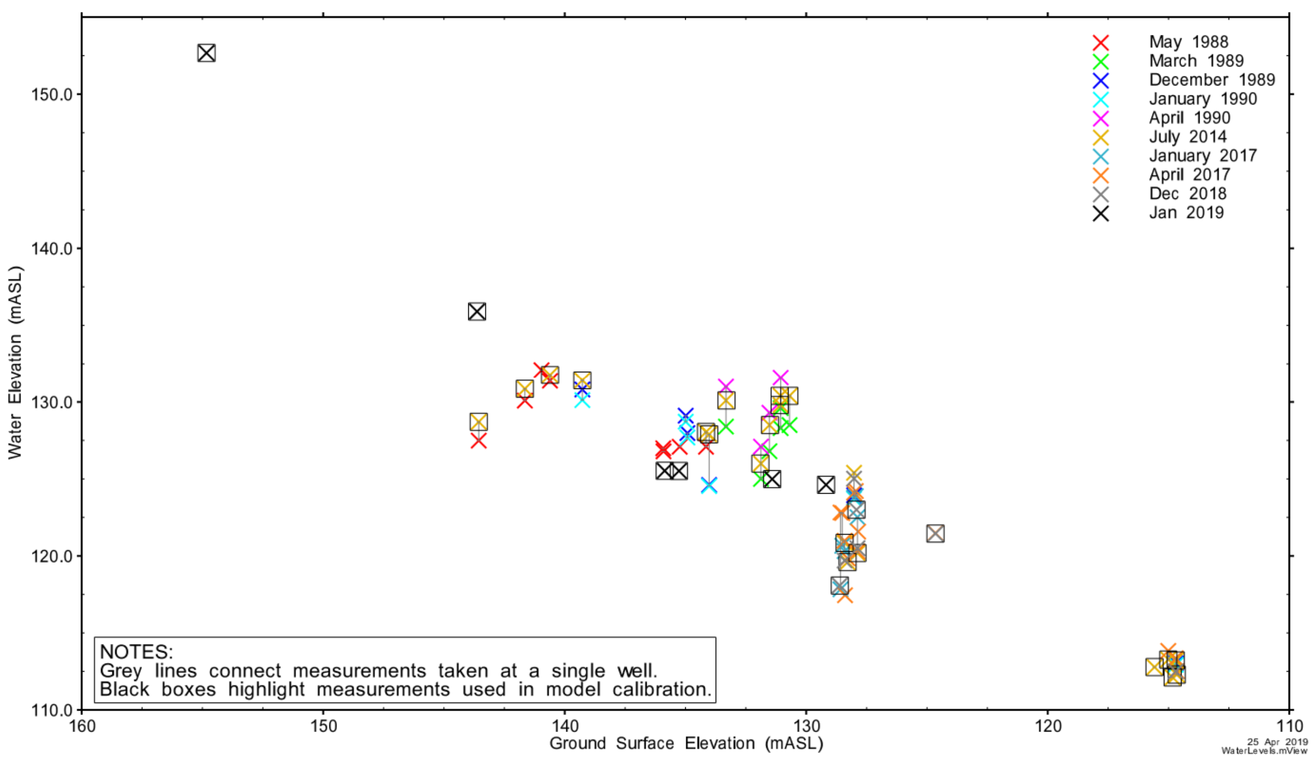


Figure 3.8 Measured Water Levels and Ground Surface Elevations

Figure 3.9 shows the elevation profiles of water level available for shallow bedrock based on hydraulic testing and water level monitoring in CMTs installed in BH18-05 to BH18-08. Water levels from hydraulic testing are interpreted values based on analyses of straddle-packer hydraulic tests. Water levels from CMTs are water levels measured with water levels tapes following installation of CMTs in each borehole. Water levels from hydraulic testing are less reliable that those from CMT monitoring because the water levels from hydraulic testing are strongly influenced by the water levels in the open boreholes immediately prior to packer inflation. Such open borehole water levels reflect inflow and outflow within the borehole and often do not reflect in-situ bedrock conditions.

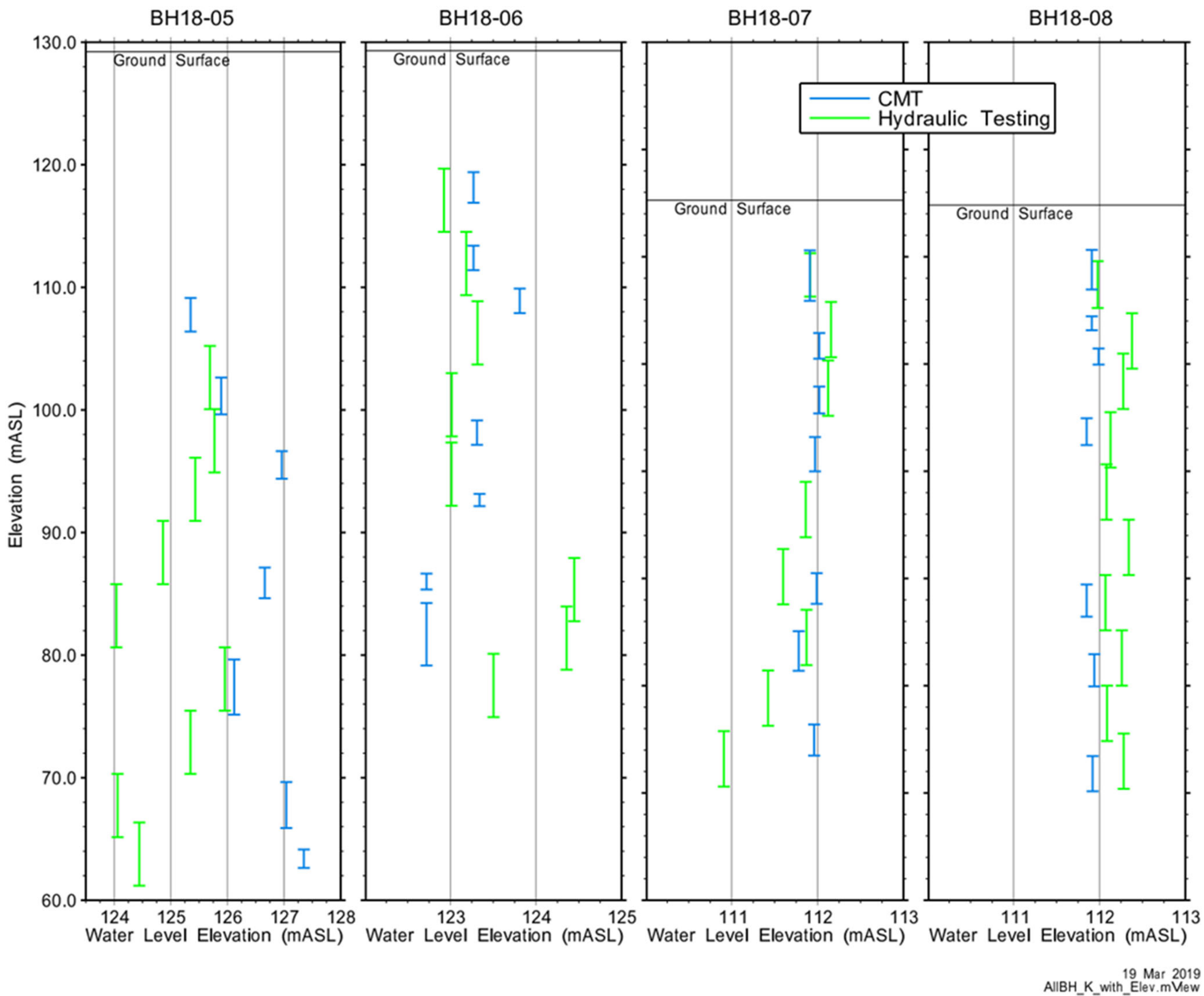


Figure 3.9 Elevation Profiles of Hydraulic Head in Shallow Bedrock Interpreted from Hydraulic Testing and Measured in CMT Installations

Based on CMT data, Figure 3.9 shows generally upward hydraulic gradients in MW18-05, downward hydraulic gradients in MW18-06 and near hydrostatic conditions in MW18-07 and MW18-08. Superimposed on these general trends are intervals with elevated hydraulic heads (P3 and P4 in MW18-05, P3 in MW18-06). These elevated heads are interpreted as propagated heads from upgradient higher head areas via subhorizontal permeable fractures and fracture zones, due to the association of the higher heads with elevated hydraulic conductivity. The near hydrostatic hydraulic head profiles in MW18-07 and MW18-08 near the Ottawa River likely reflects increased vertical hydraulic conductivity of the shallow bedrock as evident from hydraulic testing and fracture logging.

3.6.2 Groundwater Recharge and Discharge Areas

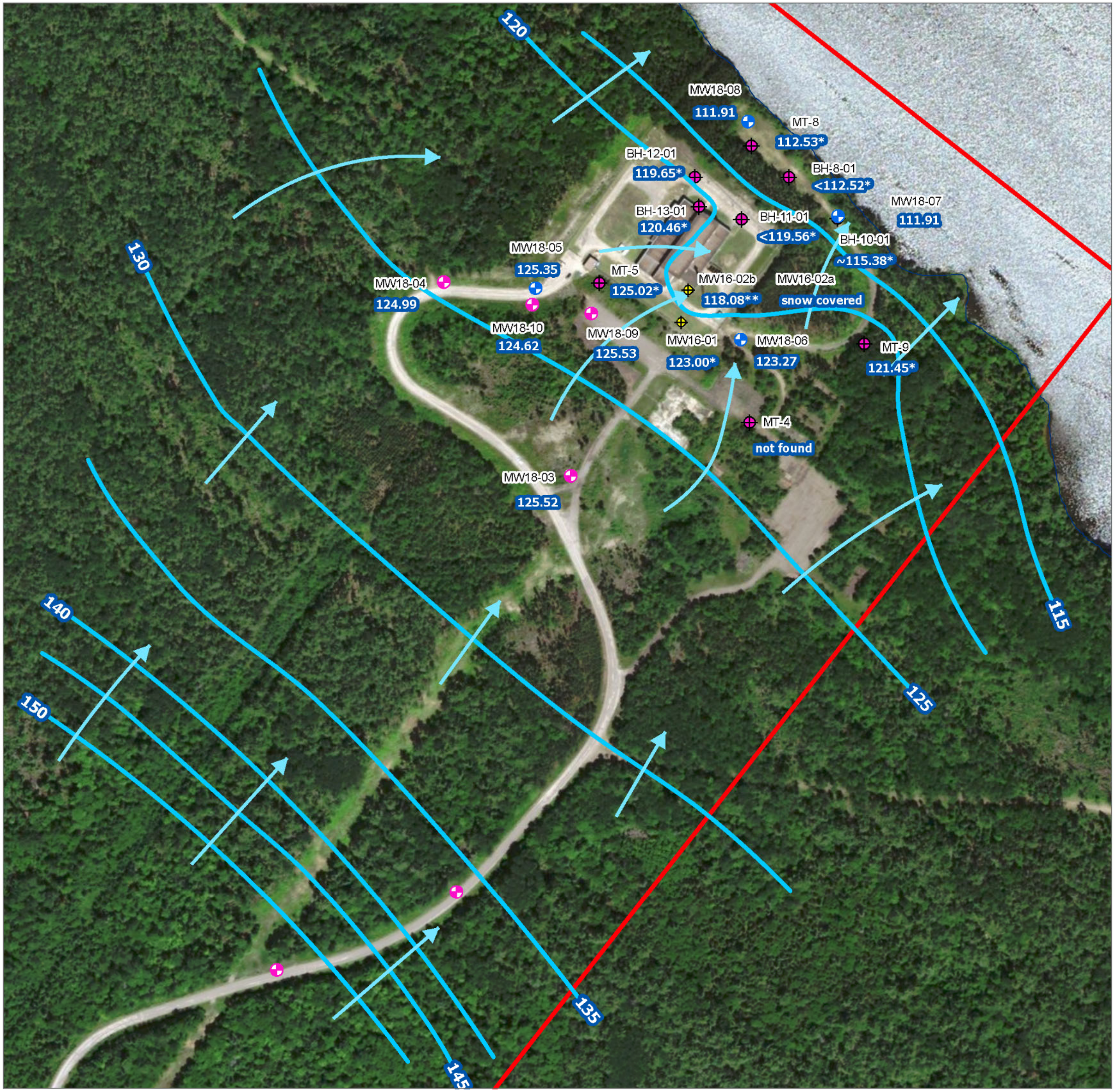
Local groundwater recharge and discharge areas for the NPDWF site are identified based on topography (Figure 2.2), surficial geological mapping (Figure 2.3), conceptual geological-hydrogeological cross sections (Figures 2.5 and 2.6), and groundwater levels as reported in historical investigations (Figure 3.6) and 2019 site investigations (Figure 3.10). Figure 3.10 shows contoured water level measurements and interpreted directions of horizontal groundwater flow in overburden units and the uppermost intervals in shallow bedrock based on January 16, 2019 data.

Recharge of the local groundwater system at the NPDWF site occurs primarily in the highland area northeast and southwest of Highway 17 where glacial till is exposed at surface. Some recharge also occurs on the upslope areas of the site between Highway 17 and Landfill 1 where permeable alluvial (fluvial sand and gravel) deposits are exposed at surface. Groundwater discharge areas were historically noted on the overburden ground slopes between the area of the NPDWF and the Ottawa River. Numerous springs were observed on the slope towards the river (Hydro Electric Power Commission of Ontario, 1961, Canadian General Electric Company Ltd. 1962), prior to building excavation. These springs are no longer observed at the site due tile drain dewatering.

A large portion of groundwater southwest of the NPD building, at least as far as Landfill 1 and likely upgradient of Landfill 1, as well as potentially northwest of the NPD building at least as far as Landfill 2 (see Figure 3.6) discharges to the tile drain system that was trenched into the surface of the bedrock, surrounds the NPD reactor building and drains into the Ottawa River. The distortions in shallow groundwater table due to drainage to the tile drain system are apparent in Figures 3.6 and 3.10. The tile drain system is divided into two separate systems, one draining the southern and western sides of the building, and the second draining the western and northern edges of the building, as shown in Figure 3.11.

The tile drains are only functional for tile drain 1 (Killey and Benz, 2009), likely due to the location of tile drain 2 above the water table. Bedrock elevations on the south-eastern side of the building are elevated, and the tile drain invert elevations are correspondingly higher on the south-eastern side of the building. Invert elevations at about 121.3 mASL are the same at Manhole 2 and Manhole 3 (the tile drain outlets for tile drain 1 and 2, respectively), but are above water table elevations at nearby wells.

Groundwater flow in the underlying shallow bedrock discharges upward to the overlying overburden in the area of the NPDWF as evident from limited shallow bedrock water levels at BH16-02A/B (Golder Associates Ltd., 2017a) and water level profiles at MW18-05 (Figure 3.9). At MW18-06 the elevated bedrock surface appears to create locally downward hydraulic gradients in the shallow bedrock. Near MW18-07 and MW18-08, groundwater likely discharges to the Ottawa River either directly or via the Mattawa Fault that defines the course of the Ottawa River.



LEGEND

- 2019 Rolphton NPDWF Model Boundary
- Ottawa River Outline

Boreholes and Monitoring Wells

- Geofirma Overburden
- Geofirma Bedrock
- Golder
- AECL
- MacLarentech / J.D. Paterson
- Interpreted Water Level Contour (mASL, Jan 16, 2019)
- Interpreted Horizontal Groundwater Flow

* = water level measured on Dec 12, 2018
** = water level measured on Dec 19, 2018

Figure 3.10
Shallow Groundwater Elevations and Flow Directions at NPD Site (January 16, 2018)

SCALE 1:4,500

0 25 50 100 150 200
Meters

N

Coordinate System: NAD 1983 UTM Zone 18N
Source:
Basemap: LIO, MNR
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

PROJECT No. 16-212-11

Updated Geosynthesis -
Rolphton NPDWF EIS

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR
REV: 0

DATE: 28/02/2019

Geofirma Engineering Ltd

G:\Data\Project\ChalkRiver\Map\16-212-11_NPDWF_Geosynthesis\16-212-11_Fig3_10_GroundwaterElevation_Jan16_19.mxd

Figure 3.11 Tile Drain Layout and Invert Elevations (from Shkarupin and Miller, 2016)

3.6.3 Groundwater Flow Directions and Velocities

Groundwater flow directions in saturated overburden and bedrock hydrostratigraphic units are inferred from groundwater table elevation contours as shown in Figures 3.6 and 3.10. These water level contours are assumed to be representative of hydraulic heads in all hydrostratigraphic units. For homogeneous isotropic hydrostratigraphic units, groundwater flow directions will be normal to contours of water level elevation.

Horizontal Darcy velocities (specific discharges) and linear groundwater velocities for sand and gravel fill unit, fluvial sand and gravel unit, silt to cobble glacial till unit, boulder glacial till unit and shallow bedrock hydrostratigraphic units are calculated from Darcy's Law and modifications to Darcy's Law using horizontal hydraulic gradients and hydraulic conductivities and porosities. Average horizontal hydraulic gradients between Landfill 1 and the Ottawa River are calculated as (130-111 m)/425 m = 0.045 m/m and are applicable to all hydrostratigraphic units except the silty sand glacial till located near and southwest of Landfill 1. For this unit average horizontal hydraulic gradients between MW18-01 and Landfill 1 are calculated as 150-130 m/270 m = 0.074 m/m. Table 3.6 summarizes the results of these calculations using best estimate values of hydraulic conductivity and porosity given in Section 3.4 above.

As per Section 3.4.3, two members of the silt to cobble glacial till unit are recognized, a lower permeability silty sand glacial till and a higher permeability sand to cobble glacial till. As per Section 3.4.5, two zones of shallow bedrock hydraulic conductivity are recognized, a lower K zone near the NPDWF and a higher K zone near the Ottawa River.

Table 3.6 shows that calculated linear groundwater velocities for the sand and gravel fill unit and fluvial sand and gravel unit are comparable at about 1.7 to 3.4 m/day, whereas linear groundwater velocities in the sand, gravel and cobble member of silt to cobble glacial till unit and boulder glacial till unit are lower to comparable at 0.23 to 2.6 m/day. The lowest calculated linear groundwater velocities are within the silty sand member of the silt to coble glacial till unit at 0.00070 m/day. For shallow bedrock the calculated velocities are for homogeneous fractured bedrock without major structural features such as shear zones and faults range from 0.057 to 0.28 m/day.

Table 3.6 Summary of Estimates of Darcy Velocity and Linear Groundwater Velocity in Hydrostratigraphic Units

Hydrostratigraphic Unit	***Hydraulic Conductivity (m/s)***	***Porosity (-)***	***Darcy Velocity ($m^3/s/m^2$)***	***Linear Groundwater Velocity (m/day)***
Sand and Gravel Fill Unit	1.3E-04	0.3	5.8E-06	1.7
Fluvial Sand and Gravel Unit	3.5E-04	0.4	1.6E-05	3.4
Sand, Gravel and Cobble Member of Silt to Cobble Glacial Till Unit	2.0E-05 to 2.0E-04	0.3	9.0E-07 to 9.0E-06	0.26 to 2.6
Silty Sand Member of Silt to Cobble Glacial Till Unit	3.3E-08	0.3	2.4E-09	0.00070
Boulder Glacial Till Unit	1.7E-05	0.3	7.9E-07	0.23
Shallow Bedrock - NPDWF	7.3E-08	0.005	3.3E-09	0.057
Shallow Bedrock – Ottawa River	3.6E-07	0.005	1.6E-08	0.28

3.6.4 Interactions with Surface Water

Groundwater interactions with surface water at the NPD site occur via direct discharge and via groundwater flow. The tile drain systems installed in shallow bedrock around the NPD building collects and directly discharges overburden groundwater to the Ottawa River via tile drain systems 1 and 2 shown in Figure 3.11. Volumes of groundwater directly discharged to the Ottawa River from the tile drains show seasonal variations with a best estimate steady state value of 7.5 L/s (Calder, 2018). Based on Figures 3.6 and 3.10, a significant portion of the tile drain discharge appears to be surface water recharged southwest and west of the NPDWF and Landfill 1.

Groundwater in overburden and in shallow bedrock also discharges to the adjacent Ottawa River via groundwater flow. For overburden groundwater, the discharge is likely directly to the Ottawa River via the sand and gravel fill and fluvial sand and gravel hydrostratigraphic units. The volume of overburden groundwater discharged via groundwater flow is likely to be much less than that from the tile drains due to upgradient interception of overburden groundwater by the tile drains. For shallow bedrock, the discharge pathway is most likely via upward flow in the steeply dipping fracturing near BH18-07 and BH18-08 or the Mattawa Fault that underlies the Ottawa River. Based on the Darcy velocities or specific discharges given in Table 3.6, the shallow bedrock groundwater discharge to the Ottawa River would be a small percentage of that discharged directly via the tile drains.

3.7 Potable Water Supplies and MECP Well Records

Potable water supplies in the nearby communities such as Rolphton, Meilleurs Bay and Rapides des Joachims are sourced from domestic groundwater wells and in all likelihood will continue to be so in the future. Figure 3.12 summarizes the location of bedrock and overburden domestic water supply wells and groundwater monitoring wells in the vicinity of the NPD site based on MECP (2018) well records. Table 3.7 summarizes the statistics on the groundwater wells shown in Figure 3.12 as presented in MECP well records.

Table 3.7 Summary of MECP Groundwater Well Records in Vicinity of NPD

Well Type	*Number of Wells*	*Well Depths (m)*	*Static Water Level Depth (m)*
Overburden	13	3.0 – 32.6	Not Reported
Bedrock	69	4.7 – 193.5	0.9 – 21.9 with one artesian well

The five groundwater wells noted at or near the NPDWF site including three overburden wells and two bedrock wells are groundwater monitoring wells installed in 2016 and 2017.

Figure 3.12 and Table 3.7 show that the majority of potable water supplies in the area of Ontario surrounding the NPD site are based on bedrock wells installed to maximum depths of about 190 m. This is typical for most residences and communities located on the Canadian Shield.

3.8 Hydrogeological Modeling

3.8.1 Purpose and Scope

Three-dimensional hydrogeologic modelling was undertaken for two purposes:

1. To provide estimates of groundwater flow and velocity that would come into contact with the proposed decommissioned reactor building and surrounding facilities (referred to herein as the NPDWF). Groundwater flow modelling outputs are used to support safety assessment modelling.
2. To determine the resaturation time of the NPDDF. Resaturation occurs through the infiltration of precipitation inputs and seepage of groundwater into the facility, which is proposed to be filled with grout.

Two models were constructed to meet these objectives, the first a groundwater model that encompasses the local groundwater flow system around the NPDDF, and the second a subset of this groundwater model, focusing on the resaturation of the NPDDF.

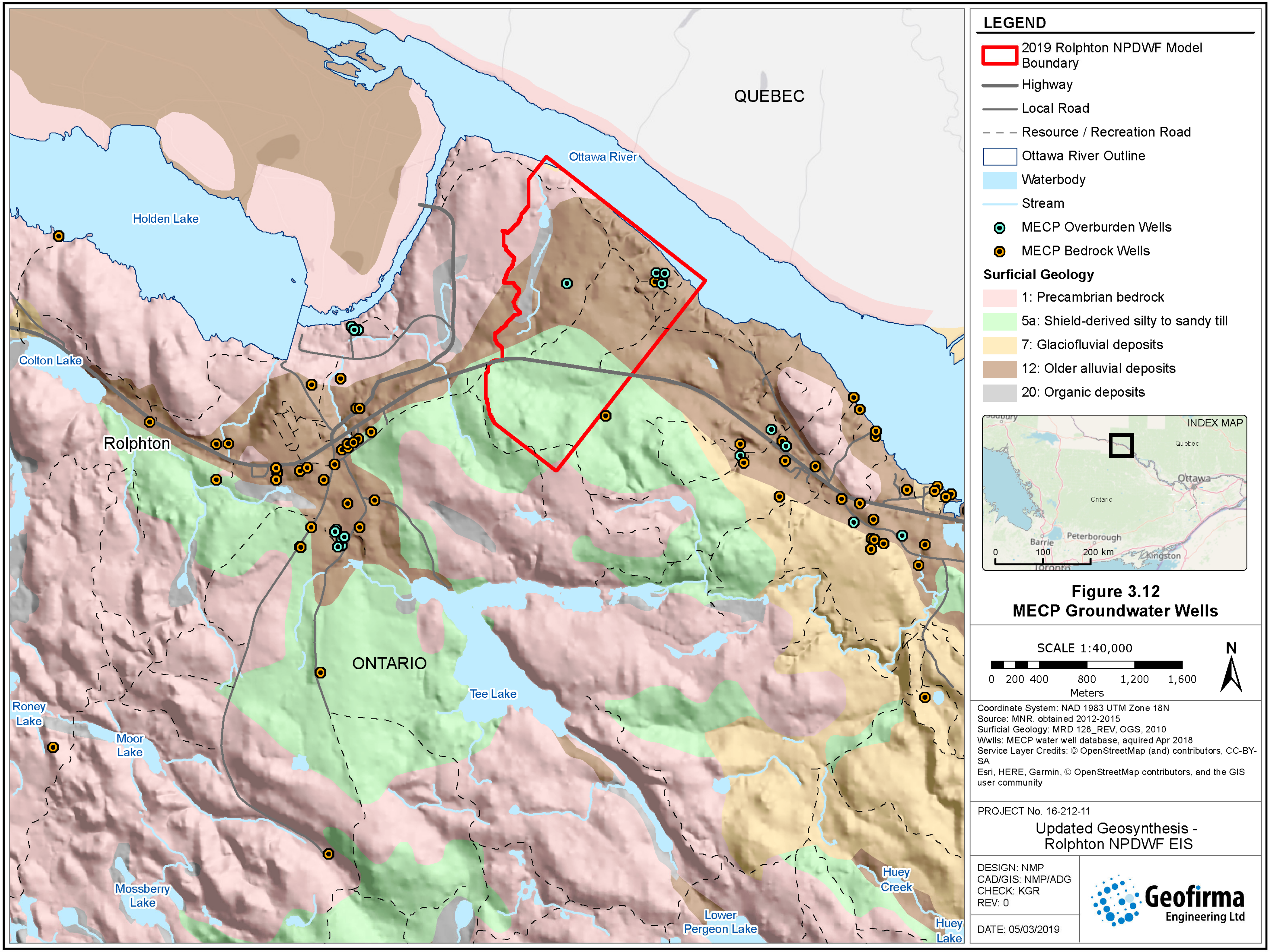


Figure 3.12
MECP Groundwater Wells

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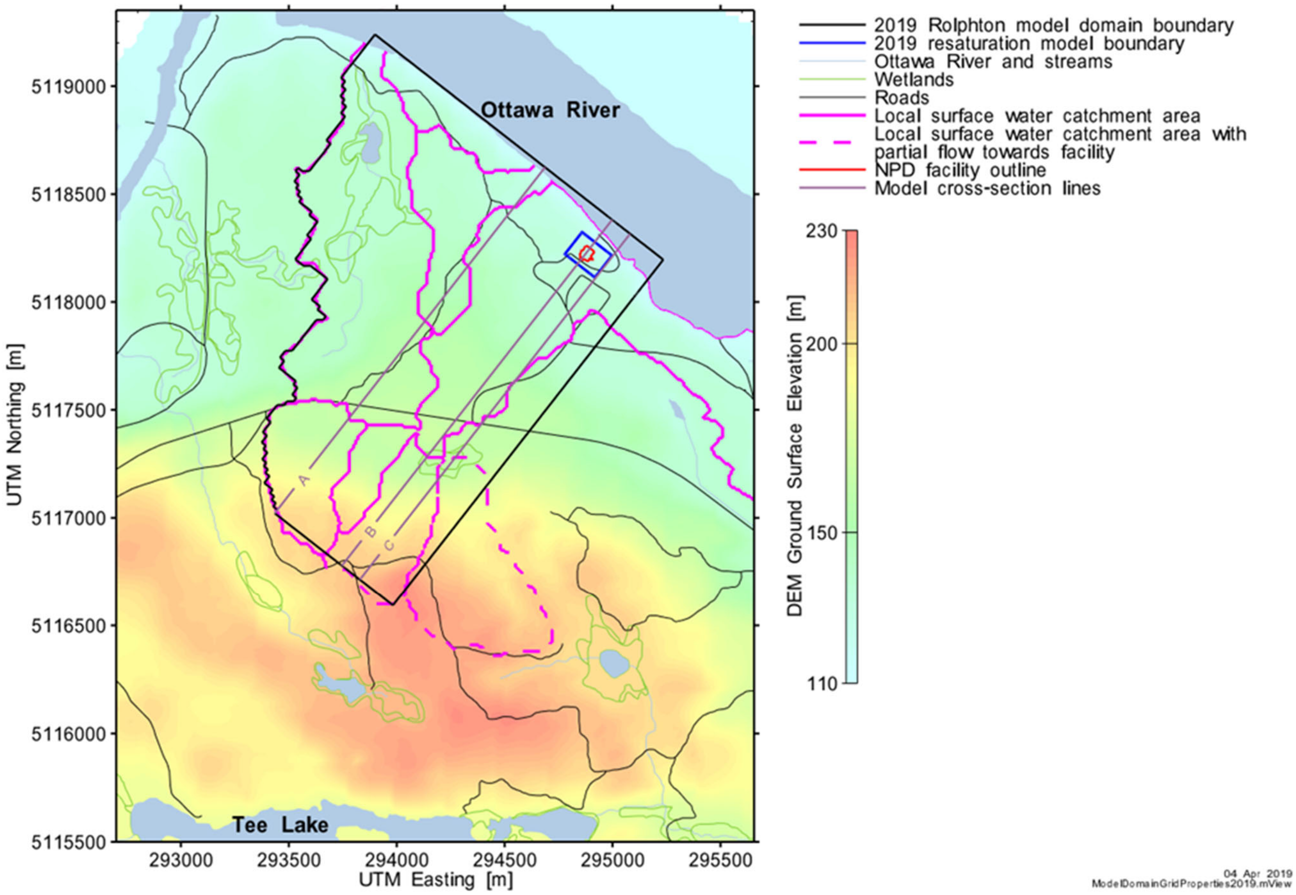


Figure 3.13 2019 Groundwater Flow and Resaturation Model Domains

The two model domains are shown in Figure 3.13. These two models are described in Calder (2019a) and Calder (2019b), respectively. The resaturation model (Calder, 2019b) has been updated for consistency with the first groundwater flow model. The first model, encompassing the local groundwater flow system, is described in more detail below.

3.8.2 <u>Modeling Approach</u>

Groundwater flow modelling simulated the local groundwater flow system, from the topographic high between Tee Lake and Highway 17 to the Ottawa River and includes the five hydrostratigraphic units described in Section 3.4. The unsaturated zone above the water table was also modelled in addition to the saturated groundwater flow system. The model domain is shown by the black polygon in Figure 3.13. Boundary conditions are infiltration applied to the surface of the model (400 mm/yr over sand and gravel and 10 mm/yr over glacial till), fixed head at an elevation of 111.5 m at the Ottawa River, fixed head at the wetland to the southwest at an elevation of 164 m and fixed head at the wetland to the northwest at an elevation of 137.4 m.

The model includes the NPDDF, which has been excavated into the bedrock to an elevation of 104 m. The facility consists of concrete walls and floors, filled with a grout. The space between the concrete floors and walls and the bedrock is filled with concrete.

Groundwater flow modelling was conducted using FRAC3DVS_OPG V1.3 (Therrien *et al*., 2010), a 3D finite element/finite difference code. Particle tracking was also conducted, using MODPATH version 7 (Pollock, 2016).

The groundwater flow model was calibrated to two objectives:

1. Measured water levels in July 2014, the most complete data set of water levels. Additional water levels were provided by the measured water levels in December 2018 and January 2019, which provided data in the till upgradient of the facility and in the shallow bedrock.
2. A steady-state tile drain flow rate of 7.5 L/s.

Calibration was conducted using the parameter estimation tool PEST++ (Welter *et al.* 2015). Hydraulic conductivities for sand and gravel fill, fluvial sand and gravel, glacial till, boulder till and bedrock were adjusted in the calibration. Both sand and gravel horizontal hydraulic conductivity and anisotropy ratio were calibrated. Both the till and bedrock are split into two units, one near the river, based on the description of the hydrostratigraphic units in Section 3.4. The fluvial sand and gravel unit was split into three sections for calibration purposes. While such horizontal sand units parallel to the river have not been characterized by drilling and well testing, they are consistent with the geological deposition of fluvial sediments at the site, the heterogeneity of sands observed at the site, and are currently the only mechanism in the groundwater model capable of increasing tile drain flowrates near observed values. All other conductivities (e.g., concrete walls and grout within the facility) and parameters were fixed and not calibrated. 2019 final calibrated values of hydraulic conductivity and anisotropy are shown in Table 3.8 and include calibration to all hydrostratigraphic units of Section 3.4.

Table 3.8 also shows the best estimates of material properties for the model layers based on site characterization data as presented in Section 3.4 of this report. Generally, the 2019 final calibrated model parameter values are similar to or within the range of values measured during site characterization work. The exceptions are the hydraulic conductivity of till near river, and sand and gravel fill. For till near river, the final calibrated value is only very slightly greater than the best estimate values and is therefore considered reasonable. For till near river 2, the final model calibrated K of 2.3E-06 m/s is less than the range of values from site characterization, but the closest tested well (MT-8) has the lowest value of the range suggesting the model calibrated value is reasonable given other values for till measured at the NPD property. For sand and gravel fill, the final model calibrated K of 3.4E-04 m/s is larger than the best estimate from site characterization which was based on a single well test result. Given the paucity of field data for this unit and the fact that 2018 model calibration indicated a K value of 1.3E-04 m/s, the final model calibrated K value is reasonable.

Table 3.8 also shows the mean sensitivity of calibrated parameters to the final model solution listed in order of decreasing sensitivity. Mean sensitivity is a statistical measure of the importance of the model parameter to model calibration, calculated from a composite of the derivatives of model-generated observations (water levels and tile drain flow rate), modulated by the weight attached to each observation. Based on Table 3.8, the model calibration is most sensitive to the hydraulic conductivity of the fluvial sand and gravel, bedrock near river and till near river units.

Table 3.8 Final Calibrated Parameter Values and Parameter Sensitivity from Hydrogeological Modeling

Calibrated Parameter	*Best Estimate Value from Site Characterization (Section 3.4)*	*Final Calibrated Value*	*Mean Sensitivity x 1000*
Fluvial Sand and Gravel Horizontal K (m/s)	2.0E-07 to 1.0E-03	1.0E-03	66
Fluvial Sand and Gravel Sand Near River Horizontal K (m/s)	2.0E-07 to 1.0E-03	2.4E-05	13
Permeable Fluvial Sand and Gravel Horizontal K (m/s)	2.0E-07 to 1.0E-03	6.6E-04	3.1
Bedrock Near River K (m/s)	3.6E-07	3.3E-07	2.3
Till Near River K (m/s)	2.0E-05 to 2.0E-04	2.9E-04	0.8
Bedrock K (m/s)	7.3E-08	9.3E-08	0.75
Sand and Gravel Fill K (m/s)	5.0E-06	3.4E-04	0.48
Fluvial Sand and Gravel Anisotropy Ratio	2.0 to 10.0	3.9	0.16
Till K (m/s)	3.3E-08	2.0E-08	0.06
Boulder Till K (m/s)	1.7E-05	1.8E-05	0.03
Till Near River 2 K (m/s)	2.0E-05 to 2.0E-04	4.4E-06	0.01

3.8.3 Results

A good match to water levels was obtained in the model calibration, as well as tile drain flow rates. The 2019 groundwater flow model found the water table to sit slightly above the bedrock surface, and the tile drain system surrounding the facility channels groundwater towards the facility before discharging to the Ottawa River.

A portion of the capture area for the tile drains is west of the facility, made possible by relatively low conductivity fluvial sand and gravel near the river. Without this additional capture area to the west, there is insufficient water upgradient to obtain the tile drain flow rate. Figure 3.14 shows a cross section showing head contours, linear groundwater velocity magnitude and direction and the water table at three cross sections (A, B and C) in the vicinity of the facility shown on Figure 3.13. Figure 3.15 shows the particle tracks illustrating the capture area of the tile drains, as well as the property assignment dividing the sand into three parts (sand, permeable sand and sand near river). Note that the properties shown are at the bottom of the overburden, and sand is also above a large portion of the till.

The improved groundwater flow model calibration results achieved in the 2019 hydrogeological modeling relative to the 2018 modeling are due to an improved conceptual hydrogeological model that, based on 2019 site characterization work, captures the spatial heterogeneity in overburden and bedrock hydrogeological properties. Inclusion of such spatial heterogeneity in overburden hydraulic properties expands the capture area for groundwater discharging to the tile drain (see Figure 3.15) toward wetlands located west and southwest of the NPDDF and consequently allows larger volumes of groundwater to be removed by the tile drains than in the 2018 groundwater flow model.

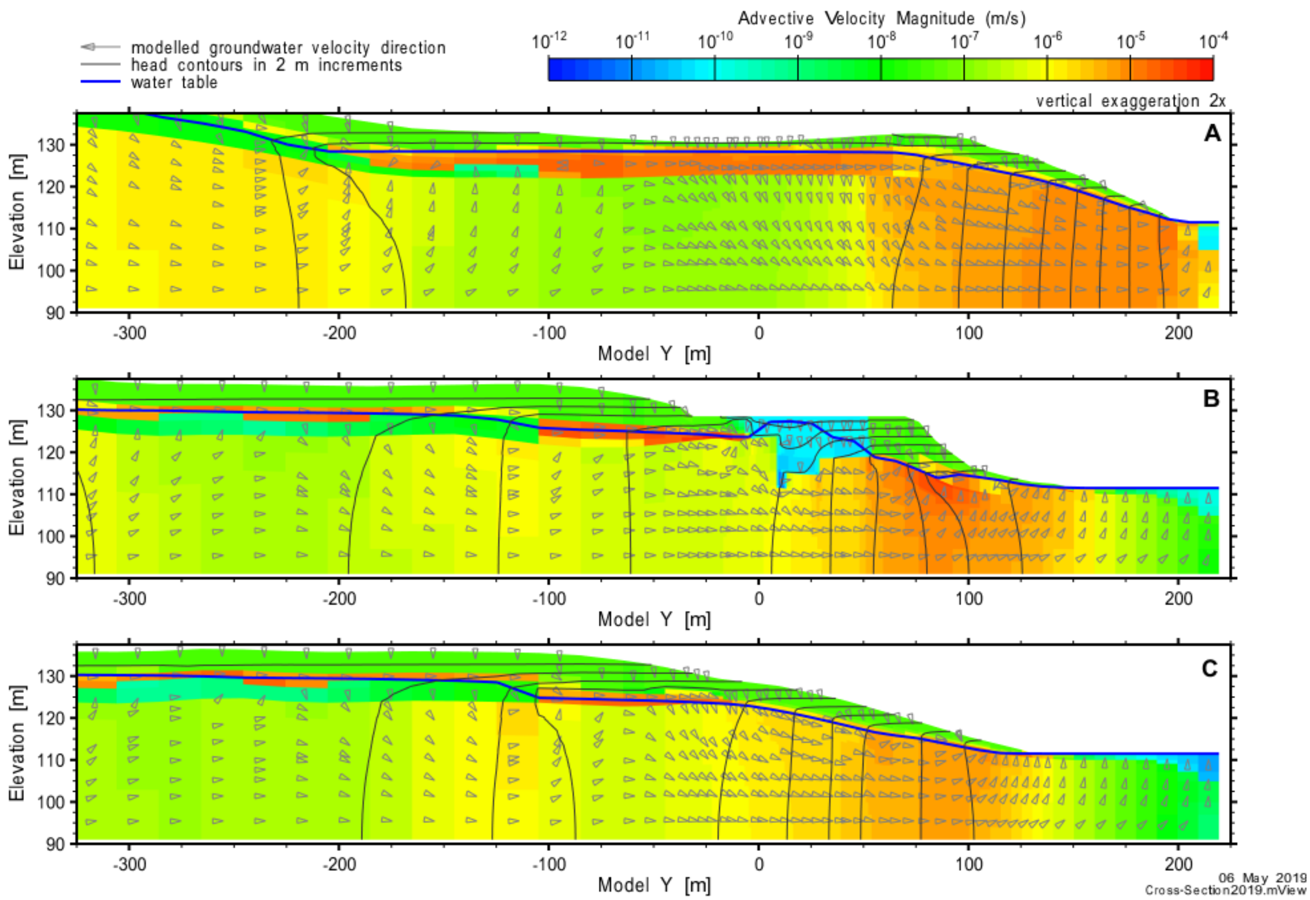


Figure 3.14 Groundwater Head Contours, Linear Groundwater Velocity Magnitude and Direction and Water Table for Hydrogeologic Model

The bulk of the groundwater flows in the area surrounding the facility flows through the overburden and flows out through the tile drains. The amount of groundwater flowing through the bedrock in the area surrounding the facility is approximately two orders of magnitude less the volume flowing through the overburden and tile drains. Groundwater flowing into the facility itself is governed by the hydraulic conductivity of the concrete walls and grout, and consists mainly of the infiltration into the facility, which was calculated in resaturation modelling to be approximately 1 mm/yr. Approximately half of the water infiltrating into the building leaves the building at the overburden horizon. The remainder percolates through the building and leaves at bedrock horizons.

Sensitivity cases were also conducted to examine the impact on groundwater flows of the degradation of the facility materials, the effect of a seismic event on facility materials and failure of the tile drains. General conclusions of these sensitivity cases are that the facility hydraulic conductivity has little impact on the groundwater flows in the general area of the facility. Only failure of the tile drains had any substantive impact on groundwater flows in the general area of the facility, resulting in springs along the bluff face downgradient of the facility and reducing groundwater flow in the area surrounding the facility by approximately 45%.

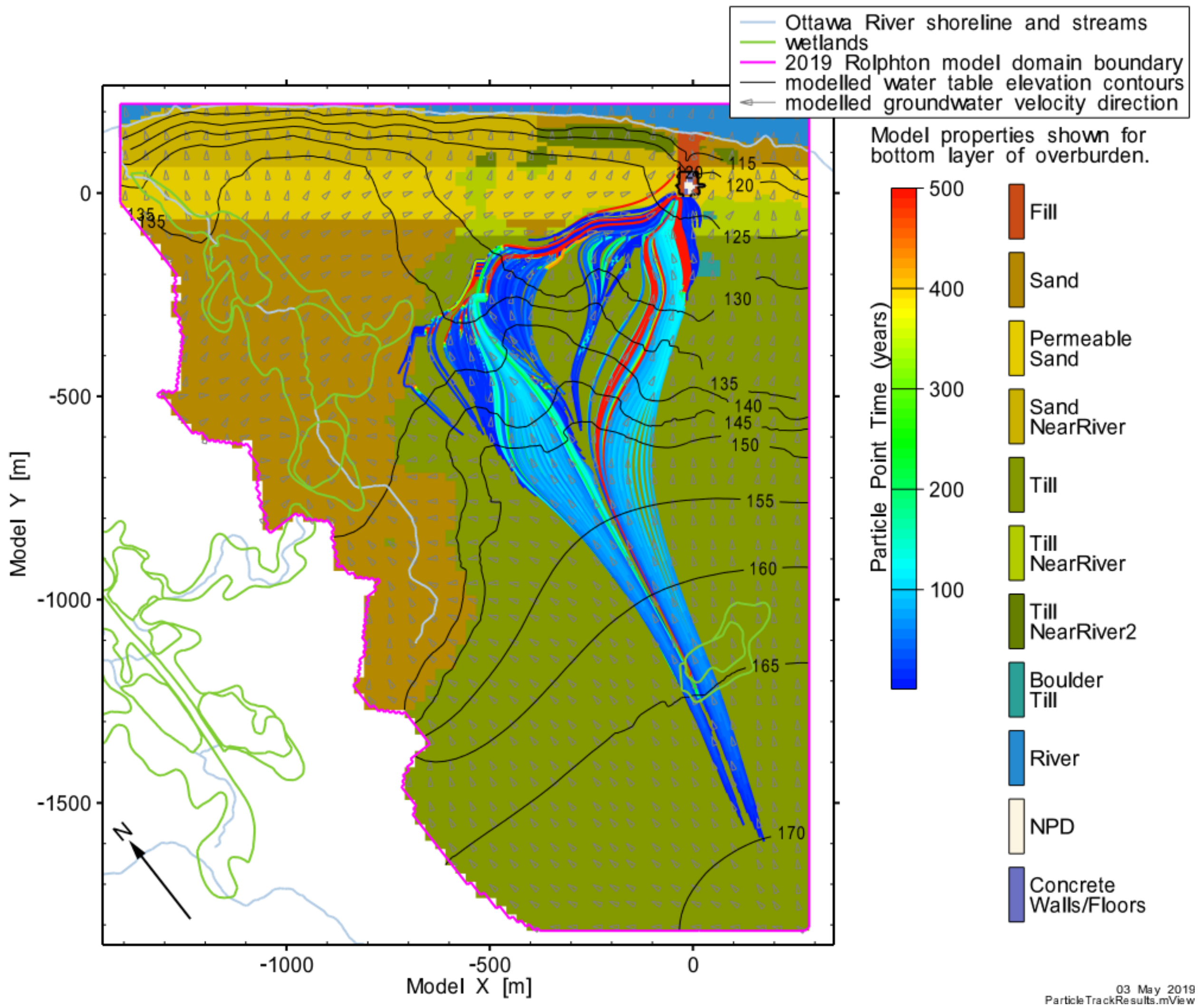


Figure 3.15 Particle Tracks Illustrating Capture Zone of the NPD Facility Tile Drains

3.8.4 Uncertainties

The presence and hydrogeological properties of the permeable fluvial sand and gravel layer that sub-parallels the Ottawa River and extends tile drain capture of overburden groundwater northwest of the NPDWF is identified as an uncertainty in modeling of groundwater flow at the NPDWF site.

There is a paucity of full-depth overburden drilling and monitoring well results in the area northwest of the NPDWF to Landfill 2 that prevents accurate mapping and description of the hydrogeological properties of the assumed permeable fluvial sand and gravel layer. While there is compelling indirect information to support the presence of this inferred drain extension layer (see third paragraph on page 105 of Section 3.8.2), there is no direct drilling data to prove its existence. Additionally, the documented dewatering of surface water (ponds, marshes) in this area during NPD construction and the very high K intervals (K= 1-2E-03 m/s) observed at the top of bedrock and top of boulder till proximate to the tile drain support the existence of this permeable unit that extends tile drain capture northwest of the NPDWF.

Uncertainty in the extent and hydrogeological properties of the fluvial sand and gravel layer located northwest of the NPDWF will have a negligible effect on the rate and location of overburden groundwater discharge from the NPDWF to the Ottawa River and hence the NPD closure and post-closure phases. Resolving the uncertainty on the location and hydrogeological properties of this fluvial sand and gravel layer would enhance the confidence in the 3-D groundwater flow model and the volumes of tile drain water, but that uncertainty primarily concerns the completeness of the site characterization work and not the fate of overburden groundwater discharge from the NPDWF to the Ottawa River.

3.9 Descriptive Hydrogeological Framework

The above information on conceptual groundwater flow systems in the Canadian Shield, hydrogeological investigations of the NPD site, hydrostratigraphic units, hydrogeochemistry and groundwater quality, local groundwater flow systems, potable water supplies, and hydrogeological modeling are used to interpret and develop a descriptive hydrogeological framework for the NPDWF site and surrounding area. The descriptive hydrogeological framework of the NPDWF site includes the following key elements and information:

1. Groundwater flow systems in the sediments and bedrock at the NPD site can be broadly categorized into regional, intermediate and local systems. Regional groundwater flow systems in such Shield terrain exist in deep bedrock and will be bounded by major topographic highs and lows and influenced by geological conditions, including presence of major structural features such as faults, dykes and shear zones. Regional topographic highs exist beyond the NPD property to the southwest and likely extend to the highlands of Algonquin Park. Regional groundwater flow will occur within the deep bedrock (>150 m deep) on the NPD site with direct discharge to the Ottawa River via upward flow along the geological structure associated with the Mattawa Fault below the Ottawa River.

2. Local groundwater flow systems, and to a lesser degree intermediate groundwater flow systems at the NPD site are influenced by recharge rates, topography and geology. Local groundwater flow systems within the permeable sand and gravel overburden will be the dominant groundwater system at the NPDWF site. These local groundwater flow systems will likely be recharged near Highway 17 and without the tile drain would discharge along the ground slope extending northeast to the Ottawa River and directly to the Ottawa River. Local flow also occurs within shallow bedrock likely to depths of about 30 to 50 m; however, these flow rates are typically a small percentage of flow rates in the overlying sandy deposits.

3. Intermediate groundwater flow systems will exist between the regional and local groundwater flow systems described above. Intermediate groundwater flow systems will likely exist at the NPD site between topographic highs located southwest of Highway 17 near Tee Lake with discharge to the Mattawa Fault and the Ottawa River. These intermediate flow systems will likely extend to depths of about 50 to 150 m based on available groundwater chemistry data and the elevation changes between bedrock near Tee Lake and the Ottawa River (~ 100 m).

4. The available geological and hydrogeological data for the NPD site supplemented by similar regional information from the CRL property and surrounding area indicate that the hydrogeology of the

NPDWF site is conveniently described with reference to five hydrostratigraphic units. The five hydrostratigraphic units at the NPDWF site are: sand and gravel fill unit, fluvial sand and gravel unit, silt to cobble glacial till unit, boulder glacial till unit and shallow bedrock unit.

5. The sand and gravel fill hydrostratigraphic unit including reworked fluvial deposits and excavated bedrock is the youngest hydrostratigraphic unit. It is present near the NPD buildings and in the area northeast of the buildings that were subject to excavation for construction of water intake and discharge lines and tile drainage lines between the buildings and the Ottawa River. Fill thickness at the NPD site is variable ranging from about 2 m near the Ottawa River to about 5-6 m near the NPD building.

   Based on final 2019 groundwater model calibration, the best estimate for hydraulic conductivity of the sand and gravel fill hydrostratigraphic unit is 3.4E-04 m/s increased from an initial pre-modeling estimate of 1.0E-04 m/s. Lacking other information, the sand and gravel fill unit is assumed to be isotropic with porosity of 0.3 and specific storage of 1.0E-05 m^{-1}.

6. The fluvial sand and gravel hydrostratigraphic unit is the most widespread overburden unit at the NPD site and is the youngest hydrostratigraphic unit consisting of native material. It includes sand with various amounts of gravel, boulders and trace amounts of silt. The thickness of this hydrostratigraphic unit averages 5 m to 10 m at the NPD site. It extends southwest from NPDWF toward Highway 17 (to about BH18-02), northwest to at least Landfill 2 (NPD-14) but is limited to the southeast of NPDWF by the bedrock high at BH18-06. Based on on-site hydraulic conductivity measurements, the fluvial sand and gravel unit is heterogeneous, with a wide range of conductivity (2.0E-07 to 1.0E-03 m/s).

   The 2019 final groundwater model calibration shows that the best estimates for horizontal hydraulic conductivity of the fluvial sand and gravel hydrostratigraphic unit are between 2.4E-05 and 1.0E-03 m/s with an anisotropy ratio (K_h/K_v) of 3.9 reflecting the presence of lower hydraulic conductivity silt layers. The range of hydraulic conductivity in the 2019 groundwater flow model reflects the three regions of sand used for model calibration. Fluvial sand and gravel unit porosity is 0.4 and specific storage is 1.0E-05 m^{-1}.

7. The silt to cobble glacial till hydrostratigraphic unit is the most widespread overburden hydrostratigraphic unit at the NPD site. It is found at ground surface near Highway 17 and at depth below the fluvial sand and gravel hydrostratigraphic unit northeast of Highway 17 on the NPD site. The upper metre or so of the silt to cobble glacial till unit has been locally subject to fluvial erosion by wave action resulting in a texture and likely hydraulic conductivity similar to the overlying fluvial sand and gravel unit. The thickness of the silt to cobble glacial till unit ranges from 0 to 2 m near NPDWF up to 5 to 10 m northwest and southeast of NPDWF. Available hydraulic testing suggest two sets of K values are necessary to represent silt to cobble glacial till. Testing completed at borehole NPD-5 and MW18-01 to MW18-04 indicate geometric mean K of 3.3E-08 m/s that is considered representative of a silty sand member located southwest of MW18-03 and MW18-04. A K value range of 2.0E-05 to 2.0E-04 m/s is used as the best estimates of hydraulic conductivity for the sand to cobble till member in the vicinity of NPDWF from site characterization recognizing the

potential for presence of metre thick layers with elevated K that are likely glacial-fluvial washed beach deposits.

The 2019 final groundwater model calibration indicates a K range of 2.0E-08 to 2.9E-04 m/s for the silt to cobble glacial till hydrostratigraphic unit with higher values near the NPDWF and the Ottawa River. All till K estimates are assumed to be isotropic. Silt to cobble glacial till porosity is 0.3 and specific storage is 1.0E-05 m^{-1}.

8. The boulder glacial till hydrostratigraphic unit is the oldest overburden unit at the NPD site and locally directly overlies competent bedrock in areas of bedrock depression. It consists of metre-size boulders with granular matrix material and underlies silt to cobble glacial till and fluvial sand and gravel where the silt to cobble till is absent. It is found northwest and southwest of the NPDWF based on intersections with BH18-03, BH18-05, BH18-09 and BH18-10 with thicknesses of 2 to 5 m. Hydraulic testing data suggest the best estimate of hydraulic conductivity for the boulder till as 1.7E-05 m/s, recognizing the potential for inclusion of sub-metre thick higher K gravel and cobble layers with K up to 1.7E-03 m/s.

   The 2019 final groundwater model calibration indicates hydraulic conductivity of 1.8E-05 m/s for the boulder glacial till hydrostratigraphic unit, essentially the same as the best estimate from site characterization. The boulder till is assumed to be isotropic with respect to K. Boulder glacial till porosity is 0.3 and specific storage gravel is 1.0E-05 m^{-1}.

9. The shallow bedrock hydrostratigraphic unit at bedrock depths of 0 to 50 m is the only bedrock unit considered for the NPDWF site based on the relatively shallow excavations completed for construction of the NPD (about 18 m into rock) and the assumption that essentially all of the local groundwater flow in bedrock will occur in the upper 50 m of bedrock. Continuous profiles of straddle-packer hydraulic testing completed in the four shallow bedrock boreholes BH18-05 to BH18-08, indicate an overall geometric mean horizontal K of 1.7E-07 m/s based on a range of measurements of 2.8E-09 to 6.6E-06 m/s. As the hydraulic conductivity of intact bedrock is several orders of magnitude lower than the lowest K value measured from straddle-packer testing, all of the reported K values are attributed to the presence of fractures, either as individual discontinuities or as part small fracture zones. Given the ubiquitous occurrence of small-scale fractures and fracture zones, the bedrock in groundwater flow models is represented as an equivalent porous media (EPM) with spatially-variable, isotropic representation of the rock mass K.

   The majority of intervals with elevated hydraulic conductivity (i.e., >~ 1.0E-06 m/s) correlate with specific subhorizontal and subvertical open fractures and metre- and sub-metre-scale fracture zones. The best initial estimates of hydraulic conductivity in shallow bedrock at the NPD site are 7.3E-08 m/s near BH18-05, BH18-06 and the NPDWF, and 3.6E-07 m/s near BH18-07, BH18-08 and below the Ottawa River. Based on the frequency and orientation of borehole and outcrop fractures the shallow bedrock K is isotropic. The spatial variability of K correlates with observed increases in fracture frequency and decreases in RQD with proximity to the Ottawa River. These spatial trends most likely reflect attendant fracturing related to the regional Mattawa Fault that defines the course of the Ottawa River.

The 2019 final groundwater model calibration indicates hydraulic conductivities of 3.3E-07 and 9.3E-08 m/s for the shallow bedrock hydrostratigraphic unit near and away from the Ottawa River, respectively. These model K values are essentially the same as the best estimates from site characterization. Best estimate of specific storage of 1.2E-06 m^{-1} is recommended for shallow bedrock at the NPD site based on 2019 hydraulic testing. Best estimate of porosity, for the moderately fractured and fair to good rock quality shallow bedrock is 0.005.

10. Shallow overburden groundwater is dilute (total dissolved solids [TDS] of 100 to 200 mg/L), Ca-HCO_3 type with Na-Cl/SO_4 as subordinate major ions. The NaCl signature likely reflects road salting of upgradient Highway 17 and NPD site roads. The shallow overburden groundwater is moderately oxidizing as evident by low iron concentrations (about 10 to 100 µg/L) and for Landfill 2 Eh of 200 to 530 mV. Deeper overburden groundwater from depths of 12 to 20 mBGS is less dilute (total dissolved solids [TDS] of 210 and 545 mg/L), Na-HCO_3 type with Ca-Cl/SO_4 as subordinate major ions. The elevated TDS and NaCl/SO_4 signature relative to shallow overburden groundwater analyses likely reflects road salting of upgradient Highway 17 and NPD site roads (NaCl), deeper sampling intervals and influence of shallow bedrock groundwater (SO_4). Compared to shallow overburden groundwater, deeper overburden groundwater is slightly less oxidizing as evident by slightly higher iron concentrations (81.5 and 168 µg/L) and Eh of 343 and 332 mV. Tritium, gross alpha activity and gross beta activity are generally low in overburden groundwater. Only gross alpha activity at MW19-09 in deep overburden groundwater (1.1 Bq/L) slightly exceeded Health Canada drinking water guidelines or screening levels (0.5 Bq/L).

11. Shallow bedrock groundwater in proximity to the NPDWF is dilute (TDS of ~200 to 925 mg/L), predominantly Na-HCO_3 type with Ca-Cl/SO_4 as subordinate major ions. Locally near MW18-06-P4, MW18-06-P6 and MW18-07-P7 the shallow bedrock groundwater is Na-SO_4 type with Ca-Cl/HCO_3 as subordinate major ions. Near MW18-07-P1 and MW18-07-P2 the shallow bedrock groundwater is Ca-HCO_3 type with Na/Mg-Cl/SO_4 as subordinate major ions. Compared to inferences from CRL data, the 2019 shallow bedrock groundwater at NPD is slightly more oxidizing as evident by lower iron concentrations (<5 to 35 µg/L) and Eh of 321 to 412 mV. Relatively elevated tritium concentrations (650 to 1350 Bq/L) are reported near MW18-05 and MW18-06 upgradient of the NPDWF. Downgradient of the NPDWF at MW18-07 and MW18-08 tritium concentrations are lower at <100 to 190 Bq/L. Gross alpha and gross beta activity in shallow bedrock range from 0.11 to 3.6 Bq/L and <0.10 to 3.7 Bq/L, respectively. The cause of the elevated tritium concentrations in shallow bedrock upgradient of the NPDWF is not known.

12. The relatively wide range of shallow bedrock groundwater chemistries suggests that some CMT monitoring intervals are influenced by residual drilling water used for bedrock coring which was mostly Ottawa River water. Given the very dilute chemistry in Ottawa River water, the reported 2019 chemistry of many of the shallow bedrock monitoring intervals may be underestimated. Subsequent groundwater sampling of the shallow bedrock is necessary to confirm this suggestion and representativeness of the 2019 data for shallow bedrock groundwater.

13. The major ion and trace element chemistry and radiological chemistry of the tile drain water, as reported from sampling in 1990, 2014 and 2019, are very similar to shallow overburden groundwater at the NPDWF site. This similarity and plotting of major ion chemistry of tile drain water and other

water types at the NPD site on Piper diagrams shows that groundwater from the area of Landfill 1 and the reactor area are the most likely sources of water to the tile drains. This is entirely reasonable as these two groundwater types are in close proximity to the tile drains or are clearly upgradient of the tile drains. Piper diagrams also show that upper and lower shallow bedrock groundwater and Ottawa River water are not sources of water to the tile drains.

14. Groundwater flows in the saturated sand and gravel fill, fluvial sand and gravel and glacial till hydrostratigraphic units are predominantly from southwest to northeast across the NPD site toward the tile drains and the Ottawa River. Groundwater flow via the sand and gravel backfill of the pumping intake and discharge line bedrock excavations is also a potentially important flow pathway for the NPD site under high water table conditions. For shallow bedrock, the predominant groundwater flow direction assuming a lack of major structural features such shear zones and faults is also from southwest to northeast toward the Ottawa River.

15. Recharge of the local groundwater system at the NPDWF site occurs primarily in the highland area northeast and southwest of Highway 17 where glacial till is exposed at surface. Some recharge also occurs on the upslope areas of the site between Highway 17 and Landfill 1 and near Landfill 2 where permeable alluvial (fluvial sand and gravel) deposits are exposed at surface. Groundwater discharge areas as springs and wetlands were historically noted on the overburden ground slopes northwest of NPDWF and between the area of the NPDWF and the Ottawa River prior to NPD construction. These springs are no longer observed at the site due groundwater collection by the tile drains.

    A large portion of groundwater southwest and west of the NPD building, at least as far as Landfill 1 and likely upgradient of Landfill 1 and toward Landfill 2 discharges to the tile drain system that was trenched into the surface of the bedrock, surrounds the NPD reactor building and drains into the Ottawa River. Groundwater flow in the underlying shallow bedrock discharges upward to the overlying overburden in the area upgradient of the NPDWF, but mostly discharges to the Ottawa River either directly or via the Mattawa Fault that defines the course of the Ottawa River.

16. Linear groundwater velocities calculated from Darcy's Law for the sand and gravel fill unit and fluvial sand and gravel unit are comparable at about 1.7 to 3.4 m/day, whereas linear groundwater velocities in the sand, gravel and cobble member of silt to cobble glacial till unit and boulder glacial till unit are lower to comparable at 0.23 to 2.6 m/day. The lowest calculated linear groundwater velocities are within the silty sand member of the silt to coble glacial till unit at 0.00070 m/day. For shallow bedrock, the calculated velocities are for homogeneous fractured bedrock without major structural features such as shear zones and faults, and range from 0.057 to 0.28 m/day.

17. Groundwater interactions with surface water at NPD site occur via direct discharge and via groundwater flow. The tile drain systems installed in shallow bedrock around the NPD building collect and directly discharge overburden groundwater to the Ottawa River. Groundwater in overburden and in shallow bedrock also discharges to the adjacent Ottawa River via groundwater flow. For overburden groundwater, the discharge is likely directly to the Ottawa River via the sand and gravel fill and fluvial sand and gravel hydrostratigraphic units. The volume of overburden groundwater discharged via groundwater flow is likely to be much less than that from the tile drains

due to upgradient interception of overburden groundwater by the tile drains. For shallow bedrock, the discharge pathway is most likely via upward flow in the steeply dipping Mattawa Fault that underlies the Ottawa River. The shallow bedrock groundwater discharge to the Ottawa River is a small percentage of that discharged directly via the tile drains.

18. Potable water supplies in the nearby communities such as Rolphton, Meilleurs Bay and Rapides des Joachims are sourced from domestic groundwater wells and in all likelihood will continue to be so in the future. The majority of potable water supplies in the area of Ontario surrounding the NPDWF site are developed from bedrock wells installed to maximum depths of about 190 m, although some shallower overburden water supply wells are identified in the MEPC groundwater well records. This is typical for most communities located on the Canadian Shield.

4 GEOMECHANICAL FRAMEWORK

4.1 Introduction

The geomechanical framework for the NPDWF site is based on historical site investigation and site characterization work completed at the CRL site, local site characterization work completed in support of the NPD construction and the nearby Rapides des Joachims power site summarized in the Report on Rock Conditions prepared by the Hydro-Electric Power Commission of Ontario (1943), and 2019 geoscientific characterization of the NPD site.

As described in preceding sections, specifically Section 2, the geological and lithostructural framework for the NPD site is similar to the CRL site; therefore, it is reasonable and appropriate to incorporate CRL site geomechanical data into the NPDWF geomechanical framework.

2019 geomechanical investigations of the NPD site were completed as part of geoscientific characterization of the NPD site (Geofirma Engineering Ltd., 2019a). These investigations focused on geomechanical characterization of the shallow bedrock to depths of 50 m below competent bedrock surface in the vicinity of the NPDWF.

4.2 Overburden Geotechnical Properties and Hazards

The native overburden at the site, as described in Section 3.3, is comprised of fluvial sands and gravels and fills around the building and along the shoreline, and silt, sand, cobble, and boulder glacially deposited till upgradient (Hydro-Electric Power Commission of Ontario, 1956; Killey and Munch, 1988; 1989; Killey 2014; MacLarentech Inc., 1990; Geofirma Engineering Ltd., 2019).

Historical NPD site characterization work included advancement of several boreholes around the main reactor building at the site (MacLarentech Inc., 1990). It was noted that the area surrounding the reactor building was subject to infilling with approximately 5 m of bouldery sand fill (of glacial origin) during construction. Based on geological cross sections constructed by Hydro-Electric Power Commission of Ontario (1956), Killey and Munch (1988; 1989), and MacLarentech Inc. (1990), and shown in Figures 2.5 and 2.6 of this report, overburden thickness at the NPD site ranges from about 2 m near the Ottawa River to greater than 15 m, generally increasing in thickness to the southwest.

Site stratigraphy can be characterized by topsoil/fill, underlain by a fluvial sand and gravel unit consisting of gravelly sand, massive coarse sand, and fine to medium sand with coarse sand laminations. Glacial till was encountered underlying the fluvial sand and gravel unit, and consists of boulders, cobbles and sand, with trace fine sand and silt (MacLarentech Inc., 1990). Shallow groundwater at the NPDWF site was encountered in the fluvial sand and gravel overburden unit, approximately 10 m below ground surface south of the NPD reactor building (MacLarentech Inc., 1990). Shallow groundwater flow generally follows topography and discharges to the NPDWF tile drains and the Ottawa River to the northeast.

Geotechnical hazards at the NPDWF site are predominantly related to earthquake-induced liquefaction of saturated homogeneous granular soils, soil erosion and instability of ground slopes located northeast of NPDWF to the Ottawa River. Arcadis Canada Inc. (2021) provides an assessment of earthquake-induced soil liquefaction and slope stability of the NPDWF site.

4.2.1 Grain Size Analyses

Grain size distribution of overburden is an important property for assessing and understanding the overburden performance under external impacting factors, such as their erosion potential and liquefaction potential. The Slope Stability Assessment Report (Arcadis Canada Inc., 2021) provides grain size distribution data and curves for overburden units at the NPDWF site based on testing of 11 archived soil samples collected during 2018 site investigations. In selecting samples for grain size analysis, primary preference was given to deep saturated soil samples near the slope from the NPDWF to the Ottawa River (North Slope) to assist in liquefaction assessment of soils that comprise the North Slope with secondary preference for saturated soils representative of soil types found elsewhere on the NPDWF site.

Archived samples of fluvial sand and gravel, sand and gravel till and boulder till historically collected from boreholes completed southwest of the North Slope and the NPDWF building were submitted for grain size analyses. No samples of granular fill were collected for grain size analyses as the volume of saturated granular fill at the NPDWF site is quite limited.

The results of the grain size analyses (see Table 4.1) confirm that all soils at the NPDWF site are predominantly coarse granular materials, with soil textures of fine to coarse sand, with fine to coarse gravel. As shown on Table 4.1, the grain size analyses are consistent with the field descriptions of texture as sand and gravel with cobbles and boulders, given the inability of soil sampling equipment to collect representative samples with cobbles and boulders.

Table 4.1 Summary of NPDWF Soil Samples Submitted for Grain Size Analyses

Sample ID	*Sample Depth (mBGS)*	*Field Description*	*Hydrostratigraphic Unit*	*Soil Texture Description from Grain Size Analyses*
BH18-03-SS-2	6.63 to 7.24	Sand and gravel, 6” cobbles in coarse sand matrix	Fluvial Sand and Gravel	Fine to medium sand with trace of gravel
BH18-04 CR-3	5.33 to 6.86	Coarse sand with some cobbles	Fluvial Sand and Gravel	Medium to coarse sand
BH18-05 CR-7	9.14 to 10.67	Sand with cobbles	Fluvial Sand and Gravel	Medium to coarse sand
BH18-09 CR-8	11.46 to 12.98	Coarse sand with trace of silt	Fluvial Sand and Gravel	Medium sand
BH18-10 CR-2	2.32 to 3.84	Coarse sand	Fluvial Sand and Gravel	Medium sand
BH18-02 CR-6	8.03 to 9.75	Silty sand with gravel and cobbles	Sand and Gravel Till	Fine sand with coarse gravel
BH18-03 CR-6	9.91 to 11.43	Silty sand with 6“ cobbles	Sand and Gravel Till	Fine sand with fine gravel
BH18-09 CR-9	12.98 to 14.51	Coarse sand with cobbles and boulders	Sand and Gravel Till	Medium sand with fine gravel
BH18-03 CR-7	11.43 to 12.19	Sandy silt with 60% cobbles and boulders	Boulder Till	Fine sand with coarse gravel
BH18-09 CR-13	19.08 to 20.60	> 2m boulders with silty sand	Boulder Till	Medium sand with fine gravel
BH18-10 CR-10	8.23 to 9.75	80% boulders with silty coarse sand	Boulder Till	Fine to medium sand with coarse gravel

4.2.2 Standard Penetration Tests

Standard penetration test (SPT) N-values in the granular soils range from 11 to 50, indicating compact to very dense overburden conditions. There are no reported N-values in the glacial till; however, it is anticipated that till compactness conditions would be dense to very dense. Table 4.2 presents an estimate of the material properties under drained conditions. Given the soil units at the site are granular (i.e., cohesionless and well-draining), there will be negligible difference between the static and dynamic material properties. Static properties are those strength properties (cohesion, internal friction) that are used in non-seismic static loading slope stability assessments. Dynamic properties are those strength properties (cohesion, internal friction) that are used in seismic dynamic loading slope stability analyses.

Table 4.2 Preliminary Estimates of Overburden Geotechnical Material Properties

Overburden Unit	***Bulk Unit Weight (kN/m^3)***	***Effective Cohesion (kPa)***	***Effective Internal Friction Angle, Φ (degrees)***
Sand	17 - 21	0	30 - 40
Gravelly Sand	17 - 21	0	30 - 40
Glacial Till	19 - 22	0	30 - 35

Source: City of Ottawa Slope Stability Guidelines for Development Applications (2012) and Ministry of Natural Resources, Geotechnical Principles for Stable Slopes (1998).

4.2.3 Soil Liquefaction

Liquefaction is the process by which soils below the water table temporarily lose strength as a result of the application of earthquake-induced cyclic shear stresses and behave as a viscous liquid rather than a soil. This loss of shear strength or internal friction between soil grains can be caused by soil grain rotation and/or densification that results in increases in pore pressure resulting in reduction of effective stress. Soils most susceptible to liquefaction are loose, uniformly graded, clean sands and silty sands.

Assessment of the likelihood of liquefaction at the NPDWF site in response to earthquakes was undertaken both qualitatively and quantitatively in accordance with guidance provided in the geotechnical literature (Arcadis Canada Inc., 2021). Design basis earthquakes considered in the soil liquefaction assessment are those given in Table 5.3 of Section 5.2.5 and include event with earthquake probability of 1:2,250, 1:10,000 and 1:50,000 years.

The results of the liquefaction assessment indicate that the fluvial sand and gravel at borehole MT-1 is considered to be susceptible to liquefaction during the 1:10,000-year and 1:50,000-year events. The silt to boulder till as measured at borehole MT-5 may be susceptible to liquefaction during the 1:50,000-year earthquake event. Given the likely variability in relative density and properties of these soils across the site and that the assessment method is based on typically smaller earthquake events, these results are considered preliminary and screening-level for the significantly larger shaking of the 1:10,000-year and 1:50,000-year earthquakes.

4.2.4 Slope Stability

To assess stability of the overburden slope located north of the NPDWF to the Ottawa River (the North Slope), two stratigraphic cross sections (C-C' and D-D') were constructed based on results of available overburden drilling and soil sampling and elevation surveying of ground surface at drilling locations. Cross sections A-A' and B-B' were constructed following the same methods used to create site-wide cross sections A-A' and B-B' described in Section 2.3.2. Figure 4.1 shows the location of the two cross sections and the drilling and soil sampling data used to construct the two cross sections. Figure 4.2 shows the soil and bedrock stratigraphy of cross sections C-C' and D-D' of the North Slope.

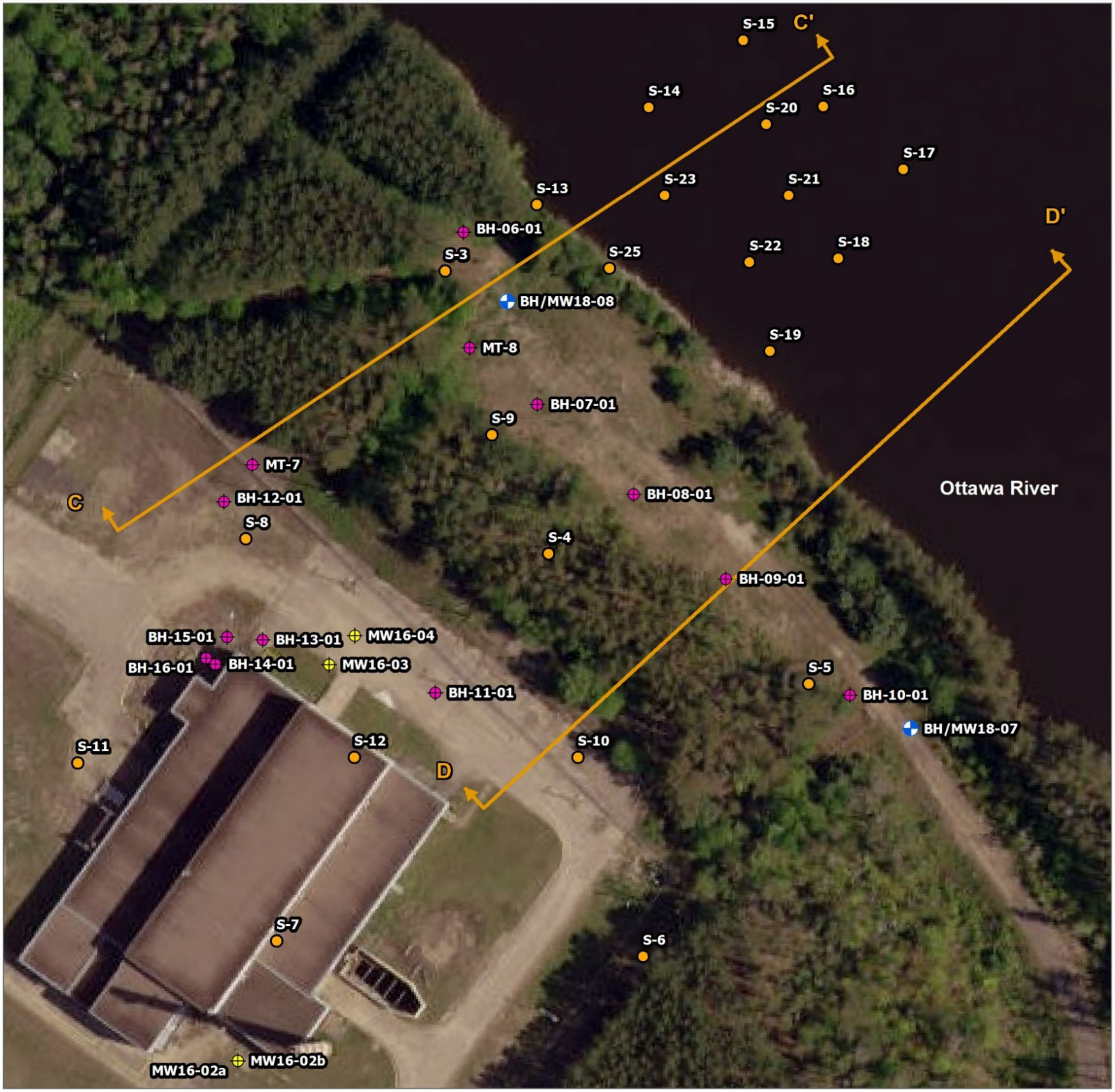
Boreholes used to construct each cross section are shown across the top of each cross section. Both cross sections are constructed with vertical exaggeration of 3.85 times the horizontal scale and extend from the flat area near the NPDWF building into the Ottawa River. Cross section C-C' includes a soil profile of sand and gravel fill and fluvial sand and gravel over silt to boulder till over crystalline bedrock. Cross Section D-D' includes a soil profile of sand and gravel fill over fluvial sand and gravel over crystalline bedrock. Average slopes in cross sections C-C' and D-D' approximate 16° and 23°, respectively, from horizontal.

Slope stability was evaluated for slopes C-C' and D-D' using the SLOPE/W code as described in Arcadis Canada Inc. (2021). Factors of Safety against slope failure were calculated using limit equilibrium analyses for static (non-earthquake) conditions and pseudo-static conditions for 1:2,250-year, 1:10,000-year and 1:50,000-year earthquake events.

The results of the slope stability assessments using the SLOPE/W code are given in Table 4.3; this Table summarizes the results of slope stability assessments as factors of safety. Acceptable factors of safety are different for static and pseudo-static loading conditions based on the degree of conservatism inherent in the assumptions used to assess slope stability. Based on industry practice and guidance a safe factor of safety for static (non-seismic) loading is 1.3. For seismic loading conditions a safe factor of safety is 1.0 to 1.1. Factors of safety less than safe thresholds indicate a potential for slope instability to occur.

Table 4.3 Summary of Factors of Safety Against Slope Failure Based on SLOPE/W Modeling

Loading Condition	***Cross Section C-C'***	***Cross Section D-D'***
Static (Non-Seismic)	3.5	2.1
Pseudo-Static (1:2,250-Year Earthquake)	2.1	1.4
Pseudo-Static (1:10,000-Year Earthquake)	1.2	**0.9**
Pseudo-Static (1:50,000-Year Earthquake)	**0.2**	**0.4**
Bold: Factor of Safety less than safe thresholds of 1.3 for Static; 1.1 for Pseudo-Static loading		



LEGEND

Boreholes and Monitoring Wells

- Geofirma Overburden and Bedrock
- Golder
- MacLarentech / J.D. Paterson
- Preconstruction Diamond Drill Hole
- Cross Section

Figure 4.1
Locations of Boreholes, Monitoring Wells, and Stratigraphic Cross Sections at North Slope

SCALE 1:1,000

0 5 10 20 30 40
Meters

N

Coordinate System: NAD 1983 UTM Zone 18N
Source: MNR, GeoBase Ontario, several historical reports for the site, NHIC air photo

PROJECT No. 16-212

Updated Geosynthesis - Rolphton NPDWF EIS

DESIGN: ADG
CAD/GIS: ADG
CHECK: KGR
REV: 0

DATE: 2021-11-12

Geofirma Engineering Ltd

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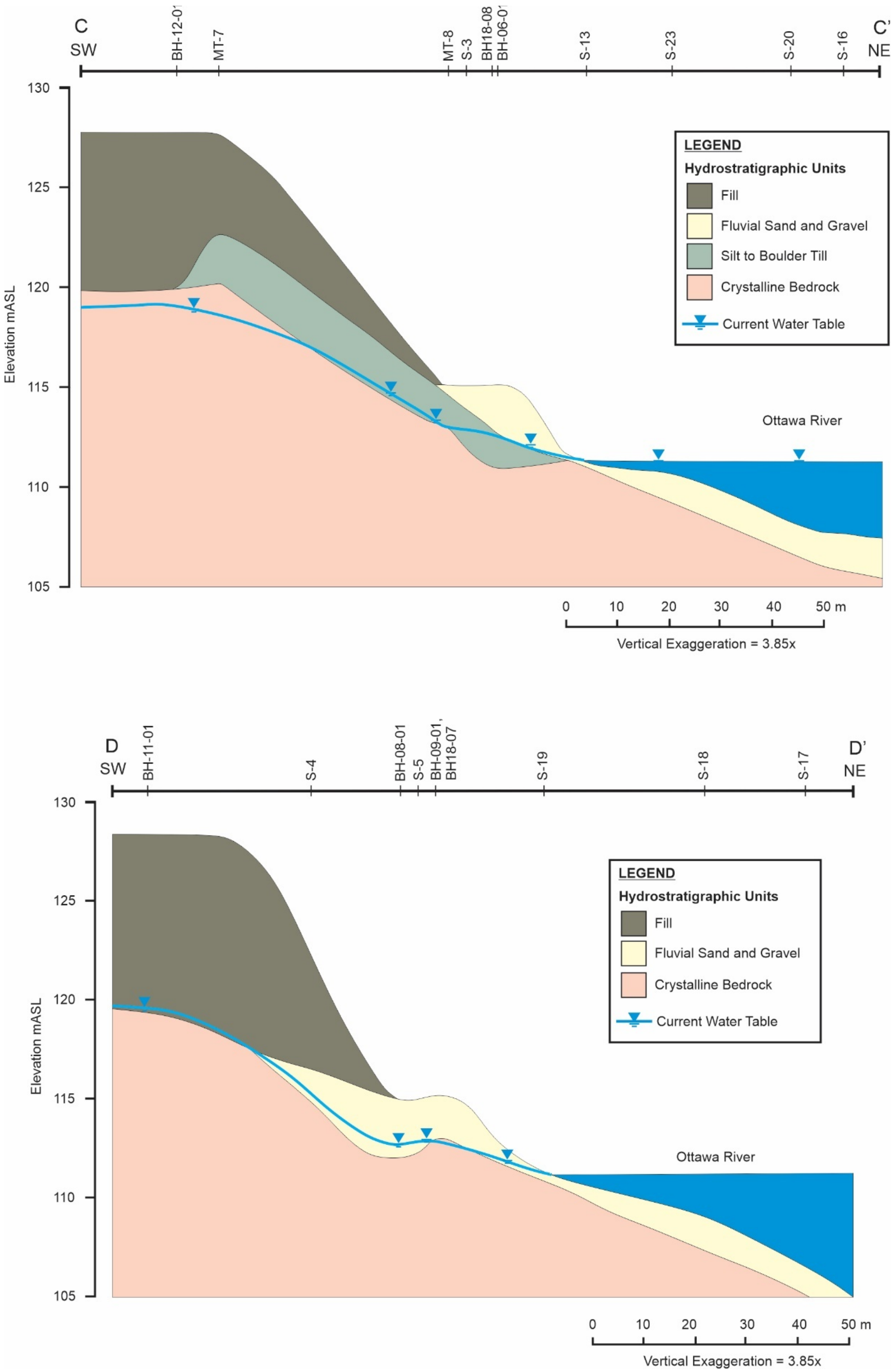


Figure 4.2 Stratigraphic Cross Sections C-C' (above) and D-D' (below) at North Slope

The results of this preliminary slope stability assessment that considers earthquake-induced soil liquefaction, show that the North Slope under current water level conditions is stable under static loading conditions and under loading conditions associated with a 1:2,250-year earthquake. Parts of the North Slope (cross section C-C') are stable, and parts of the North Slope (slightly steeper slope of cross section D-D') are unstable under a 1:10,000-year earthquake. The North Slope is likely to fail during a 1:50,000-year earthquake.

It is unlikely that the predicted failures of the North Slope at cross section C-C' and D-D' will result in groundwater flow changes from the NPDWF to the Ottawa River or direct exposure of groundwater to a new ground surface that would be established following earthquake induced slope failures.

The NPDWF building is founded on bedrock. Although this bedrock is sparsely to highly fractured, it is suitable as a foundation for the building (Canadian General Electric Company Ltd., 1962). Bearing capacity is not a concern for the building foundations.

4.2.5 Uncertainties

Due to limited overburden sampling and geotechnical testing on the North Slope there is uncertainty in the results of the earthquake-induced soil liquefaction and slope stability assessments. The results of the current slope stability assessment are based on available information from historical investigations and testing of archived soil samples much of it remote from the actual North Slope. Given the limited information on material properties within the North Slope, material properties for the North Slope were conservatively selected based on extrapolations from areas southwest of the NPDWF building. The results of the liquefaction and slope stability assessments are preliminary and intended to provide a screening-level evaluation of the North Slope.

Should a more rigorous and reliable liquefaction and slope stability assessment be required to refine current results, it is recommended that additional boreholes and associated lab testing be completed. Such additional field and lab testing should include ground surface elevation profiling, continuous SPT testing and soil sampling/grain size analyses in boreholes intersecting the sand and gravel fill, fluvial sand and gravel and silt to boulder till at the crest, mid-height and toe of cross sections C-C' and D-D' of the North Slope. If such supplementary investigations are undertaken, it would also be prudent to assess the effects of tile drain failure on groundwater levels and stability of the North Slope under conditions of expected higher groundwater levels. Higher groundwater levels are expected to result in increased potential for liquefaction and slope instability.

4.3 Intact Rock Properties

Data on intact geomechanical properties of the bedrock at the NPDWF site are available from 2019 uniaxial compressive strength (UCS) testing of core from BH18-05 to BH18-08 (CanmetMINING, 2019) and from 2019 field outcrop hammer hardness testing. Intact rock geomechanical properties are also inferred from testing of rock core completed at nearby sites with similar lithologies; specifically, the CRL site (McCrank, 2016b), as well as from core testing completed during site characterization of the Rapides des Joachims power site in Rolphton (Hydro-Electric Power Commission of Ontario, 1943).

4.3.1 Historical Investigations

Key intact rock properties, including bulk density, UCS, elastic modulus and Poisson's ratio have been investigated and reported for the CRL site (McCrank, 2016b). Geomechanical properties were compiled and summarized by CRL rock assemblages, as follows:

- Assemblage A - consisting of granitic to granodioritic gneisses with subordinate diorite gneiss and amphibolites;
- Assemblage B – garnet-rich quartz monzonitic, monzonitic and monzodioritic gneiss and garnet-rich quartzofeldspathic gneiss; and
- Assemblage C – migmatitic granite/granodiorite gneiss with disperse mafic metadiorite/ amphibolites.

Assemblages A, B and C, as described in the descriptive geosphere site model (McCrank, 2016a), are considered comparable rock units to the bedrock at the NPDWF site identified from bedrock outcrop and borehole core logging and petrology testing completed in 2019 (see Section 2.4.7 and 2.4.8). The primary rock type at the main dam site of the Rapides des Joachims power site is hornblende biotite gneiss (Hydro-Electric Power Commission of Ontario, 1943), which is consistent with the lithology at the NPD site.

Table 4.4 summarizes the average (mean) reported intact rock properties of Assemblages A, B and C and from the Rapides des Joachims power site including bulk density, UCS, elastic modulus, Poisson's ratio and tensile strength.

The results of core testing completed on intact specimens from Assemblages A, B and C from the CRL site provide a reasonable estimate for the expected intact rock properties of the material at and near the NPDWF site.

Table 4.4 Summary of Reported CRL Intact Rock Properties Relevant to the NPDWF Site

Parameter	*CRL Assemblage A*	*CRL Assemblage B*	*CRL Assemblage C*	*Rapides Des Joachims Power Site*[1]
Bulk Density (Mg/m^3)	2.72	2.78	2.71	--
UCS (MPa)	107.6	161.9	183.8	122.5
Elastic Modulus[2] (GPa)	66.5	71.1	66.6	--
Poisson's Ratio	0.28	0.26	0.33	--
Tensile Strength (MPa)	12.1	10.6	10.8	--

Notes:
1 = Leucocratic biotite gneiss.
2 = Tangent Young's Modulus estimated from UCS stress-strain curves at 40% of peak strength.
-- = no value reported/not measured.

4.3.2 2019 Investigations

Sixteen samples of PQ-size core from BH18-05 to BH18-08 were tested for intact rock properties of bulk density, UCS, elastic modulus and Poisson's ratio by CanmetMINING (2019). As part of this geomechanical testing CanmetMINING also reported on P-wave and S-wave velocities of intact samples measured prior to testing and failure mode of each intact rock sample. The 16 core samples were selected to provide spatial coverage and lithological coverage within the four shallow bedrock boreholes (Geofirma Engineering Ltd., 2019).

Table 4.5 provides the results of the intact rock geomechanical testing of core from the vicinity of the NPDWF at the NPD site. Table 4.6 provides a summary of the arithmetic average properties of the 2019 geomechanical testing based on the lithology of the core samples determined from core logging as described in Section 2.4.7.3. (Geofirma Engineering Ltd., 2019).

Tables 4.4 and 4.6 show that the heaviest NPD rocks are dioritic gneisses, followed by hornblende gneisses and granite gneisses, and the strongest rocks are granite gneisses, followed by hornblende gneisses and dioritic gneisses. Average elastic moduli and Poisson's ratio for NPD rocks are essentially the same for all three rock types at about 56 MPa, and 0.27, respectively. These trends in bulk density and UCS are consistent with expectations based on observed and measured mineralogies of the rock samples. The relatively high mafic mineral content (e.g., biotite, hornblende) in the dioritic gneisses and to lesser extent the hornblende gneisses result in higher bulk densities and lower rock strengths (UCS). In contrast, the relatively higher quartz contents of the granite gneisses result in higher rock strengths.

Comparison of average NPD intact rock geomechanical properties (Table 4.6) to average CRL intact rock geomechanical properties (Table 4.4) suggests that NPD intact rocks, although strong, have lower peak strengths and elastic moduli than CRL intact rocks. In comparing data in Tables 4.4 and 4.6, we interpret that CRL Assemblage A rocks are roughly equivalent to NPD dioritic gneisses, CRL Assemblage B rocks are roughly equivalent to NPD granite gneisses, and that CRL Assemblage C rocks are roughly equivalent to NPD hornblende gneisses. Based on these equivalences, all categories of NPD rocks have lower strengths and elastic moduli than equivalent CRL rocks.

Based on mineralogical data presented in Sections 2.4.7 and 2.4.8, the lower strengths and elastic moduli observed in NPD rocks compared to CRL rocks are most likely due to a higher mafic mineral content (e.g., biotite and hornblende) and more strongly developed biotite gneissosity and other internal structural planes of weakness (i.e., foliation, schistosity, sealed/healed fractures, microcracks, etc.) in NPD rocks versus CRL rocks. Presence of internal structural defects in NPD rock samples correlates with reduced P-wave and S-wave velocities measured on samples prior to testing. This explanation is also supported by review of the modes of rock sample failure listed in Table 4.5 and as illustrated in Figure 4.3. Figure 4.3 shows three representative plastic-sleeved failed samples of granitic gneiss, hornblende gneiss and dioritic gneiss and the modes of sample failure during UCS testing.

The left granitic gneiss sample in Figure 4.3 shows massive shear and vertical splitting along minor structural defects associated with the feldspathic layering. The middle hornblende gneiss sample shows shear along multiple biotite foliation planes inclined at 35º to the core axis. The right dioritic gneiss sample shows shear, axial splitting and other failure planes along a network of internal structural defects and weakness planes.

Table 4.5 Summary 2019 Intact Rock Geomechanical Testing at NPD Site

Borehole	Depth (mBGS)	Rock Type	Bulk Density (Mg/m^3)	P-Wave Velocity (km/s)	S-Wave Velocity (km/s)	UCS (MPa)	Elastic Modulus* (GPa)	Poisson's Ratio (-)	Failure Mode
BH18-05	25.68	Hornblende gneiss	2.77	5.13	2.74	72.3	42.7	0.25	mostly shear along pre-existing structure, minor axial splitting
BH18-05	37.22	Granitic gneiss	2.70	4.99	2.95	90.4	56.1	0.24	vertical splitting with wedge shear (top) at 45°
BH18-05	44.87	Granitic gneiss	2.64	4.73	2.86	157.4	65.0	0.28	major planar oblique shear, 65°
BH18-05	56.56	Hornblende gneiss	2.90	5.67	3.34	182.6	76.8	0.28	localized shear, axial splitting/spalling
BH18-06	15.25	Hornblende gneiss	2.79	4.36	2.61	51.7	33.3	0.17	shear along (multiple) foliation planes, 35°
BH18-06	16.32	Dioritic gneiss	2.84	1.58	0.81	7.6	n/a	n/a	shear, axial splitting, internal defects/structure
BH18-06	36.56	Hornblende gneiss	2.79	5.25	3.05	125.6	57.9	0.33	shearing and splitting
BH18-06	49.71	Granitic gneiss	2.68	4.75	2.90	211.3	68.5	0.33	massive shear
BH18-07	21.45	Hornblende gneiss	2.77	4.63	2.70	52.7	33.8	0.25	massive shear, crushing/axial splitting, minor structural defects
BH18-07	31.72	Granitic gneiss	2.80	5.03	2.74	28.6	19.0	n/a	shearing and splitting, damage mainly on lower portion of sample
BH18-07	37.42	Granitic gneiss	2.64	4.68	2.88	134.5	58.2	n/a	massive shear and vertical splitting, minor structural defects
BH18-07	52.40	Hornblende gneiss	2.80	5.67	3.16	134.6	72.0	0.29	massive shear, secondary axial splitting and spalling, minor defects
BH18-08	13.30	Hornblende gneiss	2.86	5.82	3.21	153.1	74.5	0.30	general shear (x-shape)
BH18-08	35.43	Granitic gneiss	2.72	5.38	3.01	197.8	71.6	0.28	massive, undulating shear
BH18-08	40.43	Dioritic gneiss	2.87	5.42	2.93	96.4	35.0	n/a	shear with some spalling at mid-height
BH18-08	54.81	Granitic gneiss	2.90	5.47	3.00	129.8	57.6	0.23	planar undulating shear

Notes:
n/a – data not available/not calculated   * calculated at 40 to 60% peak UCS

Table 4.6 Summary of Average Intact Rock Geomechanical Properties at NPD Site from 2019 Testing

Parameter	*Granite Gneiss*	*Hornblende Gneiss*	*Dioritic Gneiss*	*All*
Bulk Density (Mg/m^3)	2.72	2.81	2.85	2.78
P-Wave Velocity (km/s)	5.00	5.22	3.50	4.91
S-Wave Velocity (km/s)	2.01	2.97	1.87	2.81
UCS (MPa)	135	110	52	114
Elastic Modulus (GPa)	56.7	55.9	n/a	56.3
Poisson's Ratio	0.27	0.27	n/a	0.27

Notes:
n/a – data not available/not calculated

Based on ISRM (1981, see Table 4.7) and 2019 UCS testing, intact rocks at the NPD site in the vicinity of the NPDWF are classified as moderate to high strength with an overall average rating of high strength.

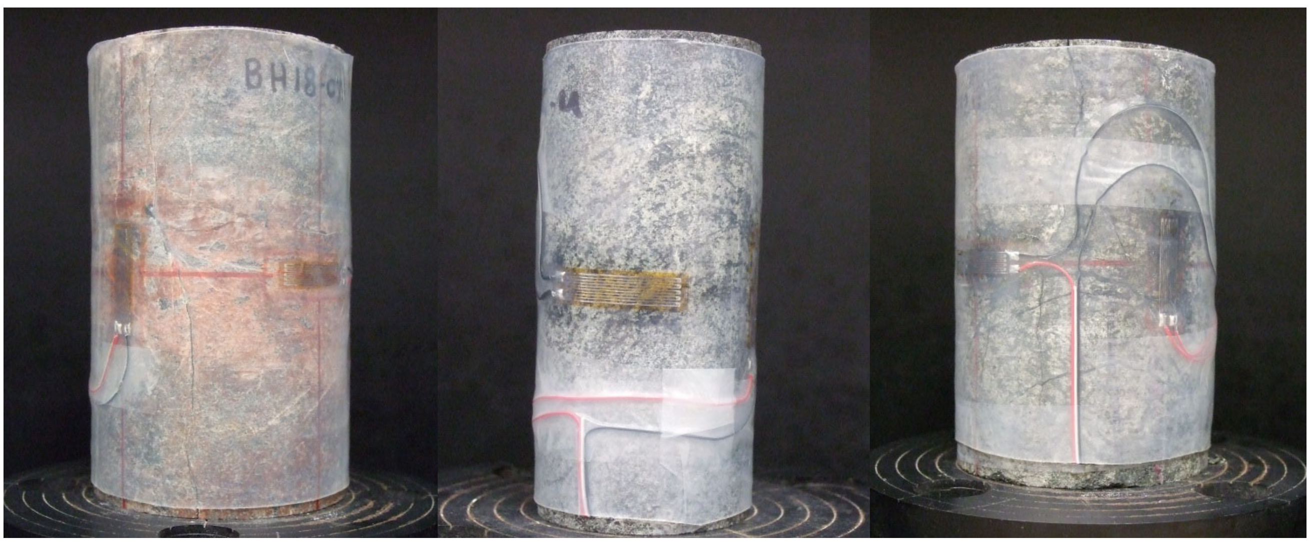


Figure 4.3 Failed UCS Intact Rock Samples, Left - Granitic Gneiss (BH18-07-37.42), Middle - Hornblende Gneiss (BH18-06-15.25) and Right – Dioritic Gneiss (BH18-06-16.32)

This classification of intact bedrock strength at the NPD site is confirmed by field outcrop estimates (R0 to R6, Table 2 – Geofirma Engineering Ltd., 2019) determined from geological hammer and other diagnostic tests. These field data (Geofirma Engineering Ltd., 2019) show that almost all mapped bedrock outcrops were assessed as R5 or R6, indicating very strong to extremely strong intact rock strength. Two exceptions were noted as R4 to R5 (strong to very strong) for an outcrop of gabbroic gneiss, and R0 to R1 (extremely weak to very weak) for a thin crushed rock zone (mylonite) in the same outcrop of gabbroic gneiss.

Table 4.7 Summary of Intact Rock Strength Classification of NPD Bedrock based on ISRM (1981)

UCS Intervals (MPa)	***Classification of intact Rock Strength***
>200	Very High
60 to 200	High
20 to 60	Moderate
6 to 20	Low
<6	Very Low

4.4 Rock Mass Properties

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, and to a lesser degree intact rock strengths. Discontinuities may include joints, fractures, faults, shear zones, or any other features that intersect an otherwise intact section of rock. The data to support geomechanical characterization of a rock mass are typically obtained from outcrop mapping, detailed core logging and laboratory geomechanical testing. Such data are directly available from 2019 geoscientific site characterization work and are inferred from work on nearby sites with similar bedrock geology (i.e., CRL site and Rapides des Joachims power site).

Detailed mapping, geomechanical core logging and laboratory testing has been completed as part of the drilling investigations and geosynthesis studies at the CRL site (McCrank, 2016b). It was noted that the rock mass at the CRL site was moderately fractured (i.e. between 10 and 25 fractures per metre), with interspersed zones of sparsely fractured rock (less than 10 fractures/m) and highly fractured rock (greater than 25 fractures/m). Comparable geomechanical data are not available for the Rapides des Joachims power site.

4.4.1 <u>Rock Mass Classification</u>

Geomechanical classification of a rock mass is typically completed by calculation of natural fracture frequency (ISRM, 1977) and rock quality designation (RQD) on recovered core (Deere *et al*., 1967), or by using more comprehensive methods such as the rock mass rating (RMR) system (Bieniawski, 1989) and/or Q-system, developed by the Norwegian Geotechnical Institute (NGI) (Barton *et al.,* 1974; NGI, 2015). RQD is an important parameter in the RMR (rock mass rating) and Q-system rock mass quality classification methods. Although RMR and Q-system rock mass classification systems were originally developed to estimate tunneling support requirements, they do provide convenient and established methods for determining geomechanical rock mass quality for other purposes.

4.4.1.1 Natural Fracture Frequency

ISRM (1977) provides guidance on rock mass fracturing descriptions based on natural fracture frequency measurements on recovered drill core. Table 4.8 summarizes this guidance. Table 2.2 shows measurements of natural fracture frequency made on recovered core from BH18-05 to BH18-08 ranging from 0 to 14 fractures/m. Average natural fracture frequency values per borehole range from 4.5 fractures/m (BH18-05) to 7.2 fractures/m (BH18-07), with an overall average of 6.0 fractures/m for all four boreholes. Based on these measurements and Table 4.8, the rock mass near the NPDWF is considered moderately fractured.

Table 4.8 Guidance on Natural Fracture Frequency and Rock Mass Quality (after ISRM, 1977)

Natural Fracture Frequency (m^{-1})	***Rock Mass Quality***
>10	Highly Fractured
>1.0 to 10	Moderately Fractured
0.5 to 1.0	Sparsely Fractured
<0.5	Very Sparsely Fractured
0	Unfractured

4.4.1.2 Rock Quality Designation System

The rock quality designation (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 (Deere *et al.,* 1967; Deere and Deere, 1988). 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, or more commonly, included in the RMR or Q-system methods of rock mass geomechanical classification. The relationship between calculated RQD and descriptive rock quality is presented in Table 4.9.

Table 4.9 Relationship between RQD and Rock Mass Quality (after Deere *et al.,* 1967)

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

RQD values at the CRL site have been reported between 60 and 85% in the upper 100 m (Raven, 1980; Raven Beck Environmental, 1994a) indicating fair to good quality rock. More recent drilling of the CRG-series boreholes at the CRL site, summarized by McCrank (2016b), found that the vast majority (89%, if excluding CGR-2 drilling into the Mattawa Fault) of the total length in all boreholes can be classified as good to excellent rock quality (i.e., RQD greater than 75%).

As geotechnical investigations of the adjacent Rapides des Joachims power site (Hydro-Electric Power Commission of Ontario, 1943) pre-date the development of the RQD system, such rock mass classification data are not available for the Rapides des Joachims power site.

2019 geomechanical logging of BH18-05 to BH18-08 (see Table 2.2 in Section 2.4.6.5) show arithmetic average RQD values per borehole ranged from 59% (BH18-07) to 83% (BH18-05) with an overall average of approximately 69%, indicating fair to good rock quality conditions near the NPDWF.

4.4.1.3 RMR System

The RMR classification system was developed to assess rock mass quality and includes the following components which are individually rated and tallied to yield a RMR (Bieniawski, 1989):

- UCS of intact rock;
- Drill core quality (RQD);
- Spacing of discontinuities;
- Surface condition of discontinuities;
- Groundwater conditions; and,
- Orientation of discontinuities.

The interpreted RMR values at CRL based on drilling and testing of CRG-1 and CRG-5 boreholes range from 54 to 77 (fair to good quality rock) in CRG-1 and 40 to 88 (poor to very good quality rock) in CRG-5 (McCrank, 2016b). This is consistent with the reported range of RMR values from 64 to 76 (good quality rock) reported by Raven Beck Environmental (1994a) for the CRL site.

As geotechnical investigations of the adjacent Rapides des Joachims power site (Hydro-Electric Power Commission of Ontario, 1943) pre-date the development of the RMR system, such rock mass classification data are not available for the Rapides des Joachims power site.

RMR assessment for the NPD site relies on data from 2019 geoscientific investigations. Based on CanmetMINING (2019), average UCS of intact rock ranges from 52 to 135 MPa for major rock types, with an overall average UCS of 114 MPa (Table 4.4), (rating 11). Based on Table 2.4 average RQD per borehole ranges from 59% to 83% with an overall average of 69% (rating 15). Spacing of discontinuities, based on outcrop mapping ranges from decimetre to metre (Section 2.4.6.4), and based on core logging is decimetres (Section 2.6.4.5) (rating 10 to 15). Based on NPD outcrop mapping (Geofirma Engineering Ltd., 2019) and core logging, fractures have slightly rough surfaces with slightly weathered walls (rating 25). A rating of 10 is assigned to groundwater conditions based on the calculation of about 3.5 L/min. for 10 m length of tunnel from the overall geometric mean of shallow bedrock K of 1.6E-07 m/s (Section 3.3.2) and the observed general condition of excavation walls as damp (Figures 2.28 and 2.29).

Assuming no rating adjustment for joint orientations, the RMR for the shallow bedrock in the vicinity of the NPDWF is 71 to 76 indicating a good quality rock mass. This RMR is essentially the same as historical ratings generated for CRL bedrock.

4.4.1.4 Q-System

The Q-system of rock mass classification was developed primarily to assess stability of underground openings (Barton *et al.*, 1974; NGI, 2015), and includes the following components:

$$Q = \frac{RQD}{J_n} \cdot \frac{J_r}{J_a} \cdot \frac{J_w}{SRF}$$

Where:

RQD = rock quality designation (degree of jointing)

J_n = joint set number

J_r = joint roughness number

J_a = joint alteration

J_w = joint water reduction factor

SRF = stress reduction factor

Based on geological mapping observations, core logging and laboratory testing, the interpreted Q-values range from 2.6 to 22.2 for the CRL site (Baumgartner, 2011) indicating poor to good rock quality and from 2.6 to 7.5 for the CRL site (Raven Beck Environmental Ltd., 1994a) indicating poor to fair rock quality (Barton *et al*., 1974).

As geotechnical investigations of the adjacent Rapides des Joachims power site (Hydro-Electric Power Commission of Ontario, 1943) pre-date the development of the Q-system, such rock mass classification data are not available for the Rapides des Joachims power site.

Q-system assessment for the NPD site relies on data from 2019 geoscientific investigations. Based on Table 2.2 average RQD per borehole ranges from 59% to 83% with an overall average of 69%. Joint set number (J_n) is set at 3 based on an average of 3 joint sets in outcrops and in boreholes BH18-05 to BH18-08 (Section 2.4.6.4 and 2.4.6.5). Joint roughness number (J_r) is 1.5 to 3.0 based on most outcrop and core fractures being mapped/logged as planar to undulating roughness. Based on infilling observations in core, the joint alternation number (J_a) is 1.0 indicating tightly healed non-softening, impermeable infilling. A joint water reduction number (J_w) of 1.0 indicating minor inflows of less than 5 L/min is selected based on geometric mean K for shallow bedrock (Section 3.3.2) and inflow observations of NPD excavations (Figures 2.28 and 2.29). For the competent NPD rocks, a stress reduction factor (SRF) of 2.5 is assumed to be representative based on the likelihood that low stress conditions may exist in the near surface (Section 4.7.2).

Based on these data, the average Q-system rating for shallow bedrock near NPDWF is 4.6 to 9.2 indicating fair rock mass quality (Barton *et al*., 1974). This Q-system rock mass quality rating of the NPD site is very similar to and less than historical estimates generated by Raven Beck Environmental Ltd. (1994a) and Baumgartner (2011) of the CRL site.

4.4.2 Overall Assessment of Rock Mass Quality at the NPD Site

Available rock mass quality information for the NPD site includes geological information from drilling investigations at the site (Hydro-Electric Power Commission of Ontario, 1956; Canadian General Electric Company Ltd., 1962; Geofirma Engineering Ltd., 2019), from excavation observations, and from RMR and Q-values inferred from the CRL site and calculated from 2019 drilling and rock core logging. Geotechnical studies completed to support the adjacent Rapides des Joachims power site (Hydro-Electric Power Commission of Ontario, 1943) also provide information on the likely rock mass quality at the NPD site.

At the Rapides des Joachims site it was noted in the study that the rock was very good in the main dam site area and that extensive grouting would not be required except in the small shear zones. With the exception of comments made with respect to isolated shear zones and well cemented, narrow faults oriented parallel to the channel (Ottawa River), there is little information to suggest that the rock quality was poor.

Drilling investigations of the NPD site prior to excavation and construction noted several zones of core loss; however, these zones typically did not show loss of drilling fluid circulation, resulting in the interpretation (Canadian General Electric Company Ltd., 1962) that the rock although showing evidence of shearing and fracturing, was of suitable quality for plant foundations. 2019 geoscientific investigations of the NPD site indicate overall rock mass quality near the NPDWF as good (RMR system) to fair (Q-system).

This pre-excavation and 2019 drilling assessment is further supported by photographs taken during excavation of the NPD powerhouse facility (Figures 2.27 to 2.29). These figures, particularly Figure 2.29 show that bedrock at the NPD site is sparsely to highly fractured, although some of the observed fracturing may be damage induced by excavation activities. As shown on Figure 2.29, the large, unsupported (or marginally supported) excavation does not show any signs of major instability, suggesting the rock mass was likely of at least fair to good quality, with localized zones of lesser quality. These rock mass quality observations are consistent with the inferred RMR and Q-values for the NPD site based on CRL data and with actual RMR and Q-values determined from 2019 NPD geoscientific site data.

4.5 Summary of Intact Rock and Rock Mass Quality

Table 4.10 summarizes the descriptions of intact rock and rock mass quality of the NPDWF determined from 2019 outcrop mapping and drilling investigations based on use of standardized geomechanical intact rock and rock mass quality rating and classification systems.

Table 4.10 Summary Descriptions of Intact Rock and Rock Mass Quality at NPD Site

Intact Rock/Rock Mass Classification System	*Average System Rating (per Borehole or Outcrop)*	*Intact Rock/Rock Mass Description*
Uniaxial Compressive Strength (MPa)	114 MPa	High Strength
Outcrop Field Strength	R5 to R6	Very Strong to Extremely Strong
Core Natural Fracture Frequency (m^{-1})	4.5 to 7.2	Moderately Fractured
Rock Quality Designation (%)	59 to 83%	Fair to Good Rock Mass Quality
Rock Mass Rating	71 to 76	Good Rock Mass Quality
Q-System	4.6 to 9.2	Fair Rock Mass Quality

4.6 Major Discontinuities and Structural Features

The NPD site is located within the Ottawa-Bonnechere Graben, as shown on Figure 2.10 and Figure 2.12. Interpreted major structural features for the CRL site that may be present at the NPD site have been summarized in previous technical reports (Raven Beck Environmental Ltd., 1994a; Thivierge, 2011, McCrank, 2016a) and are discussed in detail in Section 2.4. Interpreted major discontinuities and structural features at or near the NPDWF in order of significance include the following:

- The major regional-scale northwest-southeast striking, steeply southwest dipping Mattawa Fault and interpreted faults striking parallel to this prevailing regional fault orientation.
- Less well-defined structural features include shorter north-south oriented lineaments, and northeast-southwest trending structure oriented perpendicular to the Mattawa Fault and associated parallel structures.
- East-west trending structure poorly defined in the lineament interpretation and potentially related to the Grenville dyke swarms.

Although a major 90 m-wide, east-west striking, moderately (30º to 50º) south-dipping shear zone was interpreted for the NPD site and the NPDWF (Figure 4.4), based on pre-excavation core drilling investigations, inspection of bedrock excavations (see Figures 2.27 to 2.29) indicates the suspected shear zone is not present at the NPD site.

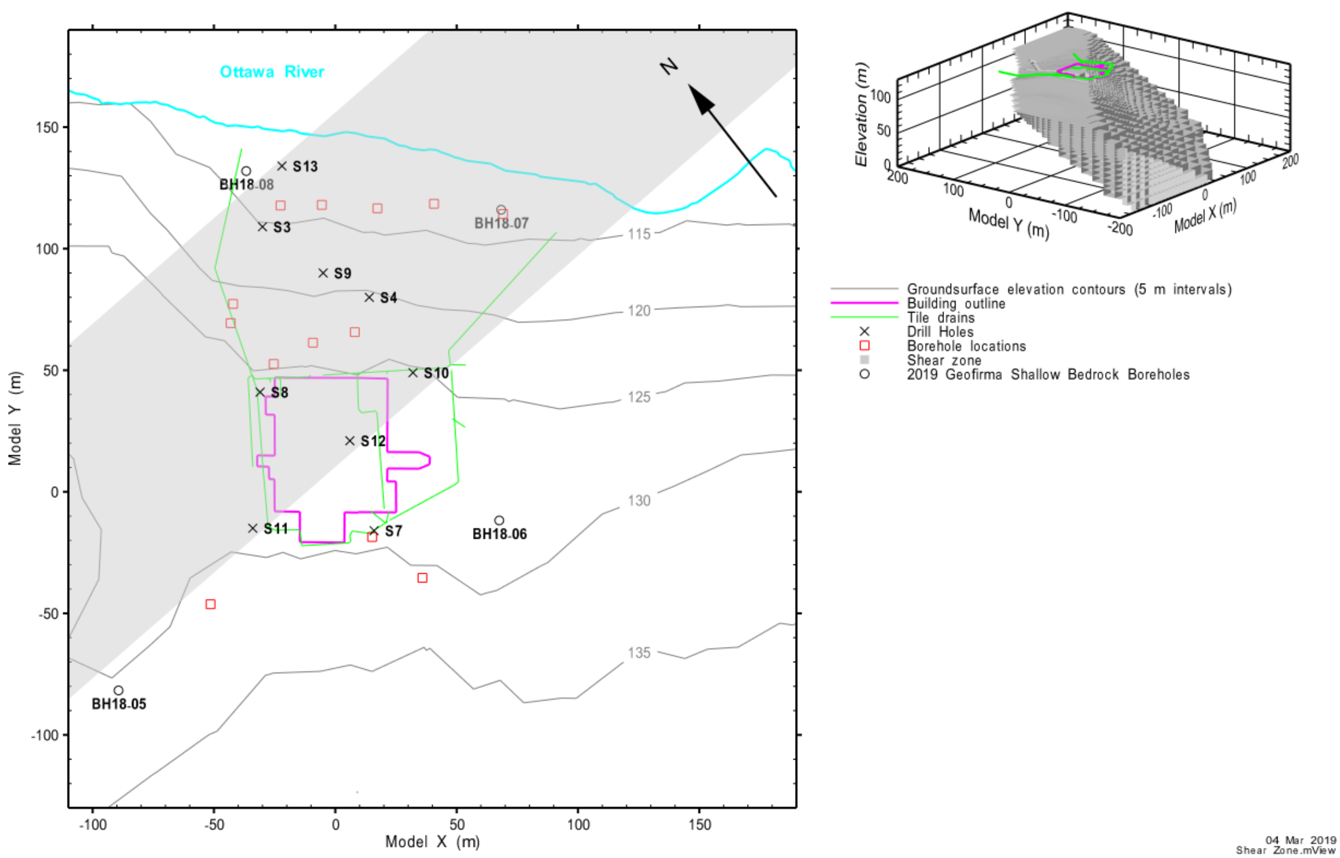


Figure 4.4 Suspected 90 m-wide Shear Zone, NPDWF and 2019 Shallow Bedrock Boreholes

2019 shallow bedrock drilling, coring and testing investigations (BH18-05 to BH18-08) provide additional data on the potential presence of a major 90 m-wide, east-west striking, moderately south-dipping shear zone. The location of 2019 shallow bedrock boreholes and the suspected location of the major shear zone are shown in Figure 4.4. Figure 4.5 shows a 3-D representation of 2019 shallow bedrock boreholes and their intersection with the suspected shear zone assuming a 35º south dipping structure.

Based on Figures 4.4 and 4.5, it is apparent that if the 90 m-wide sear zone was present at the NPD site as surmised from pre-excavation drilling, it would intersect 2019 boreholes BH18-05 and BH18-07 over most of their lengths, for the quoted dip range of 30º to 50º. It would also intersect the bottom of BH18-06 if the dip was 35º or less, and it would not intersect BH18-08 regardless of dip. Such intersections would be apparent as lengthy zones of intense fracturing, core loss and heavy drilling fluid losses. Given the borehole intersections shown in Figure 4.4, presence of a 90 m-wide shear zone would also show more intense fracturing in BH18-05 and BH18-07 than in BH18-06 and BH18-08. As shown in Table 2.2, this spatial pattern of fracturing is not observed in BH18-05 to BH18-08.

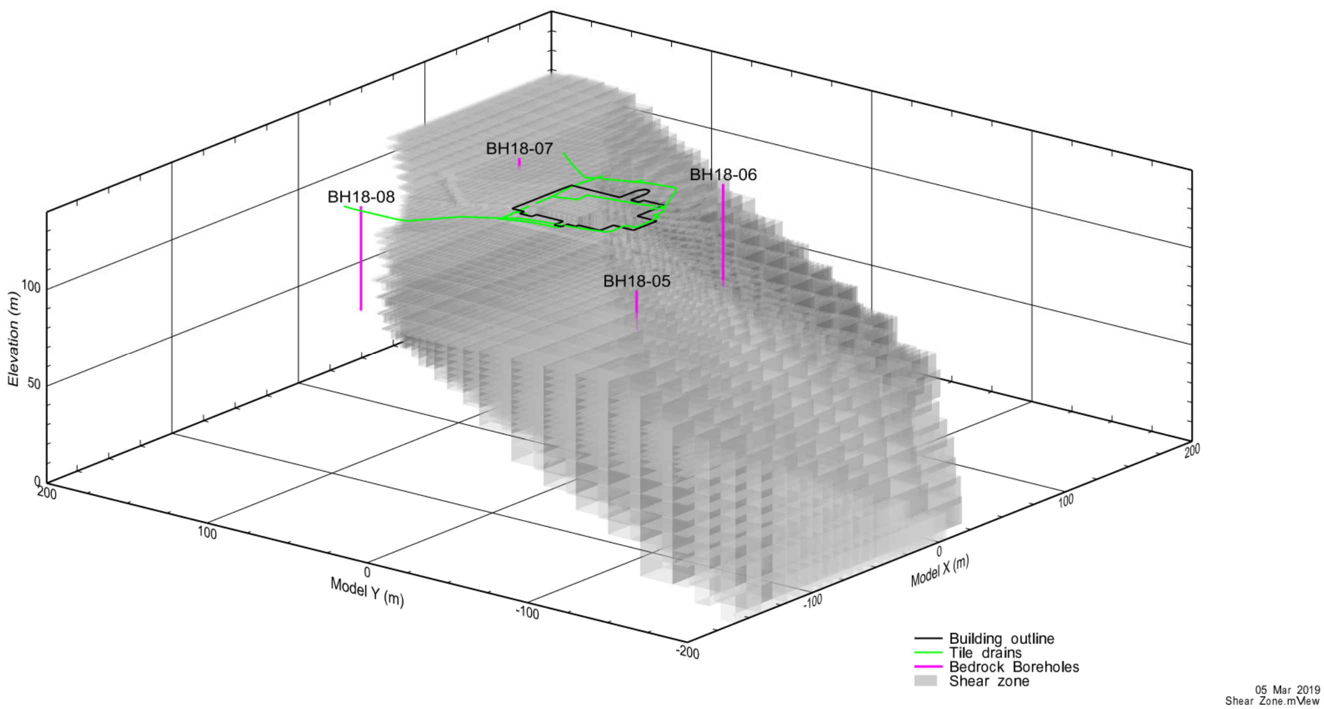


Figure 4.5 Intersection of 2019 Shallow Bedrock Boreholes with Suspected 90 m-wide Shear Zone

Review of borehole core logs, geophysical logs and straddle-packer testing shows that there is no evidence to support the existence of the hypothesized 90 m-wide shear zone at the NPD site and the NPDWF. However, as noted in Section 3.4.5, 2019 logging and testing of BH18-05 to BH18-08 does confirm the presence of subhorizontal and subvertical open fractures and metre- and sub-metre-scale fracture zones in shallow bedrock at the NPDWF.

4.7 In-situ Stresses

The in-situ stress state is an important parameter for evaluating underground excavation stability. The following sub-sections describe the interpreted regional and site scale in-situ stress conditions that may be applied to the NPDWF site.

4.7.1 Regional In-situ Stress Conditions

Regionally, it is generally accepted that one of the three stress components is oriented in the vertical direction (σ_v), with the remaining components in the horizontal plane, referred to as the maximum and minimum horizontal stresses (σ_H and σ_h, respectively). Local stress perturbations are possible surrounding major topographical or structural features, such as faults, but the orientations of regional stresses (e.g., Figure 4.6) are considered to be strongly influenced by tectonics and roughly align with the direction of tectonic plate movement.

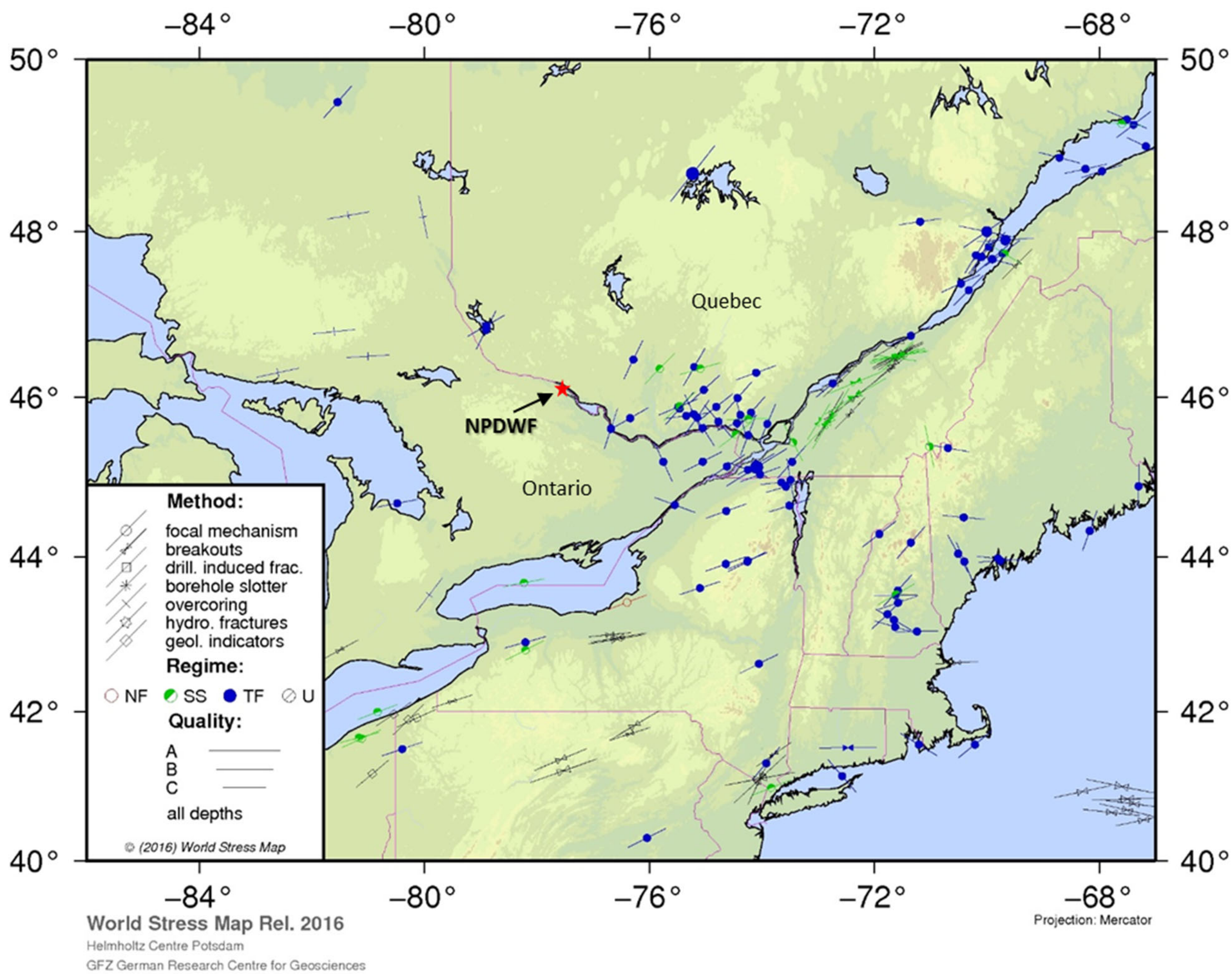


Figure 4.6 World Stress Map for Southeastern Canada and the Northeastern United States showing Maximum Horizontal Stress Orientations (Heidbach *et al.*, 2016)

In 2015, an updated stress database for the Canadian Shield (within Ontario) was prepared by Yong and Maloney (2015). This report captured a total of 304 stress measurements at depths from near surface to 2,552 m below ground surface, largely from operating mines in crystalline rock environments. Based on the data collected, this work confirmed that the principal stresses are approximately aligned with the Cartesian axes, with the minimum principal stress oriented sub-vertical and major and intermediate stresses oriented sub-horizontal. The average maximum principal stress was oriented approximately west southwest – east northeast.

Another source of regional stress data includes the world stress map (WSM), presented in Figure 4.6 (above), which provides an overview of the regional orientation of horizontal stresses in southeastern Canada (Heidbach *et al*., 2016). As illustrated on the WSM, the maximum horizontal stresses are generally oriented east to northeast, which is consistent with the current tectonic plate movement direction (i.e., ridge push from the mid-Atlantic Ridge) (Zoback and Zoback, 1991).

4.7.2 Local In-situ Stress Conditions

A comprehensive in situ stress measurement program was completed at the CRL site and is described in detail in the CRL geosynthesis report (McCrank, 2016b). It is reasonable to expect that the stress regime at the CRL site can be applied to the NPDWF site, given the relative close proximity of the sites and the similar geological and lithostructural setting.

At the CRL site, in situ stresses were estimated by hydraulic fracturing (HF) methods, as well as overcoring using the deep doorstopper gauge system (DDGS). Measurements were collected to maximum depth of over 900 m in two separate boreholes (CRG-1 and CRG-5). The interpreted orientation of the maximum horizontal stress component was east - west, which was more strongly developed in the deeper (i.e., greater than 300 m depth) tests. Shallower testing in the upper 100 m indicates a subset of north northeast – south southwest trending maximum horizontal stress measurements. Other trends, mostly in shallower tests using the DDGS were observed and concluded to represent local stress or rock fabric conditions. The overall interpreted stress conditions indicated a thrust faulting regime, where both horizontal stress components are larger the calculated lithostatic stress component.

Figures 4.7 and 4.8 from McCrank (2016b) provide a summary of the stress-depth profiles for maximum horizontal stress, minimum horizontal stress and max:min horizontal stress ratios, and a rose diagram of orientation of maximum horizontal stresses. The McCrank (2016b) plots of stresses show increases with depth with maximum horizontal stress of about 50 MPa at 600 m depth and max:min horizontal stress ratios decreasing from 3:1 at 100m depth to 1.1:1 to 1.5:1 at 900 m depth. The rose diagram of azimuths of maximum horizontal stressed from McCrank (2016b) is not dissimilar to those of Raven *et al*. (1984).

Shallow in situ stress testing was also completed at the CRL by Raven *et al*. (1984) and summarized in Raven Beck Environmental Ltd. (1994a). Testing was completed at one borehole in monzonitic gneiss between 7.0 and 29.7 m below ground surface using the U.S. Bureau of Mines overcoring tool. The testing (see Table 4.11) indicated a general tensile stress regime, with two tests completed at 29.1 and

29.7 m showing tensile stresses oriented perpendicular to the Ottawa-Bonnechere graben and the maximum horizontal stress trending 150-160°, roughly parallel to the regional structural features.

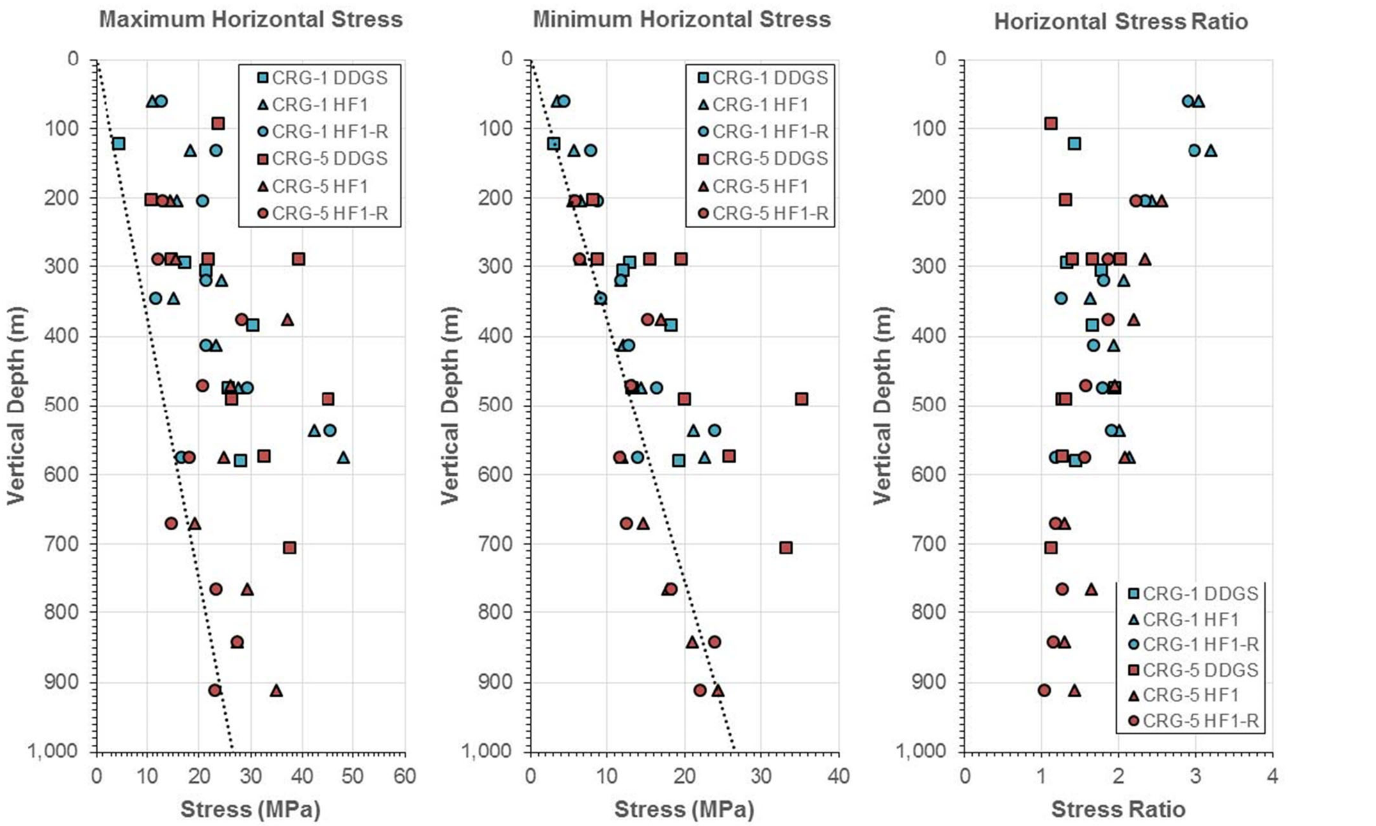


Figure 4.7 Summary of In Situ Stress Determination Results from Boreholes CRG-1 and CRG-5 based on DDGS and Hydrofracture Tests

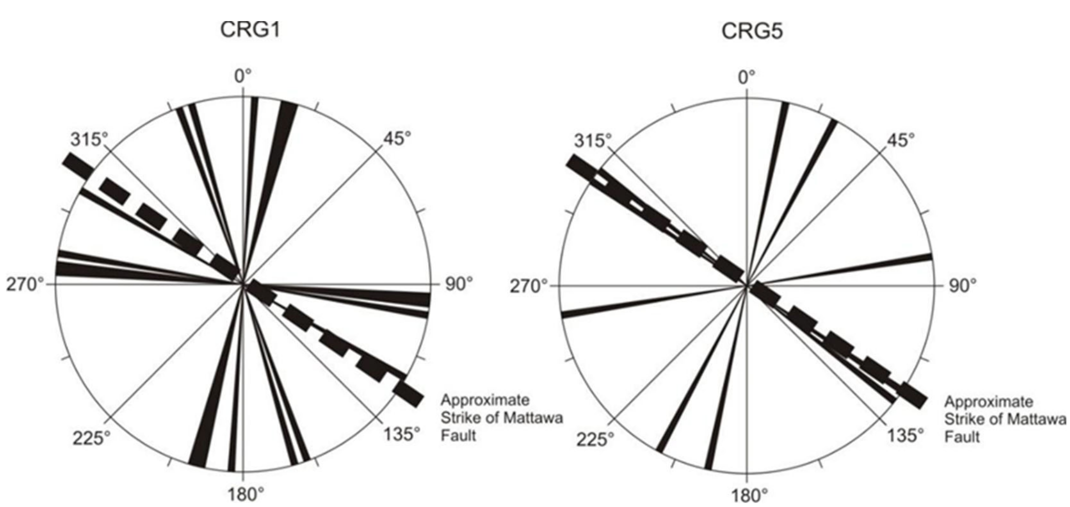


Figure 4.8 Rose Diagrams of Azimuths of Maximum Measured Stress Values. Thickness of Lines Indicates Relative Number of Tests

Table 4.11 Summary of In Situ Stress Measurements at CRL (after Raven *et al.*, 1984)

Depth (mBGS)	*Max Horizontal Stress (MPa)*	*Azimuth of Max Horizontal Stress*	*Min Horizontal Stress (MPa)*
7.04	1.21	20°	-0.15
14.06	-2.41	22°	-3.12
29.10	3.56	341°	-2.40
29.70	10.80	332°	-1.04

Based on testing completed at the CRL site (McCrank, 2016b, Raven Beck Environmental, 1994a), and the database of regional stress measurements (Heidbach *et al*., 2016; Yong and Maloney, 2015), the following interpreted in situ stress conditions are likely to exist at the NPDWF site:

- The vertical stress component can be approximated to be the lithostatic stress and the magnitude can be reasonably estimated by assuming a unit weight of 26.5 kN/m^3.
- The trend of maximum regional horizontal stress is likely to be in the general east - west direction, more strongly developed at depth and with local perturbations possible. The regional stresses indicate thrust faulting conditions, where the vertical stress is the minimum stress component.
- The shallow horizontal stresses may include a negative stress component (i.e., tensile stress), oriented perpendicular to the Ottawa-Bonnechere graben, indicative of a normal faulting stress regime.

4.8 Seismicity

4.8.1 Regional Seismicity

Figure 4.9 shows the location of earthquakes with a Nuttli Magnitude 3 or greater that are known to have occurred in southeastern Canada from about 1700 to 2015 (McCrank, 2016b). Figure 4.9 shows most of the historical earthquakes have occurred in a wide band trending northwest of Montreal known as the Western Quebec Seismic Zone (Forsyth, 1981). Prior to 1985 detection of earthquakes was limited to events with Nuttli Magnitude greater than 3.0.

The Western Québec Seismic Zone (WQSZ) northeast of the Mattawa Fault is an area of concentrated seismic activity, with events generally ranging from about M 2 to 4.5 and rare events over M 5. The WQSZ involves a broad northwest-southeast trending corridor of modern intraplate seismic activity about 160 km wide extending from the Baskatong Reservoir area to the Adirondack Highlands southeast of Montréal (Thivierge *et al*. 2011). The distribution of epicentres appears to be broadly limited to the crust east of the Ottawa-Bonnechere graben. Isoseismic studies suggest that major events in the WQSZ attenuate westward around the graben (Forsyth, 1981).

As illustrated in Figure 4.9, a number of earthquakes have occurred and been felt in the vicinity of the NPD site. These include the M 5.0 earthquake at Val-des-Bois in 2010 within the WQSZ, a M4.0 earthquake 30 km from Chalk River in 1963 and several larger earthquakes located more than 250 km from the NPD site (Montreal M 6 in 1732, Charlevoix M 7 in 1663, Timiskaming M 6.1 in 1935, and Cornwall M 5.8 in 1944).

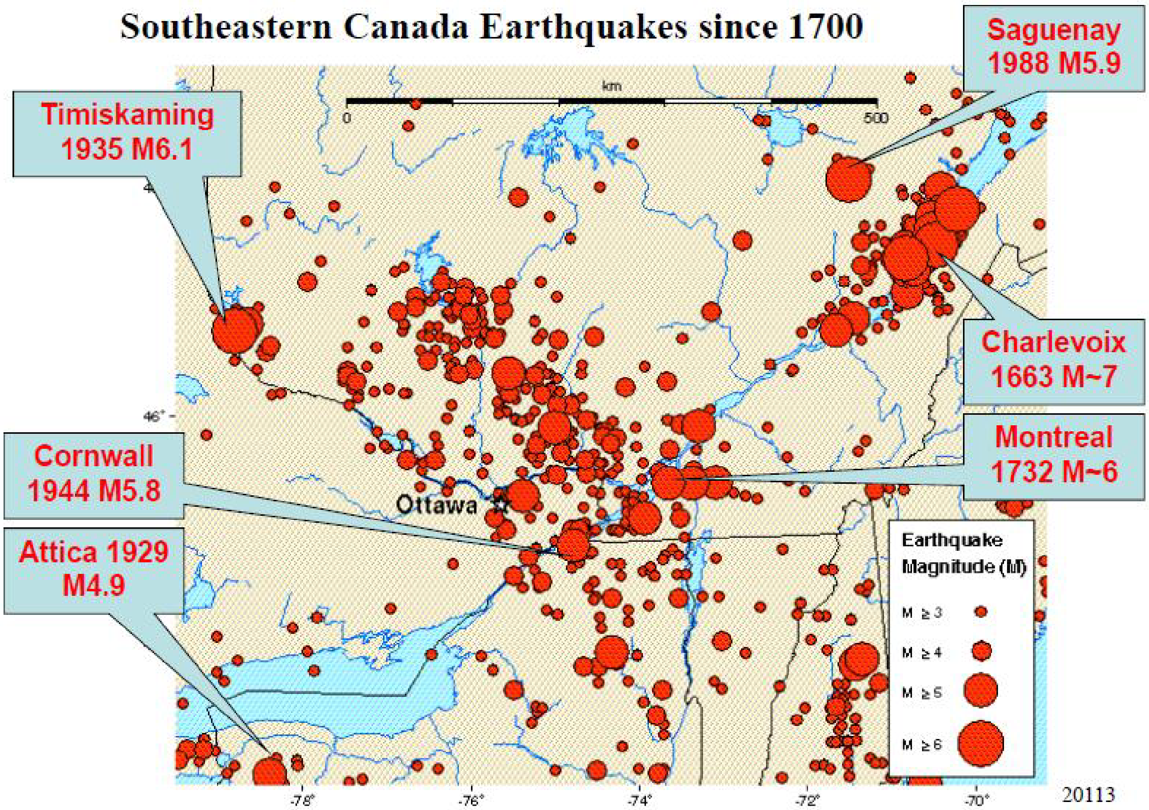


Figure 4.9 Historical Earthquakes in Southeastern Canada Since 1700

4.8.2 <u>Local Seismicity</u>

Figure 4.10 shows the 1985-2018 record of earthquakes for the local area surrounding the NPDWF site as maintained by Earthquakes Canada, (Natural Resources Canada, 2018a). The maximum recorded earthquake was a Nuttli Magnitude 2.9 event that occurred March 11, 1995 about 10 km southwest of the NPDWF site. In 1985 the Natural Resources Canada seismic monitoring network for eastern Canada was upgraded to provide detection of earthquakes with Magnitude of about 2.0 or more. This detection limit was reduced further to <1 in the area of the NPDWF site with installation of a microseismic monitoring station consisting of a Short-Period station installed at the town of Chalk River, Ontario in 1994, and two portable broadband stations installed at Pembroke and Algonquin Park in 2002.

There is no apparent clustering or alignment of recorded seismic events shown on Figure 4.10 for the local NPD area with the Mattawa Fault or other OGS-mapped faults in the vicinity of the NPD.

4.9 Neotectonics and Paleoseismology

Neotectonics is the study of motions and deformations of the earth's crust that are current or recent in geological age. Paleoseismology is the investigation of paleoseismicity (prehistoric earthquakes) through evidence such as displacement of the bedrock surface, or the deformation of Quaternary sediments (Slattery, 2011). Structures indicative of paleoseismicity at sites like the NPD, listed in order of increasing ambiguity, include clastic intruded dykes and sills, sand boils, some slumping and disturbed sediment bedding, density flows or debris flows, and some varieties of bedrock and overburden faulting and jointing (Obermeier, 1996). Furthermore, according to Obermeier (1999), such paleoliquefaction features are rarely visible at ground surface and most paleoseismic studies focus on recognition of seismically-induced soft sediment deformation in vertical sediment profiles, either through seismic and acoustic profiling or trenching.

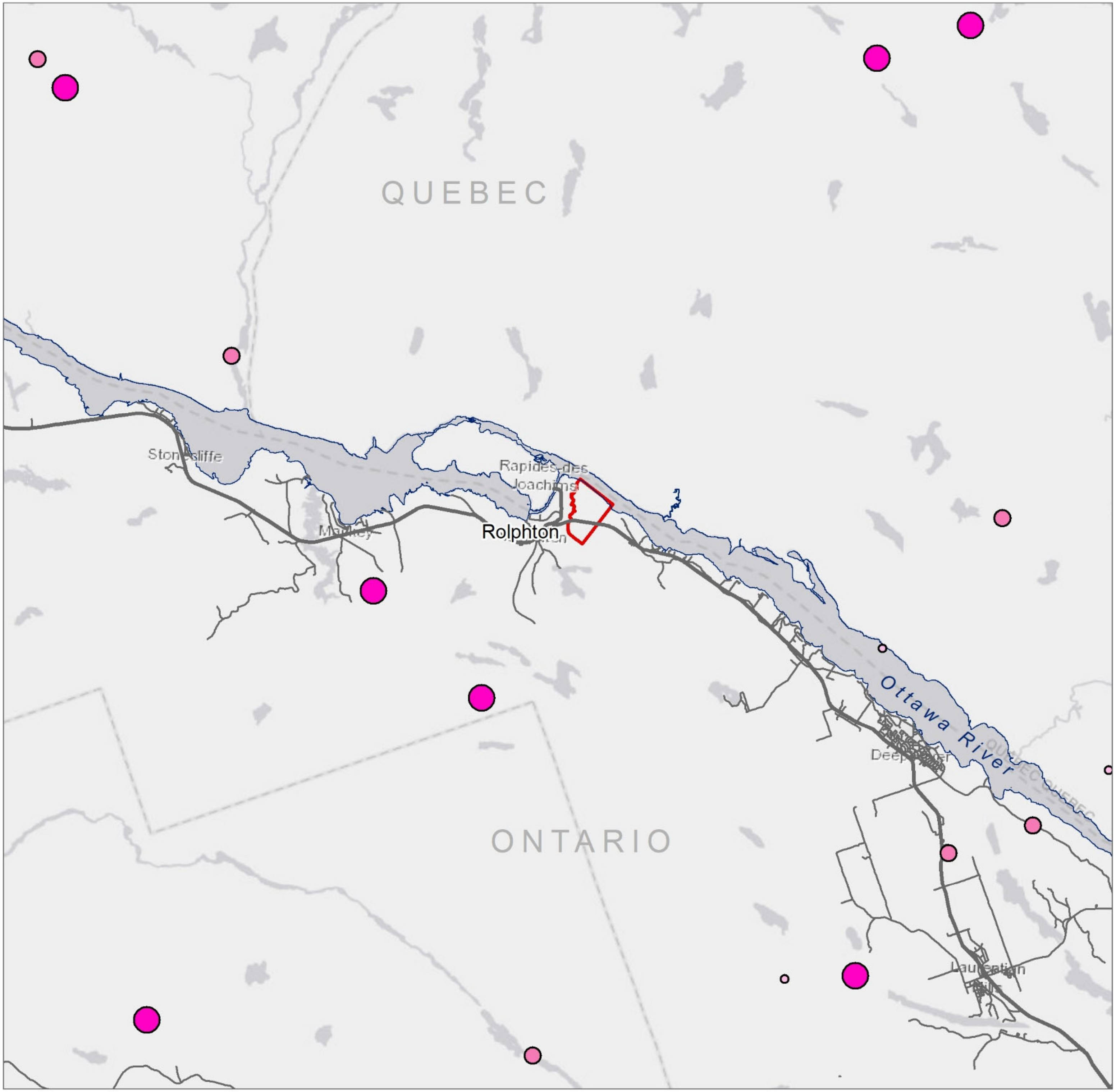
McCrank (2016b) notes that evidence for soft sediment deformation indicative of paleoseismicity in the late- to post-glacial period is well documented in the region of the Ottawa-Bonnechere graben between Ottawa and Montreal south of the NPD site and also in the Lake Timiskaming area north of the NPD site. At each of these locations evidence of prehistoric earthquakes is provided by strongly deformed post-glacial surficial sediments.

No neotectonic or paleoseismic studies have been completed at the NPD site. Given the lack of such studies at the NPD site, results of neotectonic and paleoseismic studies of the CRL site are used as a surrogate for the NPD site. Such reliance on CRL studies is reasonable and appropriate given the similar geological, regional structural and seismological setting of the NPD and CRL sites.

Raven Beck Environmental Ltd. (1994a) and McCrank (2016b) summarize the results of paleoseismic site investigations intended to identify evidence of neotectonics at the CRL site. Raven Beck Environmental Ltd (1994a), as part of bedrock geological mapping of the CRL site concluded that neotectonic features such as micro-faults displacing glacial striae in bedrock outcrops and slumping of post-glacial sediments were not present at the CRL site. McCrank (2016b) offered similar conclusions noting that post-glacial deformation had not been recognized in or adjacent to the CRL site in either bedrock or surficial sediments, despite dedicated investigations (including on-site trenching and mapping of Quaternary sediments).

McCrank (2016b) provides a summary assessment of the absence of paleoseismic structures at the CRL site that is relevant to the NPD site. McCrank (2016b) observes that the absence of paleoseismic structures in the CRL area is consistent with the absence of a surficial sediment section of sufficient composition, thickness and horizontal extent needed to have developed and preserved paleoseismic evidence. At the same time the surficial sediment cover is extensive enough to conceal any small-scale displacements of the bedrock surface that may have developed from seismic shaking.

These summary observations indicate the potential for identification of paleoseismic structures at the NPD site, which has almost no post-glacial soft sediment and very limited bedrock exposure, is extremely low.



LEGEND

2019 Rolphton NPDWF Model Boundary
Highway
Local Road
Ottawa River Outline

Seismic Events

(Magnitude)

< 1.0
1.1 - 2.0
2.1 - 3.0

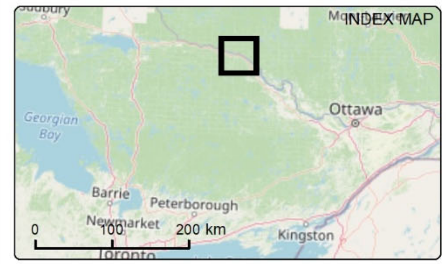


Figure 4.10
Historical Earthquakes in the Vicinity of NPDWF, 1985 - 2018

SCALE 1:225,000
0 1 2 4 6 8
Kilometers
N

Coordinate System: NAD 1983 UTM Zone 18N
Source:
Basemap: LIO, MNR
Seismic:Earthquakes Canada, GSC, Earthquake Search, April 2018
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

PROJECT No. 16-212

Updated Geosynthesis - Rolphton NPDWF EIS

DESIGN: NMP
CAD/GIS: NMP/ADG
CHECK: KGR
REV: 0

DATE: 2021-11-12

Geofirma Engineering Ltd

4.10 Descriptive Geomechanical Framework

The above information on overburden geotechnical properties and hazards, intact rock properties, rock mass properties, major discontinuities and structural features, regional and local in-situ stresses, regional and local seismicity, neotectonic and paleoseismicity, and seismic hazard assessment given in Section 5.2.5 are used to interpret and develop a descriptive geomechanical framework for the NPDWF site and surrounding area. The descriptive geomechanical framework of the NPDWF site includes the following key elements and information:

1. Overburden is comprised of well-drained, cohesionless, coarse granular soils for which static and dynamic properties will be similar. The results of grain size analyses confirm that all soils at the NPDWF site are predominantly coarse granular materials, with soil textures of fine to coarse sand, with fine to coarse gravel. Standard penetration tests of these soils indicate compact to very dense soils. Density and effective internal friction angle for these soils are 17-22 kN/m^3 and 30-50º, respectively.

2. The results of preliminary slope stability assessment considering earthquake-induced soil liquefaction, show that the slope from the NPDWF to the Ottawa River (North Slope) under current water level conditions is stable under static loading conditions and under loading conditions associated with a 1:2,250-year earthquake. Parts of the North Slope are stable, and parts of the North Slope are unstable under a 1:10,000-year earthquake. The North Slope is likely to fail during a 1:50,000-year earthquake.

   It is unlikely that the predicted failures of the North Slope will result in changes to groundwater flow from the NPDWF to the Ottawa River or allow direct exposure of groundwater to a new ground surface that would be established following earthquake-induced slope failures.

3. Intact rock geomechanical properties of the granitic gneiss, hornblende gneiss and dioritic gneiss that comprise the migmatitic biotite gneiss present at the NPDWF site are typical of crystalline gneissic rocks of the Canadian Shield. Based on testing of NPD cores, overall average geomechanical properties for shallow bedrock are: bulk density of 2.78 Mg/m^3, uniaxial compressive strength of 114 MPa, elastic modulus of 56.3 GPa and Poisson's ratio of 0.29. Testing shows the heaviest NPD rocks are dioritic gneisses, followed by hornblende gneisses and granite gneiss, and the strongest rocks are granite gneisses, followed by hornblende gneisses and dioritic gneisses.

   These trends in bulk density and UCS are consistent with expectations based on observed and analytically defined mineralogies of the rock samples. The relatively high mafic mineral content (e.g., biotite, hornblende) in the dioritic gneisses and to lesser extent the hornblende gneisses result in higher bulk densities and lower rock strengths (UCS). In contrast, the relatively higher quartz contents of the granitic gneisses result in higher rock strengths. Comparison of average NPD intact rock geomechanical properties to average CRL intact rock geomechanical properties suggests that NPD intact rocks, although strong, have lower peak strengths and elastic moduli than CRL intact rocks. These differences are attributed to higher mafic mineral (e.g., biotite and hornblende) and more strongly developed biotite gneissosity and other internal structural planes of weakness (i.e., foliation, schistosity, sealed/healed fractures, microcracks, etc.) in NPD rocks versus CRL rocks.

4. Rock mass quality at the NPDWF site based on 2019 outcrop mapping and drilling and core logging of shallow bedrock using standardized rock mass quality classification systems is good (RMR system) to fair (Q-system). Pre-excavation drilling and bedrock excavation observations at the NPD site, site investigations at the adjacent Rapides des Joachims site and inferences from the CRL property support the 2019 assessment with a rock mass quality rating is of fair to good quality. The overall average description of NPDWF rock mass is high strength intact rock that is moderately fractured with fair to good rock mass quality.

5. Major structural features found in the area of the NPDWF site include: primary faulting associated with the northwest-southeast striking, steeply southwest dipping Mattawa Fault that defines the course of the Ottawa River and subparallel related faults, secondary north-south and northeast-southwest striking structure oriented perpendicular to the Mattawa Fault, and tertiary east-west striking structure potentially related to the Grenville dyke swarm. The lineament interpretation, inspection of the bedrock excavations for construction of the NPD, and review of 2019 shallow bedrock coring and logging of BH18-05 to BH18-08 indicate that none of these major structural features intersect the bedrock of the NPDWF site.

6. Pre-construction drilling investigations of the NPD site indicated the presence of an east-west striking, moderately south-dipping, 90 m-wide shear zone within the footprint of the NPD reactor building. Inspection of bedrock excavation photographs and review of 2019 shallow bedrock drilling and logging indicates the suspected shear zone is not present at the reactor building excavation or in the vicinity of the NPDWF. The bedrock structural data from 2019 drilling and logging shows that overall rock quality and fracture spacing decrease with proximity to the Ottawa River. Such decreasing rock quality with proximity to the Ottawa River is most likely due to borehole proximity to the major Mattawa Fault that defines the alignment of the Ottawa River.

7. Bedrock exposed in the NPDWF excavation is sparsely to highly fractured (overall assessment of moderately fractured) with dominant northwest-southeast striking, moderately northeast-dipping fractures occurring subparallel to rock gneissosity and foliation, and subordinate subhorizontal sheeting fractures. 2019 logging and testing of BH18-05 to BH18-08 confirms the presence of subhorizontal and subvertical open fractures and metre- and sub-metre-scale fracture zones in shallow bedrock at the NPDWF. The combined four-borehole plot of ATV fractures shows a predominant set that is east-west to eastsoutheast-westnorthwest striking and south-southwest dipping, and minor sets that are subhorizontal and northeast-southwest striking and southeast dipping. The east-southeast striking southwest dipping fracturing is most likely associated with the regional Mattawa Fault that defines the alignment of the Ottawa River.

8. In-situ stresses in shallow bedrock are likely to show both thrust and normal faulting stress regimes. For thrust faulting, maximum regional horizontal stress is likely to be in the general east - west to north northeast-south southwest directions. For normal faulting shallow horizontal stresses may include a negative stress component (i.e., tensile stress), oriented perpendicular to the Ottawa-Bonnechere graben. The vertical stress component can be approximated to be the lithostatic stress and the magnitude can be reasonably estimated by assuming a bedrock unit weight of 26.5 kN/m^3.

9. A number of earthquakes have occurred and been felt in the vicinity of the NPD site. These include the M 5.0 earthquake at Val-des-Bois in 2010 within the Western Quebec Seismic Zone (WQSZ), a M 4.0 earthquake 30 km from Chalk River in 1963 and several larger earthquakes located more than 250 km from the NPD site (Montreal M 6 in 1732, Charlevoix M 7 in 1663, Timiskaming M 6.1 in 1935, and Cornwall M 5.8 in 1944). Most of the seismicity felt at the NPD site is from the WQSZ, an area of concentrated seismic activity, with events generally ranging from about M 2 to 4.5 and rare events over M 5, located about 150-300 km northeast of the Mattawa Fault and the NPDWF site. Isoseismic studies show that major events in the WQSZ attenuate westward through and around the graben.

10. The maximum recorded earthquake in the local area of the NPDWF was a Nuttli Magnitude 2.9 event that occurred March 11, 1995 about 10 km southwest of the NPDWF site. There is no apparent clustering of earthquakes along the Mattawa Fault below the Ottawa River indicating that the Mattawa Fault is not a localizer of earthquakes.

11. No neotectonic or paleoseismic studies have been completed at the NPD site. Given the lack of such studies at the NPD site, results of neotectonic and paleoseismic studies of the CRL site are used as a surrogate for the NPD site. Such reliance on CRL studies is reasonable and appropriate given the similar geological, regional structural and seismological setting of the NPD and CRL sites. Historical studies completed at the CRL site have not found evidence of neotectonics or paleoseismicity and have noted that the absence of paleoseismic structures in the CRL area is consistent with the absence of a surficial sediment section of sufficient composition, thickness and horizontal extent needed to have developed and preserved paleoseismic evidence, as well as the limited amount of bedrock exposure to detect small scale post-glacial displacements of bedrock due to neotectonics. These summary CRL observations indicate the potential for identification of paleoseismic structures at the NPD site, which has almost no post-glacial soft sediment and very limited bedrock exposure, is extremely low.

12. Probabilistic seismic hazard assessment (PSHA) completed in support of the proposed near surface disposal facility for the CRL property is relevant to the NPDDF site given the close proximity to CRL and similar nature of historical seismicity in regions surrounding NPDDF and CRL. The PSHA summarizes seismic source characterization and prediction of future earthquake characteristics and ground motions. The results of the PSHA show that the Iapetan Rift Margin (IRM) seismotectonic zone is the main contributing seismic source to overall hazard at all earthquake annual frequency of exceedances (AFEs) for the CRL and NPD sites. The IRM zone includes all major regional historical earthquakes within the St. Lawrence Rift, and the associated Ottawa-Bonnechere, Timiskaming and Saguenay grabens.

13. Estimated seismic hazard at selected annual frequencies of exceedances (AFEs) determined from the PSHA model are presented as peak ground accelerations (PGAs) in units of gravity (g = 9.81 m/s^2) for AFEs of 4.0E-04, 1.0E-04 and 1.0E-05. PGAs for AFEs of 4.0E-04, 1.0E-04 and 1.0E-05 are 0.25, 0.55 and 1.48 g. For reference the 2015 National Building Code of Canada uses an AFE of 4.0E-04 equal to a 2% probability of exceedance in 50 years.

14. Assessment of the potential for cracking of the underground structural walls of the NPDDF due to ground shaking from earthquakes was completed using a design basis earthquake (DBE) developed for the CRL property (1:2,250-year event at NPD site) and extrapolated earthquakes (1:10,000- and 1:50,000-year events) developed for the NPD site based on the Geological Survey of Canada seismic hazard model and Natural Resources Canada guidance. The 1:2,250-year DBE has PGA = 0.24 g loading due to an approximate M 6.0 earthquake. The NPD 1:10,000-year earthquake has PGA = 0.623 g due to an earthquake of M greater than 6.5. The NPD 1:50,000-year earthquake has PGA = 1.75 g due to an earthquake of M significantly greater than 6.5. The results of the assessment indicate that cracking of underground walls of the NPDDF structure would likely occur during all three events due to flexural and shear loading at elevations near the top of bedrock (124.1 mASL) to the ground surface (128.5 mASL).

5 FUTURE EVOLUTION OF THE NPDWF SITE

5.1 Introduction

Geosynthesis includes the description of the future natural evolution of a site (Nuclear Waste Management Organization, 2011; Jensen *et al*., 2009; McCrank, 2016b) that has potential to affect the proposed undertaking. For the NPDDF, future evolution is addressed as part of Alternative Evolution Scenarios in the Postclosure Safety Assessment TSD (Arcadis Canada Inc. *et al*., 2017a) that considers future events that may occur in the time frame after proposed period of 100 years of institutional controls.

5.2 Long-Term Natural Evolution

Natural processes that could affect the NPDDF, in the long term, include Ottawa River flooding, glaciation and geological disturbances.

5.2.1 Ottawa River Flooding – Short Term

Sections 8.11.4 and 9.13.6 of the EIS describe the potential for flooding of the NPDDF site in the short term. Flooding could occur due to high-water flooding from the Ottawa River, external flooding from heavy precipitation and flooding from failure of dams located upstream of the NPDDF on the Ottawa River.

The probability of flooding of the NPDDF site by river water in the short term is not considered likely because control of the river water is exercised by dams at the Des Joachims Generating Station located about 3 km upstream of the NPDDF (Athauda-Arachchige, 2015). The highest recorded level of the Ottawa River at NPD is 114 mASL. Seasonal fluctuations in the level of the river, between 110 and 114 mASL, would not affect the NPDDF. The only possibility for Ottawa River water to enter the nuclear portion of the NPDDF would be for the river level to rise above 118 mASL and enter the process drainage pipe – this is 4 m higher than maximum recorded levels in the Ottawa River. Water in the process drainage pipe would then need to seep through the grout backfill in order to contact the nuclear portion of the NPDDF.

The likelihood of external flooding due to extreme precipitation events is assessed in the facility Safety Analysis Report (Athauda-Arachchige, 2015). The assessment considered localized flooding due to surface run-off for meteorological extremes and/or spring thaw conditions. The assessment concluded that such flooding was extremely unlikely due to good drainage provided by site topography.

Based on Ontario Power Generation (1999), Athauda-Arachchige (2015) also assessed the potential for flooding due to failure of the Timiskaming, Otto Holden and Des Joachims dams located 193 km to 3 km upstream of the NPDDF site caused by flood waves and reservoir overtopping. The facility Safety Analysis Report concluded that the probability of dam(s) failure was negligible.

5.2.2 Ottawa River Flooding – Long Term Due to Climate Change

Potential for flooding of the NPDDF site is also assessed for the long term based on an assessment of effects of climate changes on precipitation at the NPD site. The assessment of a changing climate and climate change effect on precipitation at the NPD site is based on the CNL Near Surface Disposal Facility Project Draft EIS Report, Appendix 9.0-1 Climate Change (CNL, 2017). The future climate conditions in this report were described using the outputs from General Circulation Models (GCMs) accepted by the Intergovernmental Panel on Climate Change (IPCC) for various representative concentration pathways (RCPs) defining the radiative forcing in 2100. This CNL climate assessment used data from Chalk River AECL climate station to describe current climate conditions. The results of the CNL climate change assessment (CNL, 2017) are applicable to the NPD site because of the following:

1. The climate model projections are not made at a location, but for a series of grid cells in the scale of hundreds of kilometres in size (i.e., 1x1 degree horizontal resolution);

2. Due to the proximity of the two sites (approximately 27 km) the climate model data from the same grid cell representative for the CRL near surface disposal facility (NSDF) site are also representative for the NPD site; and

3. Chalk River AECL climate station is the station closest to the NPD project with the longest continuous and most complete data set available that falls near the desired period (1981 through 2010) and at a similar latitude and elevation as the NPD site.

The future climate model projections and RCPs available under the IPCC Fifth Assessment Report (AR5; IPCC, 2013) were used as a set of 90 unique modelling projections (i.e., 30 GCMs and three RCPs scenarios) to better capture the probable range of results. The three RCPs, namely, RCP 2.6, RCP 4.5 and RCP 8.5 are based on the future levels of radiative forcing projected to occur by 2100. Two time horizons were used for climate change model projections:

- 2041 to 2070 (denoted as Mid Term) and
- 2071 to 2100 (denoted as Far Term).

Table 2.1-1 of the NPD EIS provides the following timelines for the NPD project:

- Decommissioning Execution phase: 2021 to 2022;
- Institutional Control phase: minimum 2022 to 2122; and,
- Post-Institutional Control phase: beyond 2122.

Because the Decommissioning Execution phase occurs from 2021 to 2022, it occurs before even the earliest of the climate time horizons above. Whereas the Institutional Control phase and Post-Institutional Control phase span the Mid Term time horizon, Far Term time horizon, and beyond. Long-term effects of climate change (beyond 2100) are highly dependent on the emissions scenarios (RCPs) and are available as global values (not particularly for the NPD project region). Post-Institutional Control phase in the NPD project considered time period (2122+) and the climate change in precipitation for this phase is based on the long-term effects.

The projected annual precipitation for the NPD project for the Mid Term (2041 to 2070) period, compared to current climate observations, indicates that the future annual precipitation rates will be consistent with historical observations (CNL, 2017). The projections of annual precipitation for the Far Term (2071 to 2100) period show a slight increase in precipitation range relative to the 2041 to 2070 period. However, the range of future projections still covers the range of historical observed precipitation (see Figures 4 and 5 in Appendix 9.0-1 Climate Change, NSDF EIS, [CNL, 2017]).

Analysis of monthly projections shows that the difference between the current climate normal precipitation and the projected mean for the Mid Term and the Far Term precipitation is the largest in the fall and early winter (September through December). November shows the largest precipitation increase in both the Mid Term and Far Term (Tables 5 and 6 in Appendix 9.0-1 Climate Change, NSDF EIS, [CNL,2017]).

The future climate until 2100 in the NPD project region is projected to be likely warmer and slightly wetter, consistent with the observed current climate trends (1981 through 2006) at the Chalk River AECL climate station. The projected changes in annual and seasonal precipitation show an increase for both the Mid Term and Far Term (Table 7 and 8 in CNL, 2017).

Table 5.1 shows that the projected change in precipitation for the NPD project region until 2100 will be 88.6 mm higher than current climate normal of 852 mm at the Chalk River AECL station (based on the NSDF EIS, Appendix 9.0-1, Table 9, [CNL,2017]). This increase by approximately 10% in the projected annual average precipitation by the year 2100 will result in total annual precipitation of 940.6 mm. Long term projections predict global increases in precipitation past 2100 with increasing temperature (IPCC, 2013); however, no regional projections past 2100 are available in the literature.

Table 5.1 Projected Climate for Mid Term, Far Term and Long Term (from CNL, 2017)

Period and Variable	***Temperature***		***Precipitation***	
	Value	***Units***	***Value***	***Units***
Current Climate Normal (1981-2006)	5.7	ºC	852	mm
Mid Term Projected Changes (2041-2070)[1]	2.2	ºC	72.0	mm
Far Term Projected Change (2071-2100)[1]	3.0	ºC	88.6	mm
Long Term Projected Changes (2281-3000)[2]	0.6 to 7.8	ºC	1 to 3	%/ºC

Notes:
1 = Projected changes represent changes above current climate (1981-2006) for the NSDF Project region.
2 = Projected changes represent the changes above the reference period of 1986-2005 and are global values.

The climate change effects on precipitation at the NPD site are summarized as following climate factors and their trends (based on CNL, 2017):

- Amount of rain is projected to increase for the NPD project region up to 2100. Precipitation is projected to increase with temperature past 2100 at a global level. The largest precipitation increase is projected in spring and winter (Stone *et al*., 2000).
- Frequency of heavy rainfall events is projected to increase in Ontario until 2100 (Coulibaly and Shi, 2005; IPCC, 2013; Kunkel *et al*., 1999; Warren and Lemmen, 2014), but there are still

relatively large uncertainties associated with projections of extreme precipitation. In particular, a 1-in-20-year storm would become a 1-in-10-year storm by mid-century for mid to high latitudes under higher emission scenarios (Warren and Lemmen, 2014). Long term projections (beyond 2100) predict continued increases; no regional projections past 2100 are available in the literature.

- Amount of rainfall per event is projected to increase in Ontario (Coulibaly and Shi, 2005; IPCC, 2013; Kunkel *et al*., 1999). Long-term projections predict continued increases - however, no regional projections past 2100 are available in the literature.
- Amount of snow and frequency of heavy snowfall events is projected to increase in the northern latitudes in the near and mid-term (Colombo *et al*., 2007; IPCC, 2013; Zhang *et al.,* 2001).

Given the large elevation of the NPDDF above the river (see Figure 2.2 and Section 2.2.2) there is no potential for flooding of NPD site by the Ottawa River. The NPD site's sloping landscape diverts heavy precipitation from the facility to the Ottawa River mitigating potential external long-term flooding from site drainage.

5.2.3 Glaciation

According to Peltier (2011), 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. The NPD area is located near what was the southern edge of the Laurentide ice sheet during its sequence of Late Quaternary expansions (e.g., Peltier, 2011).

Reglaciation of the Canadian land mass is most likely to begin approximately 60,000 years from present according to Peltier (2011). This time frame is generally supported by current understanding of the long-term effects of global warming which indicates the next ice age may not occur for 100,000 years as a result of anthropogenic climate change (Ganopolski *et al*., 2016).

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 NPD site. Glacial loading as an ice sheet thickens and advances will result in downwarping or subsidence of the crust. When an ice sheet retreats and decreases in mass, isostatic forces cause rebound and uplift of the crust. These two processes, downwarping and rebound, can have a significant effect on the rock mass and any structures therein.

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. Though there have been divergent estimates made of the depth of glacial erosion that has taken place on the Canadian Shield, from as little as a few tens of metres (Flint, 1947) to as much as hundreds of metres (White, 1972), studies, such as by Kaszycki and Shilts (1980) who investigated glacial erosion of the Canadian Shield on the northwest coast of Hudson Bay concluded that between 6 m and 20 m of erosion took place in the region during the last glaciation. This estimate is comparable to that cited by Hallet (2011) at several metres to a few tens of metres for a one glacial cycle based on general erosion rates in the Canadian Shield.

Based on above glacial timing and erosion rates, the Postclosure Safety Assessment TSD assesses an early glaciation scenario, which conservatively assumes the entire facility would be removed and distributed by a glacier after 60,000 years.

5.2.4 Geological Disturbances and Hazards

Geological disturbances and hazards assessed as part of future evolution of the NPDDF site are those due to tectonism. The tectonic processes that affect the structures and properties of the earth's crust and its evolution through time include orogenic events (mountain building), development of cratons (i.e., Canadian Shield), neotectonism, earthquakes (i.e., fault rupture or reactivation), and volcanism.

The last major orogenic events that affected the NPD area were the Grenville Orogeny (~1100 million years ago) and the Alleghenian Orogeny (~250 million years ago). Given the location of the NPD within the central part of the stable North American plate - far removed from active plate margins, and the time scale of orogenic events, there is no possibility of geological disturbance due to orogenies or craton building over time frames relevant to safety of the NPDDF.

Neotectonism and related earthquakes have potential to reactivate existing structural features such as large-scale faults and shear zones. Given the pre-existing planes of weakness of faults and shear zones, neotectonism and earthquakes are more likely to reactivate such structural features than create new structural features. McCrank (2016b) concluded for the CRL site, that significant disturbances and reactivation to existing structures was unlikely to occur due to future neotectonism and earthquakes. The basis for this conclusion is relevant to the NPDDF site and is repeated here:

1. Several neotectonic studies of Quaternary sediments on the site failed to find any evidence of disturbance of the sediments since they were deposited 10,000 years ago.

2. The seismic monitoring network installed on the CRL site shows low seismicity with no patterns of continued events. Seismicity in the vicinity of the NPD is typically less than M 3.0 with no apparent pattern to mapped major structural features such as the Mattawa Fault or other OGS-mapped faults.

3. The existing fracture network intersected by boreholes consists largely of mineral filled fractures that are intact, closed and likely tight, despite having been subjected to disturbances such as the several glacial events, formation of the Ottawa-Bonnechere graben and seismic events related to the WQSZ.

4. The rock has very high RQD values, despite being located on the margin of a graben structure and despite having been subjected to number of events as mentioned in bullet 3 above

5. Anomalous attenuation of felt effects related to WQSZ seismic events in Quebec occurs at the Ottawa-Bonnechere graben rift zone (Forsyth, 1981).

There is no evidence of volcanism in the NPD area younger than early Cretaceous (100 – 145 million years ago). The youngest magmatic activity that can be considered to be associated with volcanism in the broad regional area around NPD occurred in Western Quebec in the Montreal area. Represented by the circular Monteregian intrusions, that include Mont Saint-Hilaire, Mont Rougemont, Mont Yamaska and Mont Oka, these are believed to represent sub-volcanic complexes active about 125 million years ago (McCrank, 2016b). All other magmatic activity is much older. It is extremely unlikely that new volcanic activity will occur in a time frame relevant to the NPDDF.

5.2.5 Seismic Hazard Assessment

Information on seismic hazard assessment of the NPDDF site is summarized in Section 9.13.7 of the EIS (Arcadis Canada Inc., 2017b) and qualitatively by Athauda-Arachchige (2015) as part of the Safety Analysis Report for NPD decommissioning. More detailed quantitative assessments of seismic hazard near and at the NPDDF site are provided by McCrank (2016b) and AECOM Canada Ltd. (2018) for the CRL property and by Arjmand (2018) and Zhang (2021) as part of a cracking assessment of the underground NPDDF structures.

McCrank (2016b) summarizes the results of a probabilistic seismic hazard assessment (PSHA) completed in support of the proposed geological waste management facility for the CRL property. This detailed work on seismic source characterization and prediction of future earthquake characteristics and CRL ground motions are translatable to the NPDDF site given the close proximity to CRL and similar nature of historical seismicity in regions surrounding NPDDF and CRL. However, the work summarized by McCrank (2016b) has been updated by AECOM Canada Ltd. (2018), who completed a PSHA in support of the near surface waste disposal facility (NSDF) at CRL.

AECOM Canada Ltd. (2018) completed the PSHA using the areal seismic source zones developed by the Geological Survey of Canada (GSC) that assume a uniform rate of earthquake occurrence within a spatial region. For each areal source zone, the fifth generation GSC model defines the area, seismogenic thickness, maximum earthquake magnitude and recurrence parameters. The GSC seismic source zone model was recently used to update the 2015 National Building Code of Canada seismic design data.

AECOM Canada Ltd. (2018) evaluated earthquake-induced ground motions with return periods of 2,500, 10,000 and 100,000 years, which are equivalent to AFE's of 4.0E-04, 1.0E-04 and 1.0E-05, respectively. Table 5.2 summarizes the estimated seismic hazard at selected AFEs determined from the PSHA for the CRL property. Table 5.2 lists peak ground acceleration (PGA) in units of gravity (g = 9.81 m/s^2) for AFEs of 4.0E-04, 1.0E-04 and 1.0E-05, as well as the approximate earthquake M creating the listed ground motions. For reference, the 2015 National Building Code of Canada uses an AFE of 4.0E-04 equal to a 2% probability of exceedance in 50 years.

The results of the AECOM Canada Ltd. (2018) PSHA show that the Iapetan Rift Margin (IRM) seismotectonic zone of the GSC R2 Model is the main contributing seismic source to overall hazard at all AFEs for the CRL and NPD sites. The IRM zone includes all major regional earthquakes within the St. Lawrence Rift, and the associated Ottawa-Bonnechere, Timiskaming and Saguenay grabens.

Table 5.2 Summary of Seismic Hazards Estimated for CRL Property (from AECOM Canada Ltd., 2018)

Annual Frequency of Exceedance	*Earthquake Probability (years)*	*Approximate Earthquake Magnitude*	*Peak Ground Acceleration on Hard Rock (g)*
4.0E-04*	1:2,500	6.3	0.25
1.0E-04	1:10,000	6.4	0.55
1.0E-05	1:100,000	6.6	1.48

Notes: *AFE for 2015 National Building Code of Canada

Arjmand (2018) and Zhang (2021) provide an assessment of the potential for cracking of the underground structural walls of the NPDDF due to ground shaking from earthquakes. The Arjmand (2018) assessment considered 1:2,250-year and 1:10,000-year earthquakes. The Zhang (2021) assessment is a revision of the Arjmand (2018) assessment considering an additional 1:50,000-year event. Lacking specific seismic monitoring data for the NPDDF site, the Arjmand and Zhang analyses are based on a Design Basis Earthquake (DBE) for the CRL property and extrapolated earthquakes developed for the NPD site based on the Geological Survey of Canada seismic hazard model (Natural Resources Canada [NRCan], 2018b). Table 5.3 summarizes the seismic hazards used in the Arjmand (2018) and Zhang (2021) assessments.

Table 5.3 Summary of Seismic Hazards Estimated for NPD Property (from Arjmand, 2018 and Zhang, 2021)

Annual Frequency of Exceedance	*Earthquake Probability (years)*	*Approximate Earthquake Magnitude*	*Peak Ground Acceleration on Hard Rock (g)*
4.4E-04	1:2,250	6.0	0.24
1.0E-04	1:10,000	>6.5	0.623
2.0E-05	1:50,000	>>6.5	1.75

The CRL DBE has PGA = 0.24 g loading due to an approximate M 6.0 earthquake with a probability of 1:2,250 years at the NPD site. The DBE PGA of 0.24 g is essentially the same as the 95th percentile PGA (0.25 g) determined from the PSHA of the CRL property for the National Building Code of Canada AFE of 4.0E-04. The 1:2,250-year seismic load considered in the Arjmand assessment was based on a DBE Standard Ground Response Spectra (normalized to 0.24 g) with 5% damping.

The 1:10,000-year earthquake (M >6.5) was developed by obtaining the seismic hazard for NPD using the seismic hazard calculator provided by NRCan (2018b). Following the recommendation given by NRCan for low probability earthquakes, the 1:10,000-year earthquake was characterized by extrapolating on a log-log scale using the PGAs of the 1:1000-year earthquake and the 2% exceedance in 50-year earthquake (AFE of 4.0E-04). NRCan recommends extrapolation using this method to determine an earthquake hazard which may not necessarily be accurate but is likely conservative. The PGA representing this extrapolation is 0.623 g and is conservative with respect to the AECOM Canada Ltd (2018) data for the CRL site (PGA = 0.55 g for AFE of 1.0E-04). The 1:10,000-year seismic load considered in the Arjmand and Zhang assessments was based on a Standard Ground Response Spectra (normalized to 0.623 g) with 7% damping.

The 1:50,000-year earthquake (M>>6.5) was developed following the same method used to develop the 1:10,000-year earthquake. The PGA representing this earthquake based on NRCan recommended extrapolation is 1.75 g and is conservative with respect the AECOM Canada (2018) data for the CRL site (PGA = 1.48 g for a AFE of 1.0E-05). The 1/50,000-year seismic load considered in the Arjmand and Zhang assessments was based on a Standard Ground Response Spectra (normalized to 0.623 g) with 7% damping.

The analyses of Arjmand (2018) and Zhang (2021) considered dead load and seismic load in combination with earth pressure and seismic earth pressure. A 3-D finite element model based on NPDDF building stick representation was used to assess flexural and shear cracking potential of concrete walls.

The results of the assessment indicate that cracking of underground walls of the NPDDF structure would likely occur due to both flexural and shear loading at elevations from near the top of bedrock (124.1 mASL) to the ground surface (128.5 mASL) for all seismic events. The seismically-induced cracking is due to a lack of shear capacity in the building structure above the bedrock surface. The Arjmand (2018) and Zhang (2021) studies did not indicate cracking of the NPDDF structure below the bedrock surface as the concrete backfill and bedrock provide sufficient bearing resistance to seismic forces.

Sections 4.2.3 and 4.2.4 describe the effects of Table 5.3 earthquakes on soil liquefaction and slope stability at the NPDWF site. The results of the preliminary slope stability assessment that considers earthquake-induced soil liquefaction, show that the North Slope under current water level conditions is stable under static loading conditions and under loading conditions associated with a 1:2,250-year earthquake. Parts of the North Slope (cross section C-C') are stable, and parts of the North Slope (slightly steeper slope of cross section D-D') are unstable under a 1:10,000-year earthquake. The North Slope is likely to fail during a 1:50,000-year earthquake. The plan view location of cross sections C-C' and D-D' and the actual cross sections are presented in Figure 4.1 and Figure 4.2, respectively.

6 SUMMARY AND CONCLUSIONS

6.1 Descriptive Geosphere Site Model

The descriptive geosphere site model of the NPDWF is outlined below based on the descriptive geological, hydrogeological and geomechanical frameworks given in Sections 2.6, 3.9 and 4.10, respectively. The descriptive geosphere site model of the NPDWF includes geological, hydrogeological and geomechanical models.

6.1.1 Descriptive Geological Site Model

1. The NPDWF site is located on the northeast-facing slope of a former glacial and current fluvial spillway of the Ottawa River. The elevation of the ground surface drops from 164 mASL near Highway 17, to 128 mASL at the NPD buildings, to 111 mASL at the Ottawa River. In the immediate area of the NPDWF buildings and structures, the post-glacial fluvial sand and gravel deposits of the spillway are mixed with sand and gravel fill to form the surficial overburden and directly overlay bedrock. Elsewhere the fluvial sand and gravel deposits overlay silty sand to sand, gravel and cobble and boulder glacial till. The upper metre or so of glacial till unit is locally washed by fluvial wave action resulting in removal of silt and development of material similar to the overlying fluvial sand and gravel deposits.

2. Overburden thickness at the NPD site ranges from about 2 m near the Ottawa River up to about 15-18 m southwest of the NPDWF and thinning to 5 to 7 m near Highway 17. Overburden thickness adjacent to the NPDWF building averages 5 to 6 m. Overburden thickness northwest and southeast of the NPDWF is interpreted to average about 10 to 15 m based on available borehole data and OGS (2010) and Gadd (1963a) overburden mapping. The noteworthy bedrock high at MW18-06 creates an overburden thickness of about 3 m and limits the southeastward extent of the fluvial sand and gravel unit from the area of the NPDWF. Overburden thickness northwest of the NPDWF thins to zero where bedrock is exposed in the northwest part of the NPD site. Near and southwest of Highway 17 the glacial till is the surficial overburden.

3. Bedrock at the NPD site is Precambrian Canadian Shield. Historical regional mapping of the Precambrian bedrock places the NPD site within the lithostructural Opeongo Domain of the Algonquin (Lac Dumoine) Terrane of the Central Gneiss Belt, of the Grenville Province of the Canadian Shield. Mapping of bedrock outcrops as part of 2019 geoscientific characterization of the NPD site identify NPD bedrock geology as interlayered granitic to monzonitic gneiss and biotite hornblende gneiss with minor gabbroic gneiss. Core logging of shallow bedrock boreholes completed as part of the same 2019 investigations show the subsurface bedrock is principally an interlayered sequence of metre-scale bands of granitic gneiss and hornblende gneiss, with minor bands of dioritic gneiss and hornblende K-feldspar gneiss. Metre-scale to sub-metre-scale pegmatite dykes and occasional diabase dykes intrude the gneissic rock sequence. Although these bedrock descriptions appear different, they are all consistent with the best overall description of the bedrock rock type at the NPD site as migmatitic biotite gneiss. The inferred mineralogy based on available rock descriptions and 2019 petrographic work completed on both NPD outcrop and borehole core samples is plagioclase>quartz>K-feldspar>amphibolite~biotite. Based on Streckeisen

ternary plot, the dominant lithologies at the NPD site vary from granite/granodiorite to quartz monzodiorite to quartz diorite to diorite/gabbro.

4. Regional and local structural geology of the NPD site is dominated by the major regional structural feature of the Mattawa Fault that defines the course of the Ottawa River and the northern limit of the regional Ottawa-Bonnechere graben system. The Ottawa-Bonnechere graben system runs from Montreal to Lake Timiskaming, displays a rift valley morphology and is about 60 km wide and 700 km long. In the area of the NPDWF, the graben trends west-northwesterly with the major, steeply southwest-dipping, Mattawa Fault defining the northeast margin of the graben. The graben probably developed as a plume-generated failed rift related to the opening of the proto-Atlantic (Iapetus) Ocean. The graben system is characterized by a network of faults and lineaments that strike east-west and northwest-southeast. This fault system developed after the peak of Grenville metamorphism (1180 to 1030 million years ago) and has been active intermittently since that time, with nodes of activity about 575, 450-420, and 190-170 million years ago.

5. Results of a lineament mapping study completed over a 20 km by 20 km area centred on the NPDWF site, show that major brittle structures as faults oriented east-southeast – west-northwest (120-140º azimuth) are located north of the site, along the Ottawa River and south of the site in line with a series of small lakes including Colton Lake, Tee Lake, Lower/Upper Pergeon Lake (from northwest to southeast). A series of less well-defined east-southeast – west-northwest, north-south and east-west trending lineaments are located within close proximity to the site; however, there is no evidence to suggest that any of these lineaments extend to or within the NPD or NPDWF site boundaries.

6. Historical regional, local and site geoscientific information indicates the potential occurrence of the following structural features in the bedrock of the NPDWF site: east-west striking, moderate south-dipping, 90 m-wide shear zone, fractures and minor shear zones associated with northwest-southeast striking, moderate (~30º) northeast dipping gneissosity and foliation, and subhorizontal sheeting joints. Contoured pre-excavation bedrock surfaces and excavation photographs do not indicate the presence of an east-west striking, moderately south-dipping, 90 m-wide shear zone as interpreted from pre-excavation diamond drilling investigations. Historical photographs also show that the bedrock at the NPD powerhouse excavations is sparsely to highly fractured (visually estimated frequencies of 5-30 fractures/m) with dominant northwest-southeast striking, moderately northeast-dipping fractures and subordinate subhorizontal sheeting fractures.

7. 2019 outcrop mapping of the NPD site and shallow bedrock drilling (BH18-05 to BH18-08) in the vicinity of the NPDWF provide important information on the geological structural characteristics of the bedrock at the NPD site. These data on fracture occurrence and orientation at the NPD site indicate primary fracturing orientation of northwest-southeast strike with both southwest and northeast dips, and secondary fracturing orientation of north-south strike and subhorizontal dip to the east. These on-site facture orientations from 2019 investigations are generally evident in the lineament study and NPD bedrock excavations. Borehole natural fracture frequency and RQD measurements indicate the shallow bedrock to 50 m depth below top of competent bedrock is moderately fractured and of fair to good rock quality, with an observed increase in fracturing and decrease in RQD with proximity to the Ottawa River. The 2019 geological structural data from the four shallow bedrock boreholes indicate the presence of metre-scale and sub-metre fracture zones,

and rubble/broken zones and subhorizontal sheeting fractures. The 2019 shallow bedrock investigations show no evidence of a 90 m-wide, east-west striking, south-dipping shear zone or similar major structural features in the vicinity of the NPDWF.

6.1.2 Descriptive Hydrogeological Site Model

1. Local groundwater flow systems at the NPD site are influenced by recharge rates, topography and geology. Local groundwater flow systems within the permeable sand and gravel overburden will be the dominant groundwater system at the NPDWF site. These local groundwater flow systems will likely be recharged near Highway 17 and without the tile drain would discharge along the ground slope extending northeast to the Ottawa River and directly to the Ottawa River. Local flow also occurs within shallow bedrock likely to depths of about 30 to 50 m; however, these flow rates are typically a small percentage of flow rates in the overlying sandy deposits.

2. The available geological and hydrogeological data for the NPD site supplemented by similar regional information from the CRL property and surrounding area indicate that the hydrogeology of the NPDWF site is conveniently described with reference to five hydrostratigraphic units. The five hydrostratigraphic units at the NPDWF site are: sand and gravel fill unit, fluvial sand and gravel unit, silt to cobble glacial till unit, boulder glacial till unit and shallow bedrock unit.

3. The sand and gravel fill hydrostratigraphic unit including reworked fluvial deposits and excavated bedrock is the youngest hydrostratigraphic unit. It is present near the NPD buildings and in the area northeast of the buildings that were subject to excavation for construction of water intake and discharge lines and tile drainage lines between the buildings and the Ottawa River. Fill thickness at the NPD site is variable ranging from about 2 m near the Ottawa River to about 5-6 m near the NPD building. Based on 2019 final groundwater model calibration, the best estimate for hydraulic conductivity of the sand and gravel fill hydrostratigraphic unit is 3.4E-04 m/s increased from an initial pre-modeling estimate of 1.0E-04 m/s. Lacking other information, the sand and gravel fill unit is assumed to be isotropic with porosity of 0.3.

4. The fluvial sand and gravel hydrostratigraphic unit is the most widespread permeable overburden unit at the NPD site and is the youngest hydrostratigraphic unit consisting of native material. It includes sand with various amounts of gravel, boulders and trace amounts of silt. The thickness of this hydrostratigraphic unit averages 5 m to 10 m at the NPD site. It extends southwest from NPDWF toward Highway 17 (to about BH18-02), northwest to at least Landfill 2 (NPD-14) but is limited to the southeast of NPDWF by the bedrock high at BH18-06. Based on on-site hydraulic conductivity measurements, the fluvial sand and gravel unit is heterogeneous, with a wide range of conductivity (2.0E-07 to 1.0E-03 m/s). The 2019 final groundwater model calibration shows that the best estimate for horizontal hydraulic conductivity of the fluvial sand and gravel hydrostratigraphic unit is between 2.4E-05 and 1.0E-03 m/s with an anisotropy ratio of 3.9 reflecting the presence of lower hydraulic conductivity silt layers. Fluvial sand and gravel unit porosity is 0.4.

5. The silt to cobble glacial till hydrostratigraphic unit is the most widespread overburden hydrostratigraphic unit at the NPD site. It is found at ground surface near Highway 17 and at depth below the fluvial sand and gravel hydrostratigraphic unit northeast of Highway 17 on the NPD site.

The upper metre or so of the silt to cobble glacial till unit has been locally subject to fluvial erosion by wave action resulting in a texture and likely hydraulic conductivity similar to the overlying fluvial sand and gravel unit. The thickness of the silt to cobble glacial till unit ranges from 0 to 2 m near NPDWF up to 5 to 10 m northwest and southeast of NPDWF. Available hydraulic testing suggests two sets of K values are necessary to represent silt to cobble glacial till. Testing completed at borehole NPD-5 and MW18-01 to MW18-04 indicates geometric mean K of 3.3E-08 m/s that is considered representative of a silty sand member located southwest of MW18-03 and MW18-04. A K value range of 2.0E-05 to 2.0E-04 m/s is used as the best estimates of hydraulic conductivity for the sand to cobble till member in the vicinity of NPDWF from site characterization recognizing the potential for presence of metre thick layers with elevated K that are likely glacial-fluvial washed beach deposits. The 2019 final groundwater model calibration indicates a K range of 2.0E-08 to 2.9E-04 m/s for the silt to cobble glacial till hydrostratigraphic unit with higher values near the NPDWF and the Ottawa River. All till K estimates are assumed to be isotropic. Silt to cobble glacial till porosity is 0.3.

6. The boulder glacial till hydrostratigraphic unit is the oldest overburden unit at the NPD site and locally directly overlies competent bedrock in areas of bedrock depression. It consists of metre-size boulders with granular matrix material and underlies silt to cobble glacial till and fluvial sand and gravel where the silt to cobble till is absent. It is found northwest and southwest of the NPDWF based on intersections with BH18-03, BH18-05, BH18-09 and BH18-10 with thicknesses of 2 to 5 m. Hydraulic testing data suggest the best estimate of hydraulic conductivity for the boulder till as of 1.7E-05 m/s, recognizing the potential for inclusion of sub-metre thick higher K gravel and cobble layers with K up to 1.7E-03 m/s. The 2019 final groundwater model calibration indicates hydraulic conductivity of 1.8E-05 m/s for the boulder glacial till hydrostratigraphic unit, essentially the same as the best estimate from site characterization. The boulder till is assumed to be isotropic with respect to K. Boulder glacial till porosity is 0.3.

7. The shallow bedrock hydrostratigraphic unit at bedrock depths of 0 to 50 m is the only bedrock unit considered for the NPDWF site based on the relatively shallow excavations completed for construction of the NPD (about 18 m into rock) and the assumption that essentially all of the local groundwater flow in bedrock will occur in the upper 50 m of bedrock. Continuous profiles of straddle-packer hydraulic testing completed in the four shallow bedrock boreholes BH18-05 to BH18-08, indicate an overall geometric mean horizontal K is 1.7E-07 m/s based on a range of measurements of 2.8E-09 to 6.6E-06 m/s. As the hydraulic conductivity of intact bedrock is several orders of magnitude lower than the lowest K value measured from straddle-packer testing, all of the reported K values are attributed to the presence of fractures, either as individual discontinuities or as part small fracture zones.

   The majority of intervals with elevated hydraulic conductivity (i.e., >~ 1.0E-06 m/s) correlate with specific subhorizontal and subvertical open fractures and metre- and sub-metre-scale fracture zones. The best initial estimates of hydraulic conductivity in shallow bedrock at the NPD site are 7.3E-08 m/s near BH18-05, BH18-06 and the NPDWF, and 3.6E-07 m/s near BH18-07, BH18-08 and below the Ottawa River. Based on the frequency and orientation of borehole and outcrop fractures the shallow bedrock K is isotropic. The spatial variability of K correlates with observed increases in fracture frequency and decreases in RQD with proximity to the Ottawa River. These spatial trends most likely reflect attendant fracturing related to the regional Mattawa Fault that defines the course of the Ottawa River.

The 2019 final groundwater model calibration indicates hydraulic conductivities of 3.3E-07 and 9.3E-08 m/s for the shallow bedrock hydrostratigraphic unit near and away from the Ottawa River, respectively. These model K values are essentially the same as the best estimates from site characterization. Best estimate of porosity, for the moderately fractured and fair to good rock quality shallow bedrock is 0.005.

8. Shallow overburden groundwater is dilute (total dissolved solids [TDS] of 100 to 200 mg/L), Ca-HCO_3 type with Na-Cl/SO_4 as subordinate major ions. The NaCl signature likely reflects road salting of upgradient Highway 17 and NPD site roads. The shallow overburden groundwater is moderately oxidizing as evident by low iron concentrations (about 10 to 100 µg/L) and for Landfill 2 Eh of 200 to 530 mV. Deeper overburden groundwater from depths of 12 to 20 mBGS is less dilute (total dissolved solids [TDS] of 210 and 545 mg/L), Na-HCO_3 type with Ca-Cl/SO_4 as subordinate major ions. The elevated TDS and NaCl/SO_4 signature relative to shallow overburden groundwater analyses likely reflects road salting of upgradient Highway 17 and NPD site roads (NaCl), deeper sampling intervals and influence of shallow bedrock groundwater (SO_4). Compared to shallow overburden groundwater, deeper overburden groundwater is slightly less oxidizing as evident by slightly higher iron concentrations (81.5 and 168 µg/L) and Eh of 343 and 332 mV. Tritium, gross alpha activity and gross beta activity are generally low in overburden groundwater. Only gross alpha activity at MW19-09 in deep overburden groundwater (1.1 Bq/L) slightly exceeded Health Canada drinking water guidelines or screening levels (0.5 Bq/L).

9. Shallow bedrock groundwater in proximity to the NPDWF is dilute (TDS of ~200 to 925 mg/L), predominantly Na-HCO_3 type with Ca-Cl/SO_4 as subordinate major ions. Locally near MW18-06-P4, MW18-06-P6 and MW18-07-P7 the shallow bedrock groundwater is Na-SO_4 type with Ca-Cl/HCO_3 as subordinate major ions. Near MW18-07-P1 and MW18-07-P2 the shallow bedrock groundwater is Ca-HCO_3 type with Na/Mg-Cl/SO_4 as subordinate major ions. Compared to inferences from CRL data, the 2019 shallow bedrock groundwater at NPD is slightly more oxidizing as evident by lower iron concentrations (<5 to 35 µg/L) and Eh of 321 to 412 mV. Relatively elevated tritium concentrations (i.e., 650 to 1350 Bq/L) are reported near MW18-05 and MW18-06 upgradient of the NPDWF. Downgradient of the NPDWF at MW18-07 and MW18-08 tritium concentrations are lower at <100 to 190 Bq/L. Gross alpha and gross beta activity in shallow bedrock range from 0.11 to 3.6 Bq/L and <0.10 to 3.7 Bq/L, respectively. The cause of the elevated tritium concentrations in shallow bedrock upgradient of the NPDWF is not known.

10. The relatively wide range of shallow bedrock groundwater chemistries suggests that some CMT monitoring intervals are influenced by residual drilling water used for bedrock coring which was mostly Ottawa River water. Given the very dilute chemistry in Ottawa River water, the reported 2019 chemistry of many of the shallow bedrock monitoring intervals may be underestimated. Subsequent groundwater sampling of the shallow bedrock is necessary to confirm this suggestion and representativeness of the 2019 data for shallow bedrock groundwater.

11. The major ion and trace element chemistry and radiological chemistry of the tile drain water as reported from sampling in 1990, 2014 and 2019 are very similar to shallow overburden groundwater at the NPDWF site. This similarity and plotting of major ion chemistry of tile drain water and other water types at the NPD site on Piper diagrams shows that groundwater from the area of Landfill 1 and the reactor area are the most likely sources of water to the tile drains. This is entirely reasonable as these two groundwater types are in close proximity to the tile drains or are clearly upgradient of the tile drains. Piper diagrams also show that upper and lower shallow bedrock groundwater and Ottawa River water are not sources of water to the tile drains.

12. Groundwater flows in the saturated sand and gravel fill, fluvial sand and gravel and glacial till hydrostratigraphic units are predominantly from southwest to northeast across the NPD site toward the tile drains and the Ottawa River. For shallow bedrock, the predominant groundwater flow direction assuming a lack of major structural features such shear zones and faults is also from southwest to northeast toward the Ottawa River.

13. Recharge of the local groundwater system at the NPDWF site occurs primarily in the highland area northeast and southwest of Highway 17 where glacial till is exposed at surface. Some recharge also occurs on the upslope areas of the site between Highway 17 and Landfill 1 and near Landfill 2 where permeable alluvial (fluvial sand and gravel) deposits are exposed at surface. Groundwater discharge areas as springs and wetlands were historically noted on the overburden ground slopes northwest of NPDWF and between the area of the NPDWF and the Ottawa River prior to NPD construction. These springs are no longer observed at the site due groundwater collection by the tile drains.

    A large portion of groundwater southwest and west of the NPD building, at least as far as Landfill 1 and likely upgradient of Landfill 1 and toward Landfill 2 discharges to the tile drain system that was trenched into the surface of the bedrock, surrounds the NPD reactor building and drains into the Ottawa River. Groundwater flow in the underlying shallow bedrock discharges upward to the overlying overburden in the area upgradient of the NPDWF, but mostly discharges to the Ottawa River either directly or via the Mattawa Fault that defines the course of the Ottawa River.

14. Linear groundwater velocities calculated from Darcy's Law for the sand and gravel fill unit and fluvial sand and gravel unit are comparable at about 1.7 to 3.4 m/day, whereas linear groundwater velocities in the sand, gravel and cobble member of silt to cobble glacial till unit and boulder glacial till unit are lower to comparable at 0.23 to 2.6 m/day. The lowest calculated linear groundwater velocities are within the silty sand member of the silt to coble glacial till unit at 0.00070 m/day. For shallow bedrock the calculated velocities for homogeneous fractured bedrock without major structural features such as shear zones and faults range from 0.057 to 0.28 m/day.

15. Groundwater interactions with surface water at NPD site occur via direct discharge and via groundwater flow. The tile drain systems installed in shallow bedrock around the NPD building collect and directly discharge overburden groundwater to the Ottawa River. Groundwater in overburden and in shallow bedrock also discharges to the adjacent Ottawa River via groundwater flow. For overburden groundwater, the discharge is likely directly to the Ottawa River via the sand and gravel fill and fluvial sand and gravel hydrostratigraphic units. The volume of overburden

groundwater discharged via groundwater flow is likely to be much less than that from the tile drains due to upgradient interception of overburden groundwater by the tile drains. For shallow bedrock, the discharge pathway is most likely via upward flow in the steeply dipping Mattawa Fault that underlies the Ottawa River. The shallow bedrock groundwater discharge to the Ottawa River is a small percentage of that discharged directly via the tile drains.

6.1.3 Descriptive Geomechanical Site Model

1. Overburden is comprised of well-drained, cohesionless, coarse granular soils for which static and dynamic properties will be similar. The results of grain size analyses confirm that all soils at the NPDWF site are predominantly coarse granular materials, with soil textures of fine to coarse sand, with fine to coarse gravel. Standard penetration tests of these soils indicate compact to very dense soils. Density and effective internal friction angle for these soils are 17-22 kN/m^3 and 30-50º, respectively.

2. The results of preliminary slope stability assessment considering earthquake-induced soil liquefaction, show that the slope from the NPDWF to the Ottawa River (North Slope) under current water level conditions is stable under static loading conditions and under loading conditions associated with a 1:2,250-year earthquake. Parts of the North Slope are stable, and parts of the North Slope are unstable under a 1:10,000-year earthquake. The North Slope is likely to fail during a 1:50,000-year earthquake.

   It is unlikely that the predicted failures of the North Slope will result in changes to groundwater flow from the NPDWF to the Ottawa River or allow direct exposure of groundwater to a new ground surface that would be established following earthquake induced slope failures.

3. Intact rock geomechanical properties of the granitic gneiss, hornblende gneiss and dioritic gneiss that comprise the migmatitic biotite gneiss present at the NPDWF site are typical of crystalline gneissic rocks of the Canadian Shield. Based on testing of NPD cores, overall average geomechanical properties for shallow bedrock are: bulk density of 2.78 Mg/m^3, uniaxial compressive strength of 114 MPa, elastic modulus of 56.3 GPa and Poisson's ratio of 0.29. Testing shows the heaviest NPD rocks are dioritic gneisses, followed by hornblende gneisses and granite gneiss, and the strongest rocks are granite gneisses, followed by hornblende gneisses and dioritic gneisses.

   These trends in bulk density and UCS are consistent with expectations based on observed and measured mineralogies of the rock samples. The relatively high mafic mineral contents (e.g., biotite, hornblende) in the dioritic gneisses and to lesser extent the hornblende gneisses result in higher bulk densities and lower rock strengths (UCS). In contrast, the relatively higher quartz contents of the granitic gneisses result in higher rock strengths. Comparison of average NPD intact rock geomechanical properties to average CRL intact rock geomechanical properties suggests that NPD intact rocks, although strong, have lower peak strengths and elastic moduli than CRL intact rocks. These differences are attributed to higher mafic mineral (e.g., biotite and hornblende) and more strongly developed biotite gneissosity and other internal structural planes of weakness (i.e., foliation, schistosity, sealed/healed fractures, microcracks, etc.) in NPD rocks versus CRL rocks.

4. Rock mass quality at the NPDWF site based on 2019 outcrop mapping and drilling and core logging of shallow bedrock using standardized rock mass quality classification systems is good (RMR system) to fair (Q-system). Pre-excavation drilling and bedrock excavation observations at the NPD site, site investigations at the adjacent Rapides des Joachims site and inferences from the CRL property support the 2019 assessment with a rock mass quality rating is of fair to good quality. The overall average description of NPDWF rock mass is high strength intact rock that is moderately fractured with fair to good rock mass quality.

5. Most of the seismicity felt at the NPD site is from the Western Québec Seismic Zone (WQSZ), an area of concentrated seismic activity, with events generally ranging from about M 2 to 4.5 and rare events over M 5, located about 150-300 km northeast of the Mattawa Fault and the NPDWF site. Isoseismic studies show that major events in the WQSZ attenuate westward through and around the graben.

6. No neotectonic or paleoseismic studies have been completed at the NPD site. Given the lack of such studies at the NPD site, results of neotectonic and paleoseismic studies of the CRL site are used as a surrogate for the NPD site. Such reliance on CRL studies is reasonable and appropriate given the similar geological, regional structural and seismological setting of the NPD and CRL sites. Historical studies completed at the CRL site have not found evidence of neotectonics or paleoseismicity and have noted that the absence of paleoseismic structures in the CRL area is consistent with the absence of a surficial sediment section of sufficient composition, thickness and horizontal extent needed to have developed and preserved paleoseismic evidence, as well as the limited amount of bedrock exposure to detect small scale post-glacial displacements of bedrock due to neotectonics. These summary CRL observations indicate the potential for identification of paleoseismic structures at the NPD site, which has almost no post-glacial soft sediment and very limited bedrock exposure, is extremely low.

7. Probabilistic seismic hazard assessment (PSHA) completed in support of the proposed near surface disposal facility for the CRL property is relevant to the NPDDF site given the close proximity to CRL and similar nature of historical seismicity in regions surrounding NPDDF and CRL. The PSHA summarizes seismic source characterization and prediction of future earthquake characteristics and ground motions. The results of the PSHA show that the Iapetan Rift Margin (IRM) seismotectonic zone is the main contributing seismic source to overall hazard at all earthquake annual frequency of exceedances (AFEs) for the CRL and NPD sites. The IRM zone includes all major regional earthquakes within the St. Lawrence Rift, and the associated Ottawa-Bonnechere, Timiskaming and Saguenay grabens.

8. Estimated seismic hazard at selected AFEs determined from the PSHA model are presented as peak ground accelerations (PGAs) in units of gravity (g = 9.81 m/s^2) for annual frequencies of exceedances (AFEs) of 4.0E-04, 1.0E-04 and 1.0E-05. PGAs for AFEs of 4.0E-04, 1.0E-04 and 1.0E-05 are 0.25, 0.55 and 1.48 g. For reference the 2015 National Building Code of Canada uses an AFE of 4.0E-04 equal to a 2% probability of exceedance in 50 years.

9. Assessment of the potential for cracking of the underground structural walls of the NPDDF due to ground shaking from earthquakes was completed using a design basis earthquake (DBE) developed

for the CRL property (1:2,250-year event at NPD site) and extrapolated earthquakes (1:10,000- and 1:50,000-year events) developed for the NPD site based on the Geological Survey of Canada seismic hazard model and Natural Resources Canada guidance. The 1:2,250-year DBE has PGA = 0.24 g loading due to an approximate M 6.0 earthquake. The NPD 1:10,000-year earthquake has PGA = 0.623 g due to an earthquake of M greater than 6.5. The NPD 1:50,000-year earthquake has PGA = 1.75 g due to an earthquake of M significantly greater than 6.5. The results of the assessment indicate that cracking of underground walls of the NPDDF structure would likely occur during all three events due to flexural and shear loading at elevations near the top of bedrock (124.1 mASL) to the ground surface (128.5 mASL).

6.2 CNSC RegDoc 2.9.1 Requirements

The following Table 6.1 summarizes baseline geological and hydrogeological characterization requirements listed in Appendix B.4 of CNSC RegDoc 2.9.1. Table 6.1 also lists how the current EIS addresses these requirements and how the 2021 Updated Geosynthesis Report addresses these requirements incorporating the results of 2019 geoscientific investigations of the NPD site and 2021 slope stability studies and new geoscientific data.

Table 6.1 Summary of CNSC RegDoc 2.9.1 Appendix B.4 Requirements and EIS and 2021 Updated Geosynthesis Report Coverage

CNSC RegDoc 2.9.1 Appendix B.4 Requirement	***EIS and 2021 Updated Geosynthesis Coverage***
Section B.4.1 - Geology	
Geomorphology	Local bathymetry data is provided in Figure 8.3-10 of the EIS. Section 2.2 of Geosynthesis addresses this requirement including sub-sections on terrain physiographic features, topography and bathymetry. Geosynthesis Figure 2.1 presents regional and local physiography and geomorphology from Chapman and Putnam (2007).
Topography	Minor discussion in Section 3.3.3 and briefly in Section 8.5.2.1 of EIS. Section 2.2.2 and DEM Figure 2.2 of Geosynthesis addresses this requirement.
Quaternary geology and soil characteristics	Local conditions described in EIS Figure 8.5-2 on surficial geology, also discusses glacial till and glacially derived material. Section 2.3 and Figures 2.3, 2.5 and 2.6 of Geosynthesis addresses this requirement, including subsections on regional, local and site overburden characteristics extending the discussion to include the important mapping work of Gadd (1963a) and results of historic and 2019 on-site drilling and sampling programs.
Structural geology (regional, local and site-specific documentation of fractures and faults, primary geological features and deformation fabrics)	Section 2.4 and related figures of Geosynthesis fully addresses this requirement with sub-sections on regional geological setting, regional tectonic setting, regional and local structural geology, lineament study, and NPD site structure. 2019 local outcrop mapping and bedrock drilling, coring and logging for brittle deformation (joints, fractures, fracture zones) and ductile deformation (gneissosity, schistosity, folds) are summarized in Section 2.4.6 and several related figures and tables, including new 2021 outcrop photos as Figures 2.33 to 2.41, and core photos as Figures 2.42 to 2.46.

CNSC RegDoc 2.9.1 Appendix B.4 Requirement	***EIS and 2021 Updated Geosynthesis Coverage***
Petrology and geochemistry	Geosynthesis Sections 2.4.3, 2.4.7 and 2.4.8 and associated figures and tables address this requirement. Results of 2019 outcrop lithological mapping and core logging are presented in Sections 2.4.7. Results of 2019 laboratory petrology and mineralogy testing of outcrop and core samples are described in Section 2.4.8.
Economic geology	EIS Section 8.10.2.1 notes there are operating sand and gravel aggregate pits and no active mining claims in the local study area. Geosynthesis Section 2.5 more fully describes and maps local mining claims and aggregate pits and quarries based on current MNDM, OGS and MNR data sets.
Geomechanical properties	Geosynthesis Sections 4.2, 4.3, 4.4, 4.5, 4.6 and 4.7 and related figures and tables address this requirement by describing overburden geomechanical properties, intact rock and rock mass geomechanical properties and in-situ bedrock stresses based on historic and 2019 investigation information. Results of 2019 strength testing of intact core and rock mass quality determination from shallow bedrock core logging are fully described in Sections 4.3, 4.4 and 4.5. In situ rock stress data from CRL added in 2021 as Table 4.11 and Figures 4.7 and 4.8 in Section 4.7.2.
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	Grain size analyses added as Table 4.1 and new text in Section 4.2.1 in 2021. New 2021 Sections 4.2.3 and 4.2.4 and Table 4.3 describe earthquake-induced soil liquefaction and slope stability under static and dynamic loading conditions. Section 2.4 also discusses bearing capacity of foundations under static and dynamic loading conditions.
Coastal geomorphology (characteristics of lakefront, shoreline, near-shore and offshore zones)	The Ottawa River Shoreline is discussed as part of Sections 8.3 (Surface Water) and 8.4 (Aquatic), including substrates and formations (points, bays, cliffs). Local bathymetry data for the adjacent Ottawa River are given in Figure 8.3-10 of Section 8.3.5.1 the EIS. Geosynthesis does not add to this EIS discussion.
Geological model incorporating all overburden and bedrock information including discussion of uncertainties and any needs for additional field investigations to reduce uncertainties	A high-level conceptual geological model was developed as part of the groundwater modelling in Section 8.5.5 of the EIS. Geosynthesis Section 3.9 provides a descriptive geological model of the NPD site based on historic and recent 2019 and 2021 investigations. Figures 2.5 and 2.6 present a conceptual geological model of the NPD site in two orthogonal cross sections. New 2021 Figure 4.2 presents conceptual geological model of North Slope as two stratigraphic cross sections. New 2021 Sections 3.5.2, 3.8.4, 4.2.5 and 6.4 discuss current geoscientific data 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	Seismic hazards are discussed in Section 8.11.2 of the EIS based on description of regional seismicity (fault zones), including a historical summary and a qualitative estimate of seismic disturbances in the next 100 years. Geosynthesis Sections 4.2 and 5.2.4 and associated figures and tables updated with 2021 slope stability studies address these requirements, summarizing overburden geotechnical hazards and seismic hazards.
Seismic hazard assessment	Geosynthesis Section 5.2.5 provides a summary of seismic hazard assessment for the NPDWF site based on probabilistic seismic hazard assessment of the CRL property summarized by AECOM Canada Ltd. (2018) and the seismically-induced cracking

CNSC RegDoc 2.9.1 Appendix B.4 Requirement	***EIS and 2021 Updated Geosynthesis Coverage***
	assessments of the underground NPDDF structures by Arjmand (2018) and Zhang (2021).
Where appropriate – narrative descriptions should be supplemented by geological maps, figures, cross sections, borehole logs and photographs.	There are a few figures, one surficial soils map (bird’s eye view) and a cross section showing overburden/bedrock.in the EIS. The 2021 Geosynthesis includes about 66 pages of narrative description of the geological framework and geological model including 62 figures (maps, cross sections and photographs) and five tables.
Section B4.2 - Hydrogeology	
Physical and chemical properties of all overburden and bedrock units.	Section 8.5.5.1 describes hydraulic properties of the overburden and bedrock units currently in the EIS, with a hydrogeological cross section. Geosynthesis Figures 2.5 and 2.6 and Sections 3.4 and 3.5 described the physical and chemical properties of the overburden and bedrock units at the NPDWF site based on identification of hydrostratigraphic units for the site. Geosynthesis Section 2.4.8 provides information on bedrock mineralogy and lithogeochemistry.
Aquifer and aquitard identification including geochemical characteristics, vertical and lateral permeabilities, transport mechanisms (diffusion or advection) and directions of groundwater flow	Section 8.5.5.1 of the EIS presents some of the required information (mostly hydraulic properties) and Figure 8.5-8 on water level contours in the EIS. Geosynthesis Sections 3.3, 3.4, 3.5, 3.6 and 3.8 and associated figures and tables address these requirements illustrating (Figures 2.5 and 2.6) and describing hydrostratigraphic units, hydrogeochemistry and groundwater quality, the local groundwater flow system and hydrogeological modeling. Information on shallow bedrock properties and groundwater chemistry are included in revised Sections 3.4.5 and 3.5.2.
Identification of groundwater recharge and discharge area, and detailed description of groundwater interactions with surface waters.	Section 8.5.5.1 of the EIS provides an abbreviated discussion of groundwater recharge and discharge and directions of groundwater flow. Geosynthesis Sections 3.6.2 and 3.6.4 specifically address these requirements by describing groundwater recharge and discharge areas, and interactions with surface water.
Presentation of conceptual and numerical hydrogeological model that discusses hydrostratigraphy and groundwater flow systems.	Geosynthesis Sections 3.2 (conceptualization of groundwater flow systems in Shield terrain), 3.4, (hydrostratigraphic units) 3.5 (hydrogeochemistry and groundwater quality), 3.7 (local groundwater flow system) and 3.9 (descriptive hydrogeological model) describe the conceptual hydrogeological model and Section 3.8 describes the numerical groundwater flow models developed based on the conceptual model. Figures 2.5 and 2.6 show conceptual geological and hydrogeological cross sections developed with 2019 data.
Description of baseline groundwater quality at the site and in the local study area.	Information on baseline groundwater quality for the NPDWF site is presented in Section 8.6 of the EIS based on work by Killey (2014), for overburden and tile drain groundwater quality. Geosynthesis Section 3.5 describes overburden, shallow bedrock and tile drain groundwater quality based on Killey (2014), Golder Associates Ltd. (2017b), McVeigh (2018) and 2019 geoscientific investigations.
Description of local and regional potable water supplies including current use and potential for future use	Section 8.5.6.2 of the EIS discusses water supplies for the various surrounding communities of Point Stewart and Rapides des Joachims. Geosynthesis Section 3.7 including Figure 3.8 and Table 3.3 addresses this requirement by describing a summary of MECP well records for the local area of the NPDWF.

6.3 Implementation of Geoscience Verification Plan

The initial Geosynthesis Report (Arcadis Canada Inc., 2018a) included a tabular summary of geoscientific data uncertainties, the rationale for their identification and the recommended activities to address the data uncertainties. The recommended investigations to address geoscientific data uncertainties were incorporated into a Geoscience Verification Plan Report (Arcadis Canada Inc., 2018b) that was implemented as part of 2019 geoscientific characterization of the NPD site (Geofirma Engineering Ltd., 2019).

Table 6.2 (below) provides an updated listing of geoscience data uncertainties and recommended investigation activities to address data uncertainty provided in the initial Geosynthesis Report and how the recommended investigations were incorporated into this 2021 Updated Geosynthesis Report.

Table 6.2 Summary of Implementation of Geoscience Verification Plan in the 2021 Updated Geosynthesis

Geoscientific Data Uncertainty	***Recommended Investigation Activity to Address Data Uncertainty***	***Activity and Implementation in Updated Geosynthesis***
Thickness and hydraulic properties (hydraulic conductivity and hydraulic head) of glacial till unit upgradient of the NPDWF buildings	Overburden drilling, soil sampling, monitoring well installation, water level monitoring and slug testing investigation to bedrock surface.	Drilling, installation, testing and monitoring of six new overburden monitoring wells (MW18-01 to MW18-04, MW18-09 & MW18-10). Data used to update Sections 2.3.2, 2.6, 3.3, 3.4, 3.5, 3.6, 3.8, 3.9 and 6.1
Outcrop structural features (fractures, dykes, folds gneissosity, foliation, lineation)	Surface mapping of bedrock exposures near the NPDWF site.	Structural mapping of 13 bedrock outcrops. Data used to update Sections 2.4.6, 2.6, 4.4.1, 4.10 and 6.1. New Figures 2.33 to 2.46 showing outcrop and core structures added.
Bedrock lithology and petrology	Rock identification and thin-section petrology from surface outcrop mapping and recovered core from drilling.	Lithological mapping of 13 bedrock outcrops, core logging of shallow bedrock in BH18-04 to BH18-08, and lab thin section mineralogy and petrology. Data used to update Sections 2.4.7, 2.4.8, 2.6, 4.3, 4.10 and 6.1.
Presence of major structural features (90 m wide shear zone, foliation shear zones, open sheeting joints) in shallow bedrock	Shallow bedrock core drilling, core logging and borehole geophysical logging investigation to approximate depth of 50 m into rock.	Drilling, core logging and geophysical logging of shallow bedrock at BH18-04 to BH18-08. Data used to update Sections 2.4.6, 2.6, 3.3, 3.4.5, 3.8, 3.9, 4.6, 4.10 and 6.1
Rock mass quality using conventional geomechanical classification systems	Shallow bedrock core drilling and discontinuity core logging to approximate depth of 50 m into rock.	Drilling and discontinuity logging of core in BH18-04 to BH18-08. Data used to update Sections 2.4.6, 3.3, 4.4, 4.5, 4.10 and 6.1.
Hydraulic properties (hydraulic conductivity and hydraulic head) of shallow bedrock	Shallow bedrock straddle-packer hydraulic testing, monitoring well installation and water level	Continuous straddle-packer profile testing in BH18-04 to BH18-08, water level monitoring in multi-level CMT installations. Data used to update

Geoscientific Data Uncertainty	***Recommended Investigation Activity to Address Data Uncertainty***	***Activity and Implementation in Updated Geosynthesis***
	monitoring program to approximate depth of 50 m into rock.	Sections 3.3, 3.4.5, 3.6, 3.8, 3.9, 4.6, 4.10 and 6.1
Groundwater quality of shallow bedrock	Multi-level monitoring completion will allow measurement of vertical head gradient in bedrock and spatial distribution of bedrock heads.	Installation, water level monitoring and groundwater sampling of 7-interval multi-level CMT systems in BH18-04 to BH18-08. Data used to update Sections 3.5.2, 3.6, 3.9 and 6.1.

6.4 Conclusions

Geosynthesis provides a description of the geological, hydrogeological and geomechanical models of the geosphere at the NPDWF site based on regional, local and site geoscientific understanding and information. Current descriptions of the geosphere generated in the 2021 Updated Geosynthesis Report are reasonably accurate, best estimates of geological, hydrogeological and geomechanical frameworks based on maximal utilization of site-specific and off-site regional and local geoscientific data.

Current descriptions of the geosphere at the NPDWF site, while inevitably including some uncertainty in selected areas, support and enhance the existing geosphere model as outlined in the current Postclosure Safety Analysis Report (Arcadis Canada Inc., 2017a) and the conceptual and numerical groundwater flow models (Calder, 2018; 2019a) that form part of the current Postclosure Safety Analysis.

Geosynthesis addresses baseline geological and hydrogeological characterization requirements listed in Appendix B.4 of CNSC RegDoc 2.9.1, using site-specific geoscientific data or inferred best estimates of site-specific data based on local and regional understanding.

The 2021 Updated Geosynthesis Report identifies the following outstanding geoscientific data uncertainties considered important to NPDWF site characterization and geosynthesis:

1. Presence and hydrogeological properties of the permeable fluvial sand and gravel layer that sub-parallels the Ottawa River and extends tile drain capture of overburden groundwater northwest of the NPDWF;
2. Hydrogeochemistry and groundwater quality of shallow bedrock; and
3. Geotechnical properties of the soils located north of the NPDWF (i.e., North Slope) to support a more rigorous and reliable assessment of earthquake-induced soil liquefaction and slope stability.

Addressing these identified geoscientific data uncertainties, while beneficial for overall site characterization and geosynthesis, is unlikely to change the summary and conclusions of this 2021 Updated Geosynthesis Report.

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