APPENDIX 14A

Terrain, Soils and Permafrost Technical Data Report

Mackenzie Valley Highway Project Technical Data Report—Soils, Terrain and Permafrost

Prepared for:

Government of the Northwest Territories

Prepared by:

K'alo-Stantec Limited

March 2023

Project No.: 144903025

Limitations and Sign-off

This document entitled Mackenzie Valley Highway Project Technical Data Report—Soils, Terrain and Permafrost was prepared by K'alo-Stantec Limited ("K'alo-Stantec") for the account of Government of the Northwest Territories (the "Client") to support the regulatory review process for its Developer's Assessment Report (DAR) (the "Application") for the Mackenzie Valley Highway (the "Project"). In connection therewith, this document may be reviewed and used by the Government of the Northwest Territories Department of Infrastructure participating in the review process in the normal course of its duties. Except as set forth in the previous sentence, any reliance on this document by any other party or use of it for any other purpose is strictly prohibited. The material in it reflects K'alo-Stantec's professional judgment in light of the scope, schedule and 2 (rt ne Tc -f15V)8( )]TJ-0.0 9Tweationsmit (es in eis documen (ans in ei[ctraject coonexeliced ane eiou taketh incouor and.

, this docume.ct

Executive Summary

The Government of the Northwest Territories (GNWT), Department of Infrastructure (INF) is proposing the Mackenzie Valley Highway Project (the Project) that will extend the Mackenzie Valley Highway (MVH) from Wrigley to Norman Wells, Northwest Territories (NT). The Project consists of a 321 km all-season highway that largely follows the route of the existing Mackenzie Valley Winter Road (MVWR) and includes temporary and permanent borrow and quarry sources. The project highway alignment will pass through the Dehcho Region and a portion of the Tulita District of the Sahtu Settlement Area (SSA) within the NT.

This technical data report (TDR) presents a summary of soils, terrain and permafrost data documenting baseline conditions within the Regional Study Area (RSA; a 10 km buffer centred on the MVH alignment, access roads and primary borrow sources) and Local Study Area (LSA; a 1 km buffer centred on the MVH alignment, access roads and primary borrow sources). A large volume of information about terrain and geotechnical subsurface conditions (including permafrost) within the Mackenzie Valley is publicly available. This data includes exploratory geotechnical investigations conducted to support highway studies in the 1970s, as well as more recent investigations and monitoring conducted within the last two decades. Studies conducted to support existing or proposed pipeline projects were also found to provide significant information to that document baseline conditions within the soils LSA and RSA.

Existing regional scale mapping was used to summarize bedrock geology within the LSA and RSA. The dominant geological units consist of sedimentary bedrock, predominantly sandstone, shale, limestone and dolostone. Exposed rocks and bedrock-controlled terrain are generally limited to the easternmost section of the RSA (i.e., towards Franklin Mountains), with most of the LSA overlaid by a thick mantle of surficial material. There are a few exceptions, including shallow bedrock at river crossings and shallow or exposed bedrock alongside Mount Gaudet and Bear Rock. Published surficial geology mapping identifies glaciolacustrine materials, till (moraine), colluvium, alluvial materials, glaciofluvial materials, eolian materials, bedrock, and organic materials within the RSA. Two soil orders, Cryosols and Brunisols, were identified in the LSA and RSA. Cryosols are mineral or organic materials that have perennially frozen material (permafrost) within 1 m of the surface or within 2 m of the surface if the soil is strongly cryoturbated. Brunisols are soils with a B horizon have undergone only minor alterations from the parent material and are mainly associated with coarse-textured and/or well-drained surficial materials absent of permafrost. Based on available regional permafrost mapping, the Project spans the extensive discontinuous permafrost (predominantly near Norman Wells), intermediate discontinuous permafrost (e.g., Mackenzie Plain area), and sporadic discontinuous permafrost (area surrounding Wrigley) zones. Climate is the predominant element controlling the broad distribution of permafrost in the RSA, followed by other factors such as topography, soils characteristics, vegetation cover, snow cover, and surface water. Permafrost may be absent or found at greater depth beneath large bodies of water (including rivers and lakes).

The availability of imagery and LiDAR allowed for a more precise characterization of terrain within the LSA. Geomorphological processes are identified and described, many of which are directly related to the presence of permafrost (e.g., seepage and mass movement processes). The surficial geology and terrain conditions in the LSA are summarized in a 1:10,000 scale map atlas. This mapping was used to refine the understanding of surficial materials, geomorphic processes, and terrain hazards present in the LSA.

Table of Contents

List of Tables

List of Figures

List of Appendices

Abbreviations

%	percent
°C	degrees Celsius
AAFC	Agriculture and Agri-Food Canada
CIRNAC	Crown-Indigenous Relations and Northern Affairs Canada
cm	centimetre
CSA	Canadian Standards Association
DAR	Developers Assessment Report
DEM	digital elevation model
DIAND	Department of Indian and Northern Development
DOT	Department of Transportation
DSM	digital surface model
GIS	geographic information system
GNWT	Government of the Northwest Territories
GSC	Geological Survey of Canada
ha	hectare
INF	Department of Infrastructure
ka BP	thousands of radiocarbon years before present
km	kilometre
LiDAR	light detection and ranging
LSA	Local Study Area
m	metre
m^3	cubic metre
MGAR	Mount Gaudet Access Road
MGP	Mackenzie Gas Project
mm	millimetre
MVAP	Mackenzie Valley Airphoto Project
MVEIRB	Mackenzie Valley Environmental Impact Review Board
MVH	Mackenzie Valley Highway

MVWR .... Mackenzie Valley Winter Road

NT .... Northwest Territories

NTGS .... Northwest Territories Geological Survey

PCAR .... Prohibition Creek Access Road

PDR .... Project Description Report

PIN .... Permafrost Information Network

RSA .... Regional Study Area

SCWG .... Soil Classification Working Group

SSA .... Sahtu Settlement Area

TDR .... technical data report

the Project .... Mackenzie Valley Highway Project

TK .... traditional knowledge

TOR .... terms of reference

TLRU .... traditional land and resource use

1 Introduction

The Government of the Northwest Territories (GNWT), Department of Infrastructure (INF) is proposing the Mackenzie Valley Highway (MVH) Project (the Project) that will extend the Mackenzie Valley Highway (MVH) from Wrigley to Norman Wells, Northwest Territories (NT). The Project consists of a 321 kilometre (km) all-season highway that largely follows the route of the existing Mackenzie Valley Winter Road (MVWR), and the construction and operation of temporary and permanent borrow and quarry sources. The project highway alignment will pass through the Dehcho Region and a portion of the Tulita District of the Sahtu Settlement Area (SSA) within the NT (Figure 1.1).

The Project is subject to an environmental assessment and the requirements of Part 5 of the *Mackenzie Valley Resource Management Act*. This technical data report (TDR) presents the existing (baseline) conditions for the Soils, Terrain and Permafrost Valued Component (VC) to support development of the Developer's Assessment Report (DAR), as required by the Terms of Reference (TOR, MVEIRB, 2015).

The required elements specified in the TOR with respect to soils, terrain (including bedrock) and permafrost include the description, location, and geographic extent of the following features:

- topography and geology, including key terrain features such as rivers, lakes and wetlands and other important processes and features
- bedrock type and depth
- unconsolidated surficial materials and terrain types, including thickness of landforms
- soil types, including group, series and type, as applicable
- a description of proposed borrow sources, including information on locations, expected ice content, size of borrow areas, expected volumes to be removed, quality of materials at each location, existence and extent of ice rich permafrost areas that may be excavated and land ownership

The TOR also requires

- a description of permafrost and ice-rich soils in the study area, including their expected distribution (thickness and lateral extent)
- identification and description of permafrost processes, features and landforms and their stability
- description of subsurface ground ice conditions, temperature and ground thermal regime

Finally, the TOR specifies that the description of existing conditions for soils, terrain and permafrost should demonstrate an understanding of regional climate warming and documented warming of ground temperatures in the region; including a description of how warming ground temperatures and deepening active layers could affect the stability of the project highway and how mitigation measures will remain effective in various climate warming scenarios.

- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Granular Borrow / Rock Quarry Site and Access
- Local Study Area
- Regional Study Area
- Community
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary
- Territorial Boundary

0 40 80 Kilometres

(At original document size of 8.5x11)
1:4,500,000

N

Kálo-Stantec

Project Location: Wrigley to Norman Wells, NWT

Prepared by AT on 3/9/2023
TR by AJ on 3/9/2023

Client/Project: 144903025-0056 REVB

Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
1.1

Title
MVH Project Area

Notes
1. Coordinate System: NAD 1983 Northwest Territories Lambert
2. Data Sources: Centre for Geomatics Government of NWT, Government of Canada, Stantec
3. Background: World Topographic Map: Esri, FAO, NOAA, USGS, NRCan
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS

2 Study Area

The MVH Project is located in the Mackenzie Valley region of the Northwest Territories (NT) between the current terminus of the existing all-weather highway in Wrigley (Highway #1, km 690) and Norman Wells (KM 1011 of the MVWR). The project highway alignment roughly parallels the Mackenzie River to its east and passes through the community of Tulita (KM 938 of the MVWR).

The Local Study Area (LSA) and Regional Study Area (RSA) presented in this TDR are the areas (Figure 2.1) where data was compiled to characterize the existing environmental conditions for soils, terrain and permafrost in support of the Project-specific effects assessment and the cumulative effects assessment in the DAR.

Because the MVH alignment has not been finalized yet, the existing MVWR route and corresponding kilometre markers have been used as the reference alignment.

2.1 Local Study Area

The LSA for soils, terrain and permafrost is defined as a 1 km buffer centred on the MVWR route. This LSA size was selected because measurable Project-related effects (direct or indirect) are expected to be limited to this area.

2.2 Regional Study Area

The RSA is defined as a 10 km buffer centred on the MVWR route. The 10 km buffer was selected to provide context for determining significance of Project-specific effects and potential cumulative effects.

- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Granular Borrow / Rock Quarry Site and Access
- Local Study Area
- Regional Study Area
- Community
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

0 10 20 Kilometres

(At original document size of 8.5x11) 1:1,600,000

N

Kalo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 3/9/2023
TR by AJ on 3/9/2023

Client/Project
144903025-0057 REVB

Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
2.1

Title
Local and Regional Study Areas - Soils, Terrain and Permafrost

Notes
1. Coordinate System: NAD 1983 Northwest Territories Lambert
2. Data Sources: Centre of Geomatics of Government of NWT, Government of Canada, Stantec
3. Background: World Topographic Map: Esri, FAO, NOAA, USGS, NRCan
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS

3 Methods

The approach developed to gather information and present baseline conditions within the LSA and RSA consisted of three main tasks:

1. a review of existing traditional knowledge (TK) and traditional land and resource use (TLRU) (Section 3.1)
2. a review of literature and background data relevant to soils, terrain and permafrost (Section 3.2)
3. terrain mapping (Section 3.3)

Details regarding the methods associated with each of these tasks is presented below.

3.1 Traditional Knowledge and Traditional Use

Publicly available TK studies, along with information on current and historical TLRU, are important information sources to acknowledge when evaluating the potential effects of a project on local and regional soils, terrain and permafrost conditions. Knowledge about permafrost in the Sahtu area has been collected largely through oil and gas exploration and road construction projects (mainly bridges).

3.1.1 Data Sources

A preliminary compilation and review of relevant TLRU information has been completed as part of the Cultural and Traditional Land Use TDR (K'alo-Stantec, 2022a). The Cultural and Traditional Land Use TDR was compiled primarily using publicly available sources and will be considered complete once additional knowledge information is obtained through the engagement program for the Project. Information has been collected through the Project-specific TLRU study developed by the Tulita Renewable Resources Council (TRRC, 2022). Additional information is available from a compilation of TK relevant to permafrost, surface water, and groundwater for the Central Mackenzie Valley region (Golder, 2015).

3.1.2 Preliminary Results

A summary of existing conditions and potential project effects relevant to soils, terrain and permafrost identified by Indigenous groups in available source documents includes the following:

- interviews and conversations with Elders and land users in the Tulita region (Golder, 2015): there is "general consensus that permafrost is found in most areas except where there are natural underground springs and wet muskeg".
- warmer temperatures, melting permafrost and other environmental changes create concerns related to the environment (EBA, 2011)
- Increased temperatures and precipitation, effects on snow and vegetation conditions, effects on lake/river ice and boat access (Dehcho First Nations, 2011)

- forest fires and effects on boreal caribou habitat (Dehcho First Nations, 2011). It was reported that “wherever a forest fire has burned, all the permafrost will be disturbed for about 10 to 15 years until the moss is able to grow back. Without the moss, the permafrost is not well insulated.” (Golder, 2015)
- “Each spring, elders have noticed that melt water is draining into the soil too fast and thawing out the permafrost below. Locations such as cleared lands for seismic operations have been identified as places losing permafrost exceptionally fast” (Golder, 2015).
- public consultation for bridge projects supporting the MVWR north of Norman Wells reported community members stating that “when permafrost gets disturbed, it can cause a lot of trouble for any type of development” (GNWT, 2003)
- more erosion resulting from road construction and operation in the LSA along the MVWR (K’alo-Stantec, 2022b)
- more permafrost than before, therefore more boggy, sloughy areas in the LSA that have affect undertaking TLRU (K’alo-Stantec, 2022b)
- wood chips (collected from tree removal) should be used to insulate the road once constucted (K’alo-Stantec, 2022b)

3.2 Literature Review - Geosciences

A literature review was used to establish baseline conditions for soils, terrain and permafrost. Several different data sources were consulted, including documents and reports, open-source database as well as existing mapping data. Details on key data sources are provided in the following subsections. A complete list of references consulted to prepare this TDR is presented in Section 8.

3.2.1 Information Sources

3.2.1.1 MVH Project Description Reports

Among the first documents reviewed were the Project Description Reports (PDRs) produced in support of the scoping and development of the TOR, including:

- PDR for Construction of the Mackenzie Valley Highway through the Tulita District in the Sahtu Settlement Area (EBA, 2011)
- PDR for Construction of the Mackenzie Valley Highway through the Pehdzeh Ki Ndeh – Dehcho Region (Dessau, 2012)
- updated PDR submitted to the Mackenzie Valley Environmental Impact Review Board (MVEIRB) for the purpose of re-scoping the Environmental Assessment of the proposed MVH development (GNWT-DOT, 2014; now GNWT-INF)

These PDRs include summaries of information related to physiography, bedrock geology, and overall terrain conditions along the project highway alignment, including lists of proposed borrow sources. Relevant information has been incorporated into Section 4 of this TDR.

3.2.1.2 Historical Geotechnical Investigation Reports

The idea of building an all-weather highway through the Mackenzie Valley originated in the 1960s. During the early 1970s, the Federal Government (through Public Works Canada) conducted significant exploration work along a proposed highway corridor, including several geotechnical field investigation programs.

Historical documents consulted to develop the soils, terrain and permafrost TDR are listed in Section 8. These reports are associated with the following three main initiatives:

- geotechnical investigations conducted along the 1970s roadway alignment
- historical granular material inventory reports completed for the local communities and surrounding lands
- historical geotechnical pipeline route investigations completed for private industry

3.2.1.3 Borehole Databases

Data captured as part of historical geotechnical investigations have been compiled and released as parts of several different databases. The first compilation of publicly available geotechnical borehole data associated with the historical geotechnical investigations listed above was compiled by Proudfoot and Lawrence (1976) and Lawrence and Proudfoot (1976). This initial database was built on and improved over time, resulting in the release of a geographic information systems (GIS) compatible version containing over 13,000 boreholes extending from the Western Arctic coast to northwestern Alberta (Smith et al., 2005). Although most of this information was obtained from pipeline- and highway-related field drilling programs conducted between 1970 and 1975, the database also includes more recent boreholes, including about 1,400 boreholes compiled in the early 1990s in relation with the Enbridge's Line 21 "Norman Wells Pipeline" project, as well as other boreholes conducted/compiled as part of separate Geological Survey of Canada (GSC) projects (e.g., Chartrand et al., 2002).

In 2017-18, the GSC and Transport Canada initiated a collaborative project to develop a Permafrost Information Network (PIN) aiming to increase the public accessibility of permafrost information (Smith et al., 2017). Adapted from the existing web architecture developed for the Groundwater Information Network the PIN web application[1] allows viewing and download of borehole geotechnical data. Included in this database are data previously release by Chartrand et al. (2002), Smith et al. (2005), EBA (1989), Smith et al. (2009a), and Wolfe et al. (2010).

The information contained within these databases was downloaded and then imported into Esri's ArcGIS program to inform mappers about site-specific conditions while conducting detailed terrain mapping for the LSA.

[1] https://pin.geosciences.ca/en/

3.2.1.4 Seismic Shothole Data

Extensive seismic surveys have been conducted by the petroleum industry within the Mackenzie Valley and Delta regions over the last few decades. Seismic shothole log records are recorded by drill operators during geotechnical seismic operations when they auger/air-rotary drill holes in order to set explosive charges. The use of these driller's logs in support of surficial geology mapping activities in the Mackenzie Delta region and parts of northern British Columbia over the past five years have demonstrated them to be a reliable, albeit simplified, lithostratigraphic archive (Levson et al., 2004; Smith et al., 2007; Smith and Lesk-Winfield, 2012; Smith, 2011).

Because shothole data provides general parent material textures based on exploration drilling (e.g., some shotholes may be described as "sand and gravel", others as "gravel" and others as "clay, sand, shale"), it was used to inform on subsurface conditions as part of the LSA terrain mapping (see Chapter 5). Historical information contained in the seismic shothole database also contains information on ground ice and permafrost (Smith and Lesk-Winfield, 2012), but the results from recent site-specific geotechnical investigations conducted along the MVWR (e.g., TetraTech, 2000a, 2000b, 2000c, 2000d) are considered the most reliable source of geotechnical data for the Project.

3.2.1.5 Recent Geotechnical Evaluations

In 2020, Tetra Tech Canada Inc. (Tetra Tech) was retained by the GNWT to conduct geotechnical, geophysical and thermal evaluations to support the design and engineering of the Project and associated infrastructure (Tetra Tech, 2000a, 2000b, 2000c, 2000d). Areas of interest include the existing section of the Mount Gaudet Access Road (MGAR) near Wrigley and Prohibition Creek Access Road (PCAR) near Norman Wells.

Data from these studies were used in the descriptions of soils, terrain and permafrost baseline conditions.

3.2.1.6 Bedrock, Soils, Terrain and Permafrost Data

Bedrock

Regional bedrock geology information is available from a geological map compilation developed by the Northwest Territories Geological Survey (NTGS) (Okulitch and Irwin, 2014). The data consist of existing digital geological data that was assembled at a scale of 1:250,000 to present bedrock geology within most of the NT. Other relevant maps and papers include (but are not limited to) publications from Aitken and Cook (1976), Fallas et al. (2013), Fallas and McNaughton (2013).

Quaternary History, Surficial Geology and Landforms

Information relevant to the Quaternary history and surficial geology of the Mackenzie Valley region is available through numerous sources, including (but not limited to):

- surficial geology mapping by Hanley (1973), Hanley et al. (1975), Duk-Rodkin (2002), Duk-Rodkin and Couch (2004), Duk-Rodkin and Huntley (2009), Côté et al. (2013), as well as more recent compilation mapping by the GSC (2019a, 2019b)
- publications included in GSC Memoir 547 regarding the physical environment of the Mackenzie Valley
- historical work conducted as part of the Environmental-Social Program, Northern Pipelines (Tarnocai, 1973)
- publicly available reports associated to the Enbridge's Norman Wells Pipeline as well as the Mackenzie Gas Project (MGP), including Imperial Oil Resources Ventures Limited (2004), Burgess and Tarnokai (1997), Burgess and Lawrence (2000)

Some of the above-listed data sources include digital surficial geology (or terrain) mapping data (see additional details in Section 3.2.1.7 below).

Soils

A desktop review of existing information was completed to determine the general distribution of soil types within the MVH Project Area. The following key information sources were consulted:

- Soil Landscapes of Canada dataset and spatial maps were accessed from Agriculture and Agri-Food Canada's National Soil Database (AAFC, 1996). The spatial information was overlain on the MVH highway alignment to evaluate the distribution of soils in the LSA and RSA.
- The Canadian System of Soil Classification – Third Edition (AAFC, 1998) by the Soil Classification Working Group to classify soils in the Project area.
- Cryosolic soils of Canada: genesis, distribution, and classification by Tarnocai and Bockheim (2011) to provide general information about Cryosolic soils.

Landslides

Information on terrain stability was obtained from publications from Aylsworth et al. (2000a, 2000b), Aylsworth and Traynor (2001), Couture and Riopel (2008a, 2008b) and Huntley (2008).

Permafrost

A large volume of information regarding permafrost along the Mackenzie Valley is publicly available, including subsurface conditions, ground-thermal regime, and active-layer thickness. This information is useful for establishing baseline conditions, helping with land-use planning and the engineering design of infrastructure, and for understanding the effects of climate change on permafrost environments.

In addition to the permafrost-related papers included in GSC Memoir 547 (e.g., Heginbottom, 2000; Burgess and Smith, 2000; Wright et al., 2000; Burgess and Lawrence, 2000), key permafrost-related publications consulted in support of the TDR include work by Heginbottom et al. (1995), Smith and Burgess (2002), Smith et al. (2004, 2005), Smith and Duchesne (2017), Duchesne et al. (2020), and O'Neill et al. (2020). The list of available documents and reports discussing permafrost in the Mackenzie Valley is longer, including dozens of peer-reviewed publications and other scientific literature.

3.2.1.7 Review of Existing Mapping Data

The availability of ArcGIS shapefile mapping data, including high resolution orthophoto, LiDAR data and Digital Elevation Model (DEM) (see details in Table 3.1) allowed for the review of existing mapping datasets, including the following:

- surficial geology mapping produced by the GSC at 1:250,000 or 1:125,000 scales, including: Hanley (1973), Hanley et al. (1975), Côté et al. (2013), as well as more recent compilation mapping including portion of Map 371 and Map 375 (respectively GSC, 2019a, 2019b)
- terrain mapping conducted to support other projects led by GNWT in the region, including mapping for the PCAR and MGAR projects (G.V.M., 2016, 2019)
- terrain mapping conducted for the Mackenzie Valley Pipeline (Imperial Oil Resources Ventures Limited, 2006). Note that only the pdf version of these alignment sheets was reviewed.

Table 3.1 Aerial Photographs, Orthophoto and LiDAR and DEM Data Available for the Project

Data type	Source	Description
Aerial photography and orthophoto	Mackenzie Valley Airphoto Project (MVAP), 2004/2005	Aerial photography and ortho-imagery acquired for the Mackenzie Gas Project route. 15 km-wide corridor; covers the entire soils, terrain and permafrost RSA
	Hard copy aerial photographs	A collection of hard copy aerial photographs covering different areas of interest along the Project at various scales and acquisition dates
LiDAR and DEM data	LiDAR, 2010	Airborne LiDAR acquired in 2010 by LiDAR Services International Inc. of a 1 km-wide corridor centred on the MVWR; includes contour data, hillshade images and high resolution ortho-imagery
	Arctic DEM	Open-source 2 metre (m) spatial resolution Digital Surface Model (DSM) derived from optical imaging satellites covers the entire soils, terrain and permafrost RSA

The existing bedrock geology, surficial geology and soils data was used to describe baseline conditions within the RSA. Thematic map atlases and statistical summaries were generated from this data.

3.3 Local Study Area Terrain Mapping

Detailed terrain mapping was completed for the LSA (i.e., a 1 km-wide corridor. Mapping was conducted in an ArcGIS platform, using available aerial photography, ortho-imagery and LiDAR-derived data available for the Project (see Table 3.1).

Because the NT does not currently have specific standards for terrain mapping, widely accepted standards and guidelines developed by and for the Province of British Columbia were applied. They consist of:

- Guidelines and Standards to Terrain Mapping in British Columbia (Resource Inventory Committee, 1996)
- Terrain Classification System for British Columbia, Second Edition Ministry of Environment Manual 10 (Howes and Kenk, 1997)

As part of the mapping, relatively homogeneous terrain units (or polygons) were delineated on the basis of surficial materials (e.g., till, glaciolacustrine), surface expression (e.g., hummocky, fan), depth to bedrock (e.g., veneer, blanket) or stratigraphic composition (i.e., identifying the expected subsurface material), slopes, and geomorphological processes (e.g., groundwater seepage, mass wasting). Due to the detail of the mapping, some terrain map units (polygons) were classified using a composite label accounting for two main material types (e.g., fluvial and colluvial). For those terrain polygons, the two materials types are separated by a delimiter. These symbols (/ = 60/40, // = 80/20) indicate the relative amount (percentage) of each surficial material type.

In general, the delineation of individual terrain polygons was conducted at scales ranging from 1:2,500 to 1:7,500, with final map presentation at a scale of 1:10,000 (see Appendix B). As a general rule, surficial materials occupying less than 20% of a polygon were not indicated in the terrain unit label. Attempts were made to adhere to a minimum polygon size of 2 hectares (ha); however, in some areas, smaller polygon sizes were delineated when it was important from a terrain or ecosystem perspective (e.g., small wetlands, water bodies or geomorphic processes (geological hazards) occurring on, or immediately adjacent to the MVWR route).

A detailed map legend presented in Appendix B describes the terrain classification system (including map symbols) used for the LSA terrain mapping.

A senior terrain mapper reviewed the mapping, including both linework and terrain classification, to confirm that the mapping adhered to the standards listed above. Discrepancies in linework and classification, including comparisons with the existing terrain and surficial geology mapping datasets, were discussed with the mappers and revisions made as necessary.

4 Review of Existing Data

The following sections summarize the existing information compiled for the following key subjects:

- Bedrock Geology (see Section 4.1)
- Glacial and Post-Glacial History (see Section 4.2)
- Materials and Landforms (see Section 4.3)
- Soils (see Section 4.4)
- Permafrost (see Section 4.5)
- Geomorphological processes and Geological hazards (see Section 4.6)

4.1 Bedrock Geology

The bedrock along the MVWR route and within the RSA comprises a complex series of geologic units. These geologic units are composed of clastic sedimentary rocks (primarily shales and sandstones) and chemical sedimentary rocks (dominantly limestones and dolostones [dolomite]). Along most of the MVWR route, the bedrock is covered by a thick mantle of surficial material, primarily glaciolacustrine sediments and till (see Section 4.3). There are limited areas along the MVWR route mapped as shallow veneers of till, where bedrock is likely close to the surface. There may also be a few isolated areas where bedrock is exposed at the surface, for example, the dominating dolostone ridge of Bear Rock immediately west of the confluence of the Mackenzie River and the Great Bear River.

Table 4.1 tabulates the geologic units intersected along the MVWR route by map code, geologic unit (formation), geologic epoch, major lithology, and presence along (underlying) the MVWR route by kilometer stations (km). This data is derived from a geodatabase (shapefile) authored by Okulitch and Irwin (2014). These tabulations are organized in order of the first appearance of a geologic unit beginning at the south end of the alignment and moving north to the north end of the alignment. Some of the geologic units contain one or more minor bedrock lithologies, these rock types are enclosed in brackets in Table 4.1. These geologic units are identified by map codes on the bedrock geology figures accompanying this report (see Appendix A, Figures A.1 to A.7).

Table 4.1 Bedrock Geology Intersected by the MVWR Route

Map Code	Geologic Unit	Epoch	Major Lithologies	Kilometer Posts (approximate)
uDv-FS	Fort Simpson Formation	Middle to Upper Devonian	shale, siltstone, limestone	694-712; 712.5-717.5
mDv-N	Nahanni Formation	Middle Devonian	limestone	712-712.5
uDv-s	Upper Devonian sandstone unit	Upper Devonian	sandstone, mudstone, shale, (minor limestone)	717.5- 781
uCt-SR	Slater River Formation	Slater River Formation	sandstone, siltstone, shale, bentonite	781-793.5; 850.6-857.9; 873.5-874.6
uCt-SR	Slater River Formation	Slater River Formation	sandstone, siltstone, shale	793.5-820
uCm-SR	Saline River Formation	Furongian (Upper Cambrian)	shale, siltstone, sandstone, salt, anhydrite, gypsum, dolostone	820-820.8; 821.3-822; 827.5-832.8; 836.2-846.1; 863-868.2, 870.8-871.6; 960.1-960.5
mCm-MC	Mount Cap Formation	Lower to Middle Cambrian	shale, limestone, dolostone, sandstone, siltstone	820.8-821.3; 822-827.5; 846.1-850.6; 857.8-863; 868.2-870.8
uCm-FM	Franklin Mountain Formation (lower "cyclic" member)	Furongian	dolostone, conglomerate, shale	832.8-833.1; 960.5-961
CmOd-FM-m	Franklin Mountain Formation (middle "rhythmic" member)	Furongian to Lower Ordovician	dolostone	833.1-836.2; 961-961.5
CmOd-FM-m-c	Franklin Mountain Formation limestone facies	Furongian to Lower Ordovician	limestone, (minor conglomerate)	871.6-873.5
uCt-LB	Little Bear Formation	Upper Cretaceous	shale, sandstone	874.6-889.5
uCt-EF	East Fork Formation	Upper Cretaceous	shale, siltstone	889.5-911.3; 921-924.2; 959.5-960.1
CtpPg-SC	Summit Creek Formation	Upper Cretaceous to Paleocene	conglomerate, sandstone	911.3-921; 924.2-959.5
lmDv-BR	Bear Rock Formation	Lower Devonian to Middle Devonian	dolostone, dolostone solution-breccia, anhydrite, gypsum	961.5-962.8
mDv-Hu	Hume Formation	Middle Devonian	marlstone, limestone, shale	962.8-963.6
mDv-HI	Hare Indian Formation	Middle Devonian	shale	963.6-964
mDv-Ra	Ramparts Formation	Middle Devonian	limestone, (minor shale)	964-964.5
muDv-Ca	Canol Formation	Middle Devonian	shale; (minor limestone, ironstone, sandstone and conglomerate)	964.5-967.3
uDv-I	Imperial Formation	Upper Devonian	shale, sandstone (minor limestone)	967.3-1015.6

Source: Modified from Okulitch and Irwin (2014)

4.2 Glacial and Post-Glacial History

The following two sections describe the glacial history and the character and distribution of surficial materials within the RSA, LSA, and the MVWR route. The entire MVH Project Area is contained within the southern portion of the physiographic region known as the Mackenzie Plain.

The Mackenzie Valley, including the entire RSA, was covered by the by the Laurentide Ice Sheet during the Late Wisconsinan glaciation. The Laurentide Ice Sheet moving west and northwest from the Canadian Shield reached its maximum about 30 ka BP (thousands of radiocarbon years before present); extending north to the Beaufort Sea and pushing west onto the eastern slopes of the Mackenzie Mountains, extending up and blocking pre-existing east-draining valleys (Duk-Rodkin and Lemmen, 2000).

By 12 ka BP to 11.5 ka BP the Laurentide ice front in the Mackenzie Valley had retreated south to a position a short distance north of Norman Wells, while the eastern slopes of the Mackenzie Mountains were ice-free. About this time, Glacial Lake Mackenzie begun to form near Fort Good Hope; by 11 ka BP the lake had extended south southeast to a point a short distance south of Wrigley, and by about 10.5 ka BP reached a maximum southerly extent just south of Fort Simpson. During the same period, the Laurentide ice retreated to a roughly concave front extending north from south of Fort Simpson and east of Great Bear Lake to the to the Beaufort Sea. By about 10 ka BP, Glacial Lake Mackenzie had fully drained, leaving behind extensive deposits of glaciolacustrine silts and clays that extend along the Mackenzie Valley in a broad, occasionally discontinuous band, that ranges from five to ten km wide within the RSA.

The Mackenzie River and tributary rivers and streams have, subsequently, down-cut though the glacial deposits of the Laurentide Ice Sheet and the silts and clays of Glacial Lake Mackenzie to form extensive areas of alluvial sediments along their channels. Concurrently, mass wasting processes have generated colluvial deposits of various types found along the steep escarpments that now confine many of these streams and on steeper mountain sides and hillslopes. Organic deposits have accumulated gradually since the Laurentide Ice Sheet left, forming fens and bogs that now occupy many levels, and depressional areas on the uplands that bound the Mackenzie River.

4.3 Materials and Landforms

Published surficial geology mapping covering the RSA identifies glaciolacustrine materials, till (moraine), colluvium, alluvial materials, glaciofluvial materials, eolian materials, bedrock, and organic materials. The following descriptions of the character of these materials and their landforms are based in part on information gathered from publications and maps released by the GSC (Duk-Rodkin, 2002; Duk-Rodkin and Couch, 2004; Duk-Rodkin and Huntley, 2009; Côté et al., 2013; GSC, 2019a, 2019b).

Figures presenting existing surficial geology mapping for the RSA are located in Appendix A, Figure A.8 to A.23.

Glaciolacustrine materials are sediments deposited in and along the margins of glacial lakes and can include materials released by the melting of floating ice. Within the southern and central portion of the RSA, glaciolacustrine materials are dominantly composed of silt and fine sand, but locally can contain gravel and/or clay. In the northern part of the RSA, clay-textured glaciolacustrine materials are more common.

Within the RSA, glaciolacustrine deposits occur primarily as plains and blankets; but, to a lesser degree, as shallow veneers and as hummocky and ridged terrain. These materials generally overlay till and can range from less than 1 m to up to 50 m thick. In the Mackenzie Plain, in the area separating Big Smith Creek to the Great Bear River, glacio-deltaic sands overlay silty clay that had accumulated in the former glacial lake basin. Savigny (1989), in his investigation of the engineering geology of the Great Bear River area, describes how this sequence sits overtop Late Wisconsinan aged till. Glaciolacustrine beaches are rare. They are mapped locally as glaciolacustrine ridges and may also occur around the margins of Glacial Lake Mackenzie.

Till deposited directly by glacial ice likely occupies limited areas at higher and mid-elevations on local hills and ridges but, till will occur more frequently on lower elevation slopes and valley floors. Tills in the area are composed of clay, silt, minor sand and a small percentage of pebbles, cobbles, and boulders. These tills can be strongly calcareous, and the deposits range from thick plains to blankets and veneers overlying bedrock. Minor areas of hummocky and steeply sloping till occur locally. Depending on their surface morphology, these deposits range from a less than 1 m to up to 30 m thick.

Investigations of till in the Mackenzie Plain south of the Great Bear River (Savigny, 1989) suggest that the till is compact, matrix-supported and characterized by rare pockets and lenses of stratified material. The till matrix consists of a near-equal sand-silt-clay mixture, while clasts are subrounded and consist mainly of granite (40% to 50%) and carbonate (40%) with random sandstone, quartzite, syenite, and local siltstone and shale. The average clast size is 10 millimetres (mm), with only a few rare cobbles and boulders.

Colluvium is surficial material that has reached its present position as a direct result of gravity-induced movement, either by slow mass movement (soil creep, rock creep, periglacial processes such as solifluction) and by both slow-moving landslides and rapid landslides (e.g., rock avalanches, debris avalanches, debris flows, and thaw flows). Within the RSA, colluvial materials can be derived both from bedrock and from pre-existing deposits of other surficial materials. Consequently, they are generally rapidly to moderately-well drained and occasionally poorly drained. These deposits can range in depth from veneers less than a metre thick to landslide deposits tens of metres thick.

Within the RSA, colluvium derived from sandstone, or mixed sandstone and limestone or limestone, can take the form of a rubbly sandy deposit. These materials are predominant along the base of moderately steep to steep slopes marking the western side of the Franklin Mountains, as well as Mount Gaudet and Bear Rock. Colluvium derived from shale tends to be composed of small angular rubble in fine matrix, dominated by silts and clays. Colluvium derived from pre-existing surficial deposits will have textures reflective of the source material; for example, sandy or gravely from glaciofluvial deposits, fine sands, silts and clay when derived from glaciolacustrine deposits, or a diamicton when derived from till.

Colluvium mapped in the RSA on level to gently sloping surfaces are materials that could be more appropriately identified as weathered bedrock. Weathered bedrock will often form shallow to very shallow, often discontinuous veneers overlying bedrock and may be interspersed locally with bedrock outcrops. Weathered bedrock comprises bedrock decomposed or disintegrated in situ by mechanical and/or chemical weathering. Rock debris produced by mechanical weathering typically consists of angular fragments and, in the case of chemical weathering, may contain a high portion of residual silts and clays.

Colluvial deposits coded as “Cz” on the RSA surficial geology maps identify areas considered by the original mappers to be landslide deposits; however, our review suggests that some additional areas symbolled as “C” may also be subject to landslides and contain landslide debris. Due to the regional scale of most existing mapping, there are areas of colluvium and past landslide activity that are not mapped or identified as such (e.g., along the escarpments adjacent to fluvial plains or on steeper slopes along incised tributary rivers and smaller streams). A more precise inventory of colluvial and landslide deposits is presented in the LSA terrain mapping (see Section 5).

Alluvial (fluvial) materials are those that have been transported by streams and rivers and typically occupy valley floors. Alluvial materials are mostly imperfectly drained and moderately to rapidly permeable. Textures range from clayey silty sand to very gravelly sand. Alluvial soils often experience periodic flooding and sediment deposition; therefore, have either weak or no (pedogenic) soil development. These deposits typically occur as plains (floodplains) and terraces. In a few isolated upland locations, there are small areas mapped as alluvial fans and alluvial veneers. There is a reasonable chance that the steeper fans (i.e., slope gradients greater than or equal to 5%) are colluvial fans built up by periodic debris flow and/or debris flood events rather than by stream action. Subsequent re-working of these colluvial deposits by stream action does occur.

Glaciofluvial materials have been deposited by glacial meltwater streams, often close to glacial ice, are typically well to moderately-well drained, and rapidly permeable. These materials are composed of gravel, sand and silt in varying amounts. Within the RSA, these materials are generally found as plains and terraces, with lesser areas mapped as veneers, fans, ridges and hummocky terrain. These deposits can range from less than 1 m deep to depths in excess of 30 m.

Organic materials are deposits mainly composed of organic materials resulting from the accumulation of vegetative matter, typically in poorly to very poorly drained, level and depressional areas. These areas are generally level to very gently sloping, and bogs can have scattered mounds of organic material. Within the RSA, organic deposits occur both as fens and as bogs. The fens range in thickness from 2 m to 3 m and the bogs from 1.5 m to 7 m. Surface water may be present in fens in the summer months and be unfrozen to depths of 3 m or more.

Eolian materials are eroded, transported and deposited by wind action. These materials generally consist of fine to medium sand and silt and are not compacted. Individual grains may be rounded and frosted. These materials will tend to be well to moderately well drained. Eolian deposits, as identified within the RSA, occur as forested, parallel to sub-parallel linear dunes and can be up to 20 m thick. Eolian materials can also occur as shallow veneers overlying other surficial materials; but are not mapped as such

Anthropogenic disturbances to soils, terrain and permafrost occur in both the LSA and RSA. They include, but are not limited to:

- developed portions of local communities
- transportation infrastructure such as all-weather roads and winter road, bridges and trails
- Enbridge Norman Wells Pipeline and associated infrastructure (e.g., valve sites, pump stations)
- the Mackenzie Valley Fibre Line
- well sites and cut lines
- limited-use trails
- existing borrow sources and quarries

4.4 Soils

4.4.1 Land Types

Landcover types within the RSA include broadleaf forest, coniferous forest, mixedwood forest, wetlands, shrubland, herbaceous and un-vegetated areas (K'alo-Stantec, 2020c). The project highway alignment overlaps and parallels existing disturbances including roads, industrial developments, and settlements. As noted above, most of the MVH highway alignment parallels an existing winter road (MVWR). The Project also overlaps existing disturbed land through the Hamlet of Tulita.

4.4.2 Soil Development Process

Pedogenic soil development is the result of complex interactions between earth material (bedrock and surficial materials), the topography, the climate, vegetation, living organisms, and time. The soil layer is distinct from the underlying rocks or surficial material because its composition has been subjected to physical, chemical, biological, and anthropogenic factors changes. An important process occurring in cold-climate soils are the annual freeze/thaw cycles. Weak pedogenic soil development on the RSA can be attributed to low temperatures, which have limited chemical and biological activity, and the presence of permafrost, which limits the movement of water and nutrients through the soil profile and contributes to profile disruption (Zoltai and Pettapiece, 1973).

Soil temperature in subarctic environments is controlled by:

- vegetation cover—dense vegetation cover shades the ground from incoming solar radiation and limit heat transfer and encourage lower soil temperatures
- thickness of the surface organic layer—the surface moss layer and surface vegetation function as insulators and do not facilitate heat transfer from the environment, causing lower soil temperatures in organic soils compared with mineral soils (Tarnocai, 1973; Tarnocai and Zoltai, 1978)
- moisture content and topographic location (Tarnocai, 1973)—higher moisture content and depression topography tend to result in lower soil temperatures

Low soil temperatures can trigger cryogenic processes, which affect soil development. Cryoturbation disturbs a soil profile, resulting in mixed, broken, displaced and disrupted horizons (AAFC, 1998). Pressures generated in the active layer during annual freezing can cause displacement of material in the soil profile (Zoltai et al., 1978).

Soils lacking permafrost occur in areas with warmer temperatures and higher precipitation. These soils have a greater degree of soil profile development (i.e., increased weathering and soils biological activity).

4.4.3 Soil Classification

Soils in the LSA and RSA were classified according to the Canadian System of Soil Classification (AAFC, 1998). The broadest element of soil classification is the soil order. Soil order is determined from the nature of the soil environment and the effects of dominant, soil-forming processes. Soil orders are then subdivided in great groups, which are identified based on properties that reflect differences in the strengths of the dominant soil forming processes. Soil subgroups are further divisions of the great group based on diagnostic soil horizons.

Two soil orders, Cryosols and Brunisols, were identified in the LSA, RSA and along the MVH alignment. A summary description of these two soil orders is presented in Table 4.2. Soils are further described to the great group or subgroup level depending on the information available. The distribution of soils within the LSA, RSA, and along the MVH alignment are presented on the soil figures presented in Appendix A (Figures A.24 and A.25), with summary metrics presented in Table 4.3 and Table 4.4.

Cryosols are the dominant soil order in the LSA, RSA, and along the MVH alignment because of the presence of extensive discontinuous permafrost. Cryosolic soils have formed on a wide variety of parent materials and have permafrost within 1 m to 2 m of the ground surface (Turnocai and Bockheim, 2011; AAFC, 1998). All three great groups of the Cryosolic Order: Turbic Cryosols, Organic Cryosols and Static Cryosols, are present in the RSA.

Static Cryosols are the dominant great group, occupying 34.1% of the length of the MVH route. Static Cryosols typically develop on coarse-textured mineral material and lack evidence of cryoturbation. Static Cryosols in the LSA and RSA are Gleysolic Static Cryosols and are present on level to gentle slopes (0 to 9%) and are poorly to imperfectly drained.

Organic Cryosols, which develop from organic material, occupying 28.4 % of the length of the route. Organic Cryosols within the LSA and RSA are present on level to gentle slopes, ranging from 0 to 9%, and are poorly drained.

Turbic Cryosols show evidence of cryoturbation, and permafrost present within 2 m of the surface. Turbic Cryosols occupy approximately 12.8% of the length of the MVH alignment. Turbic Crysols are mostly Gleysolic Turbic Cryosols, which occur in poorly to imperfectly drained areas on gentle slopes (4 to 9%). An additional subgroup, Brunisolic Turbic Cryosol are found within the RSA. These soils are moderately well drained and occur on moderate slopes (10 to 15%).

Brunisols, developed on alluvial and glaciolacustrine deposits are present within the LSA and RSA. Brunisolic soils show some evidence of soil forming processes and lack permafrost within 1 m of the ground surface. Brunisolic soils within the RSA were described to the great group level as Eutric Brunisols, which develop on parent materials with high base status (AAFC, 1998). Eutric Brunisols in the LSA and RSA are moderately well drained, occur on gentle slopes (4% to 9%) and contribute to 18% of the MVH alignment.

Table 4.2 Description of Soils in the RSA

Soil Order	Description of Soil Order	Description of Soil Great Groups	Description of Soil Subgroups
Cryosol	Soils formed on both mineral and organic parent materials and have permafrost present within 1m of the ground surface or within 2 m if strong cryoturbation is present. Mean annual temperature is <0°C.	• Turbic Cryosols are mineral soils that have evidence of cryoturbation and often form patterned ground • Static Cryosols are mineral soils where cryoturbation is absent. • Organic Cryosols have developed from organic material and are classified into subgroups based on the type of peat materials on which they were formed	• Gleysolic Turbic and Static Cryosols develop in poorly drained areas under reducing conditions and show evidence of gleying such as mottling or low chromas • Brunisolic Turbic Cryosols have a Bm horizon that is at least 10 cm thick • Organic Cryosols in the RSA are not classified to the subgroup level, however, soils in the RSA form predominantly on bog peat materials with some occurrences of fen peat materials
Brunisol	Soils with a level of development that distinguishes them from other soil orders. They are considered an intergrade between undeveloped soils (Regosols) and developed soils of the other orders.	• Eutric Brunisols develop on parent material with high base status	• N/A - Brunisolic soils in the RSA were identified at the great group level

Table 4.3 Distribution of Soils in the LSA and RSA

Soil Great Group or Subgroup	Area of LSA (ha)	% of LSA	Area of RSA (ha)	% of RSA
Eutric Brunisol	5,518	17.4	63,742	19.8
Gleysolic Static Cryosol	12,021	37.9	83,664	25.9
Brunisolic Turbic Cryosol	--	--	7,139	2.2
Gleysolic Turbic Cryosol	4,464	14.1	28,651	8.9
Organic Cryosol	8,054	25.4	105,968	32.9
Orthic Turbic Cryosol	162	0.5	17,022	5.3
Non-classified	1,532	4.8	16,288	5.1
Total	**31,752**	**100**	**322,475**	**100**

Table 4.4 Distribution of Soils Along the MVH

Soil Great Group or Subgroup	Length (km)	% of Area
Eutric Brunisol	55.0	18.0
Gleysolic Static Cryosol	104.5	34.1
Brunisolic Turbic Cryosol	--	--
Gleysolic Turbic Cryosol	39.2	12.8
Organic Cryosol	86.9	28.4
Orthic Turbic Cryosol	9.7	3.2
Non-classified	10.8	3.5
Total	**306.2**	**100**

4.5 Permafrost

The following sections summarize permafrost-related information available for the Project. This includes a summary of climate normals originally presented in the TDR for air quality, greenhouse gases (GHG), and climate (K'alo-Stantec, 2022d). Refer to that TDR for additional climate data, including tabulated summaries.

4.5.1 Climate

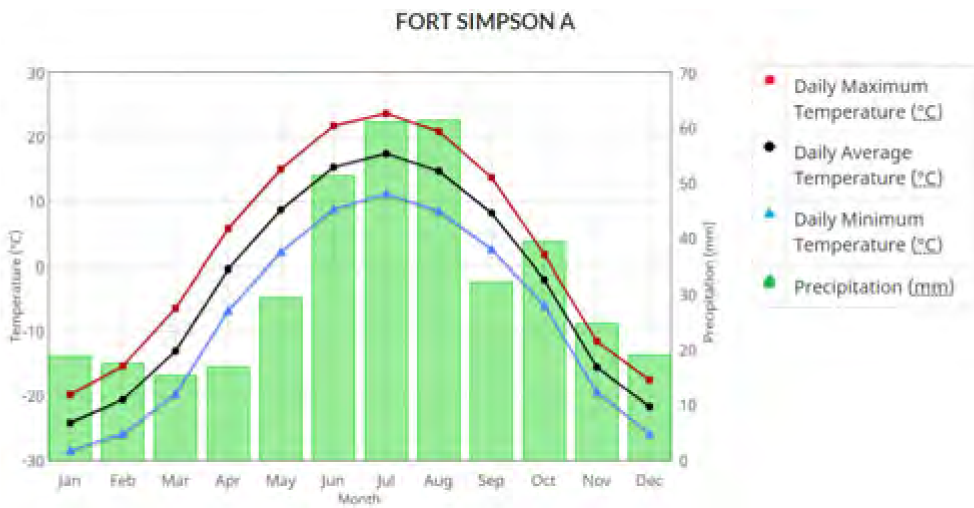
In general, the climate in NT can be described as subarctic, which usually involves short, warm summers and long, cold winters (Phillips, 1990). Environment Canada operates meteorological stations in Norman Wells and Fort Simpson, approximately 200 km south of Wrigley. Daily average temperatures are below 0 degrees Celsius (°C) for 7 months at Norman Wells and Fort Simpson stations with the coldest month being January, where daily average temperatures reach as low as -24.2°C at Fort Simpson and -26.1°C at Norman Wells. Summer months (June, July, and August) average daily temperatures reach the high teens, with the warmest month being July with average temperatures of 17.1°C and 17.4°C, respectively in Fort Simpson and Norman Wells. Extreme temperature ranges from -54.4°C to +35.0°C at Norman Wells and -53.3°C to +36.6°C at Fort Simpson. In general, the temperature data indicates that the climate near Fort Simpson is warmer than at Norman Wells (annual daily average temperature of -2.8°C in Fort Simpson versus -5.1°C in Norman Wells).

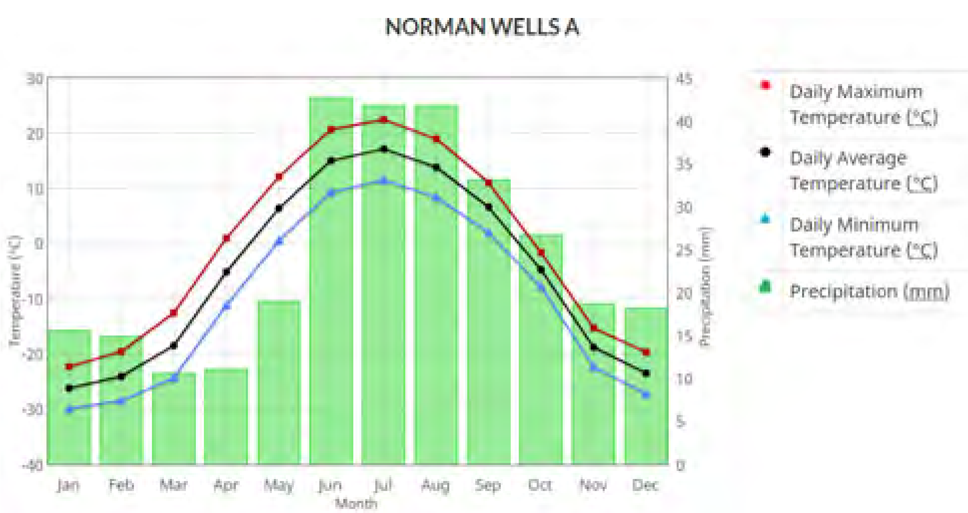
Precipitation includes rain and snowfall, with rain occurring mostly from May to September and snow from October to April for both stations. Most of the annual rain occurs during the three summer months (June, July, and August). At both climate stations, roughly 70% of the annual rainfall occurs during these months. For snowfall, the peak snow months for both climate stations are October to December, roughly 50% of the total annual snowfalls occurs during these months. However, for those peak months (October to December) the total amount of precipitation (rain and snow) is relatively low, when compared to the Canadian precipitation climatology (Government of Canada, 2020).

Annual total rainfall at Fort Simpson is slightly higher than at Norman Wells (238.6 mm versus 171.7 mm). Annual total snowfall for the two stations consists of 187 centimetres (cm) in Fort Simpson and 161.5 cm in Norman Wells. Recorded extreme daily rainfall amounts range from 49.3 mm at Norman Wells in August to 85.8 mm at Fort Simpson in July. Extreme daily snowfall values are 28.4 cm at Norman Wells and 33.8 cm at Fort Simpson, both were recorded in the month of April.

Figure 4.1 presents temperature and precipitation graphs as presented by the Government of Canada (2020) using climate normals data covering the 1981 to 2010 period.

Figure 4.1 Canadian Climate Normals - Fort Simpson and Norman Wells (1981-2010 Data)





4.5.2 Permafrost Distribution

Permafrost refers to a condition when the ground, either loose material or bedrock, remains at or below a temperature of 0°C for a minimum period of two years (Permafrost Subcommittee, 1988).

Based on regional permafrost mapping by Heginbottom et al. (1995) and Heginbottom (2000), the RSA between Norman Wells and Wrigley spans the following permafrost zones (see Figure 4.2):

- extensive discontinuous permafrost—permafrost underlying 65% to 90% of the area of exposed land surface. This zone predominantly occurs in the northern portion of the highway corridor near Norman Wells.
- intermediate discontinuous permafrost—permafrost underlying 35% to 65% of the area of exposed land surface. This zone is more likely to occur in the Mackenzie Plain on the western side of the Franklin Mountains.
- sporadic discontinuous permafrost—permafrost underlying less than 35% of the area of exposed land. This zone occurs predominantly in the southern portion of the highway corridor near Wrigley.

Regional scale permafrost distribution maps may not fully reflect current site conditions, especially when accounting that these maps were produced over two decades ago and may not account for recent impacts of climate change. The findings of recent geotechnical field investigations (Tetra Tech, 2020a, 2020b, 2020c, 2020d) and the LSA terrain mapping are considered the most useful dataset to inform on the overall distribution of permafrost along the project.

The climate is the predominant element controlling the broad distribution of permafrost. Other contributing factors influencing its distribution and local properties include the topography, soils characteristics, vegetation cover, snow cover, and surface water.

General comments on how these factors can impact permafrost distribution are provided below.

The topography and local relief (e.g., river valley, ridges or hills) influence the distribution of permafrost, primarily as a result of variation in solar radiation received at the ground surface. Differences in solar radiation could result in thinner or thicker active layer (i.e., the surface that freezes and thaws each year), or absence of permafrost, depending on the orientation of slopes. In discontinuous permafrost, frozen ground is more likely to occur on north-facing slopes and in low-lying plains where solar radiation is limited.

Soil texture affects the capacity of the material to retain water. Information on soil texture within the LSA and RSA is available from historical publications, reports and databases as well as from recent geotechnical investigations conducted for the MGAR and PCAR projects (Tetra Tech, 2020a, 2020b, 2020c, 2020d). These data, along with terrain mapping conducted for the LSA, reveals the distribution of fine- versus coarse-grained soils and, incidentally, on the distribution of soils that are frost-susceptible.

Frost susceptibility is a concept widely used in cold region to quantify the capacity of a soil in generating frost heave (i.e., upwards swelling of soil during freezing conditions caused by an increasing presence of ice) and frost damage (Sheng, 2021). Acknowledging that soil texture and material type are the most important factors affecting frost heave, special attention was given to conduct detailed terrain mapping along the MVH alignment so that this information can be used to support highway design.

Organic soils possess thermal properties effective in protecting the ground from atmospheric and solar heat. During the summer, when the surface layers are dry, the thermal conductivity may decrease and slow seasonal summer thaw. During autumn and winter, as peat becomes filled with ice, the thermal conductivity increases, thus leading to lower mean annual ground temperatures (French, 2007). Because organic matter has a high potential for water retention, high ice content permafrost is often found underneath organic soils.

Thick organic soils are often found in forest and shrub wetlands. These soils are predominant in areas associated with open water and adjacent to watercourses near the Mackenzie River. Permafrost is predominant in stands of low black spruce forest that have developed on thick organic soils. Localized peat plateaus, often elevated 1 m to 2 m above the surrounding terrain, are expected to be present in the elevated black spruce bogs.

Areas of thick organic accumulations often have ice-rich permafrost and, therefore, special attention was given to delineate wetlands (i.e., organic veneers (Ov) and organic blankets (Ob) as part of the LSA terrain mapping (see Chapter 5).

Soil drainage conditions can influence the presence of permafrost. A poorly and very poorly-drained soil may indicate that permafrost is present because the occurrence of permafrost may prevent water from draining, and thawing of the uppermost portion of permafrost may lead to accumulations of water at the ground surface.

The extent and dynamics of permafrost are tightly linked to the distribution and movement of water and, therefore, special attention was also given to observe drainage patterns as part of the LSA terrain mapping (see Chapter 5). Vegetation and snow cover both affect the thermal exchange between air and ground, influencing overall permafrost distribution. For example, the degree of canopy closure will influence how much solar radiation will reach the forest floor (i.e., the vegetation cover will shade the ground from direct solar radiation, limiting the amount of heat transferred to the ground). Similarly, a dense forest canopy can intercept more snowfall during winter than an open forest canopy. A soil with a thick organic horizon can insulate and retard heat transfer (upward and downward). Similarly, a thick snow blanket (either trapped by vegetation or by a topographic obstacle) can insulate underlying soils by retarding frost penetration in the fall, or by delaying thawing in the spring.

Vegetation types and cover help with the interpretation of terrain conditions, including potential permafrost dynamic, and special attention was given to observe vegetation patterns as part of the LSA terrain mapping (see Chapter 5),

Water bodies will influence the distribution of permafrost. Thermal exchange through bodies of water such as lakes and rivers can result in thinner, or absent permafrost. Taliks are bodies or layers of unfrozen ground in permafrost areas. Permafrost will be absent beneath large bodies of water such as the

Mackenzie River as well as large lakes (Burgess and Smith, 2000). Around lakes and tributary streams that do not freeze completely in the winter, the temperature of the water will influence the ground temperature regime, resulting in taliks that vary in size and shape.

Ares occupied by water bodies have been mapped within the LSA and RSA (see Chapter 5; these map units are good indicators of the presence of taliks.

4.5.3 Ground Ice

In permafrost soils, ground ice occurs in many forms, from ice fillings in the intergranular pores of soils to massive ice bodies several metres in thicknesses.

Segregated ice is expected to be the most common type of ground ice present within the LSA and RSA and consists of discrete ice lenses or layers that form by migration of unfrozen pore water towards a freezing front (O'Neill et al., 2019). Examples include ice structures that bond the enclosing sediments (intrusive ice), reticulate ice lenses, layers, and veins, ice crystals and icy coatings on soil particles. In the active layer, segregated ice pushes soil particles and stones to the surface and, on slopes, results in the slow, downslope movement of soil materials. The ice-content of the different overburden materials is expected to vary, from high (in peat and organic soils, fine-grained glaciolacustrine or clay-till) to low (in alluvial and glaciofluvial sand and gravels).

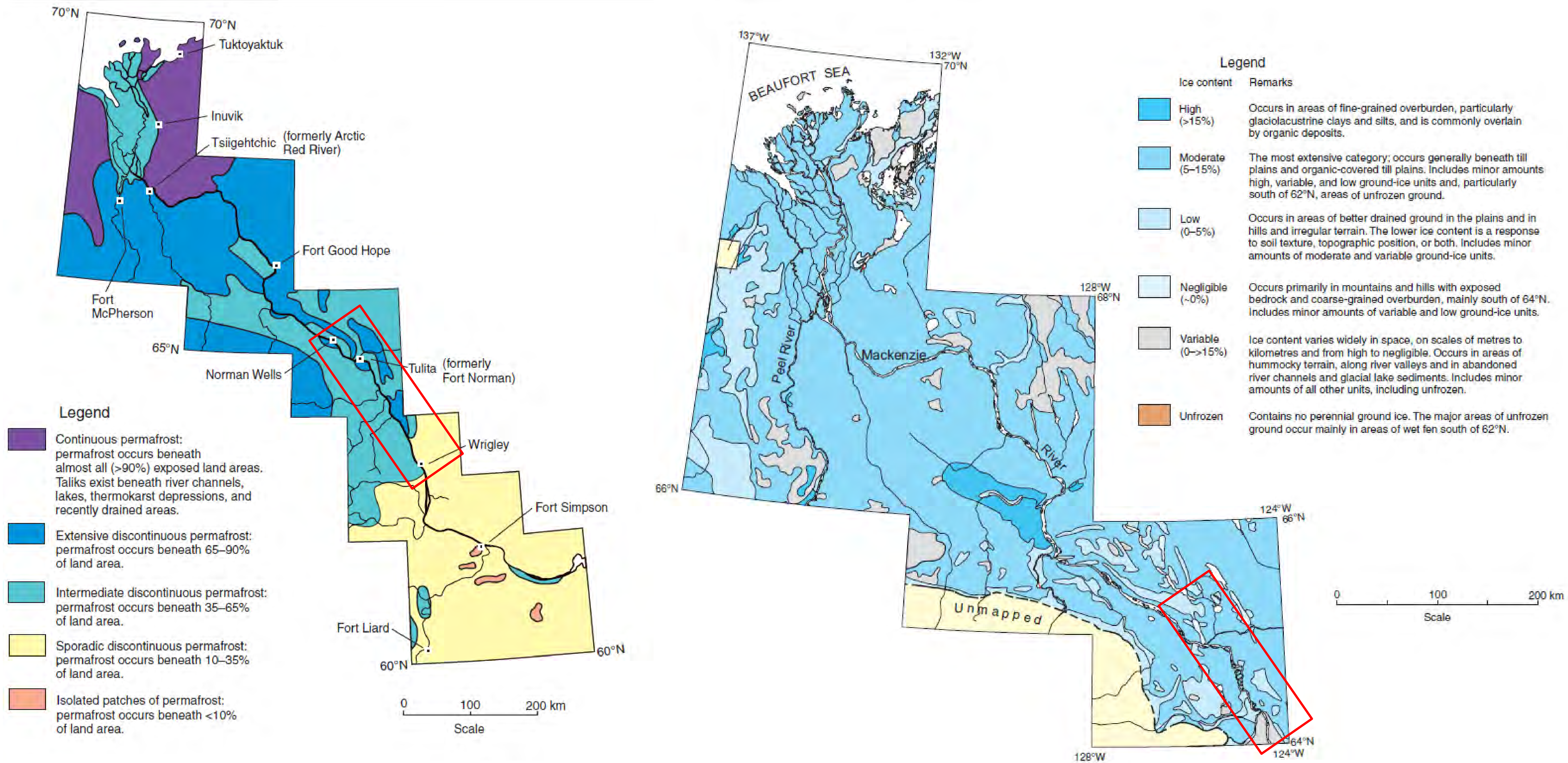
Geotechnical investigations conducted for the MGAR and PCAR projects (Tetra Tech, 2020a, 2020b, 2020c, 2020d) allowed for the classification of ground-ice encountered in different material types (see Section 4.5.5.2 MGAR and PCAR Permafrost Assessments).

Ice wedges are downward-tapering bodies of nearly pure ice that accumulate in near-surface permafrost (Lachenbruch, 1962; O'Neill et al., 2019). They form when cold winter temperatures cause the ground to contract under stress and crack. Meltwater later infills these cracks and refreezes. This repeated process results in the growth of an ice wedge over time, often leading to commonly recognizable pattern of ice wedge polygons in lowland terrain. The terrain along the LSA and RSA is expected to contain few areas characterized by the presence of ice wedges. This is supported by the review of LiDAR data available for the majority of the LSA (see results of LSA Terrain Mapping in Section 5).

Massive ice may occur as large bodies of preserved glacial ice or as thick ice beds developed in situ by segregation occurring between fine-grained materials (silts and clays) and coarser sands. These types of relic ice deposits have been described in several publications (e.g., Mackay, 1971; Mackay and Dallimore, 1992) and are expected to be limited to the Mackenzie Delta and Tuktoyaktuk Peninsula, well outside of the RSA.

Figure 4.2 presents maps showing permafrost distribution and the expected distribution of ground-ice within the Mackenzie Valley, based on mapping by Heginbottom (2000), with Figure 4.3 presenting maps showing permafrost distribution and expected ground-ice abundance based on modelling by O'Neill et al. (2019, 2020).

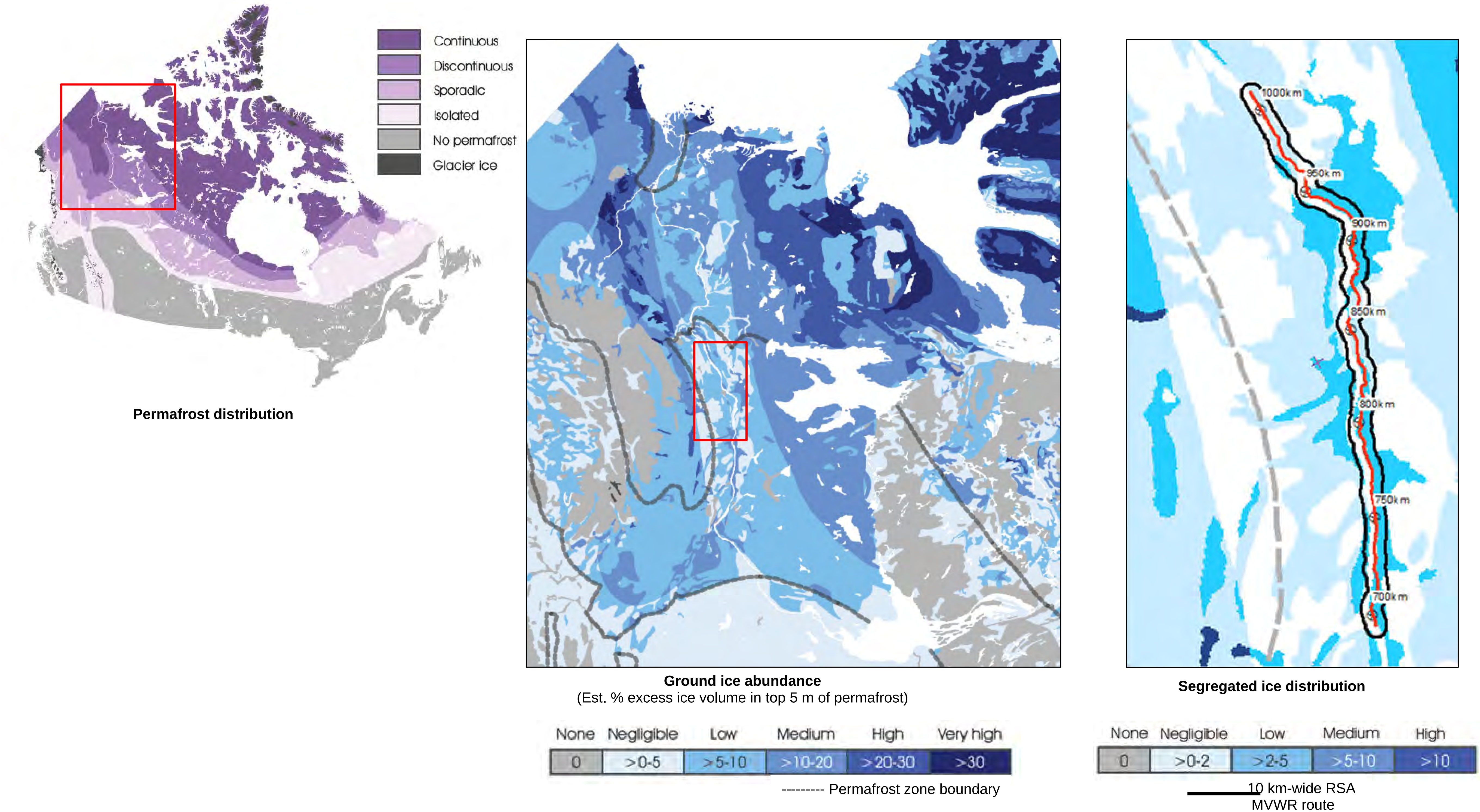
Figure 4.2 Permafrost Distribution (left) and Expected Ice Content (right) Along the Mackenzie Valley



NOTE:
*The red polygon shows the approximate location of the Project

Source: from Heginbottom (2000)

Figure 4.3 Permafrost and Ground Ice Distribution Within the RSA



Permafrost distribution

Ground ice abundance
(Est. % excess ice volume in top 5 m of permafrost)

Segregated ice distribution

Source: Modified from O'Neill et al. (2019, 2020).

4.5.3.1 Existing Field Data Specific to Terrain and Permafrost

Field data indicative of the presence or absence of permafrost along the MVWR route include historical geotechnical boreholes conducted in support of pipelines and transportation projects within the Mackenzie Valley, most of which were incorporated in the borehole database compiled by Smith et al. (2005) and, subsequently, through the PIN web portal.

Filtering to boreholes located within the RSA resulted 2,994 borehole entries falling within a maximum 5 km from the MVWR route. Out of these boreholes, 1,786 fall within the LSA (i.e., within 0.5 km of the MVWR route). As an example, a screen capture showing the concentration of existing boreholes falling within both the current RSA and LSA in the area surrounding the Ochre River (MVWR KM 724) is presented in Figure 4.4.

Figure 4.4 Existing Geotechnical Boreholes in the Area Surrounding the Ochre River

Notes: MVWR (red line), Norman Wells Pipeline (yellow line), RSA (black polygon), LSA (dashed polygon). Yellow dots are borehole locations. SOURCE: data obtained through the PIN web portal.

As identified in the paper accompanying the release of the database, the quality of data recorded for any given borehole varies widely, likely because of the defined purpose of the geotechnical study for which the hole was originally drilled. Differences in formats, structure and/or units of measurements observed as part of the data consolidation might also be responsible for some of the original data not being included in the compilation database. For these reasons, the borehole data was mainly used to support the terrain mapping through the description of surface/subsurface material types and textures, without attempts to summarize permafrost distribution and ground ice conditions.

During the construction of the Normal Wells Pipeline by Interprovincial Pipeline Ltd. (now operated by Enbridge) in the early 1980s, a continuous ditchwall log was created during the excavation of the trench for pipeline burial (Nixon et al., 1991; Burgess and Lawrence, 2000). Information recorded included soil and ice description as well as geothermal (frozen/unfrozen) interpretations. Data collected during the construction of the pipeline allowed for the confirmation of the discontinuous character of the permafrost along its right-of-way. Findings indicated that frozen ground underlay 80% to 90% of previously undisturbed ground surface near Norman Wells, a proportion declining to around 40% in the area surrounding Wrigley. Nixon et al. (1991) notes that geophysics and borehole data available for the area generally supported the ditchwall log information, with the exception of a 50 km stretch north of Wrigley (pipeline KM 250-300). The geophysics and borehole data suggested a greater occurrence of permafrost (60% to 70% versus 40%).

Summarized permafrost occurrences per surficial geology as presented by Nixon et al. (1991) along the Norman Wells Pipeline is presented in Table 4.5. That route is within the RSA and parallels the MVWR (from 0.1 km to approximately 6 km between the segments).

Table 4.5 Frozen Terrain and Interfaces by Terrain Unit along Norman Wells Pipeline

IPL spread (km range)	LP (25.5%)	MG (19.4%)	OV–LP (13.9%)	LP–MG (10.5%)	OV–MG (6.3%)	GO (4.8%)	All (100%)
1 (0.0–149.5)							
% terrain occurrences	28.7	18.7	16.1	9.2	2.5	0.1	—
% frozen	91.0	92.3	90.2	81.9	91.9	100.0	89.6
Length (km)	42.89	28.0	24.13	13.76	3.68	0.11	149.5
No. of interfaces	56	16	39	25	6	0	191
No. of interfaces/km	1.31	0.57	1.62	1.82	1.63	0.0	1.28
2 (149.5–269.3)							
% terrain occurrences	41.3	1.5	9.5	22.0	0.0	9.0	—
% frozen	56.9	44.0	38.9	69.8	—	70.2	56.5
Length (km)	49.46	1.76	11.39	26.36	0.0	10.8	111.1
No. of interfaces	87	2	13	23	—	21	173
No. of interfaces/km	1.76	1.14	1.14	0.87	—	1.94	1.44
3 (269.3–380.4)							
% terrain occurrences	31.6	24.5	9.9	0.0	3.9	7.4	—
% frozen	55.6	81.0	53.3	—	80.3	49.9	63.4
Length (km)	35.1	27.2	10.99	0	4.32	8.18	119.8
No. of interfaces	70	21	34	—	3	12	179
No. of interfaces/km	1.99	0.77	3.09	—	0.69	1.47	1.61

Notes: IPL spread refers to sections of the Norman Wells Pipeline (Norman Wells corresponds to KM 0, and Wrigley to KM 336 (spread 3). Codes for terrain units are as follow: LP, lacustrine; MG, till; OV, organic; GO, outwash.

Source: from Nixon et al. (1991)

4.5.4 Active Layer

The active layer is defined as the layer of ground that is subject to annual thawing and freezing in areas underlain by permafrost (Permafrost Subcommittee, 1988). Generally, active layer thickness varies in response to air temperature, vegetation cover and type, snow cover, summer rainfall and local soil characteristics (texture, moisture and thickness of the surface organic layer).

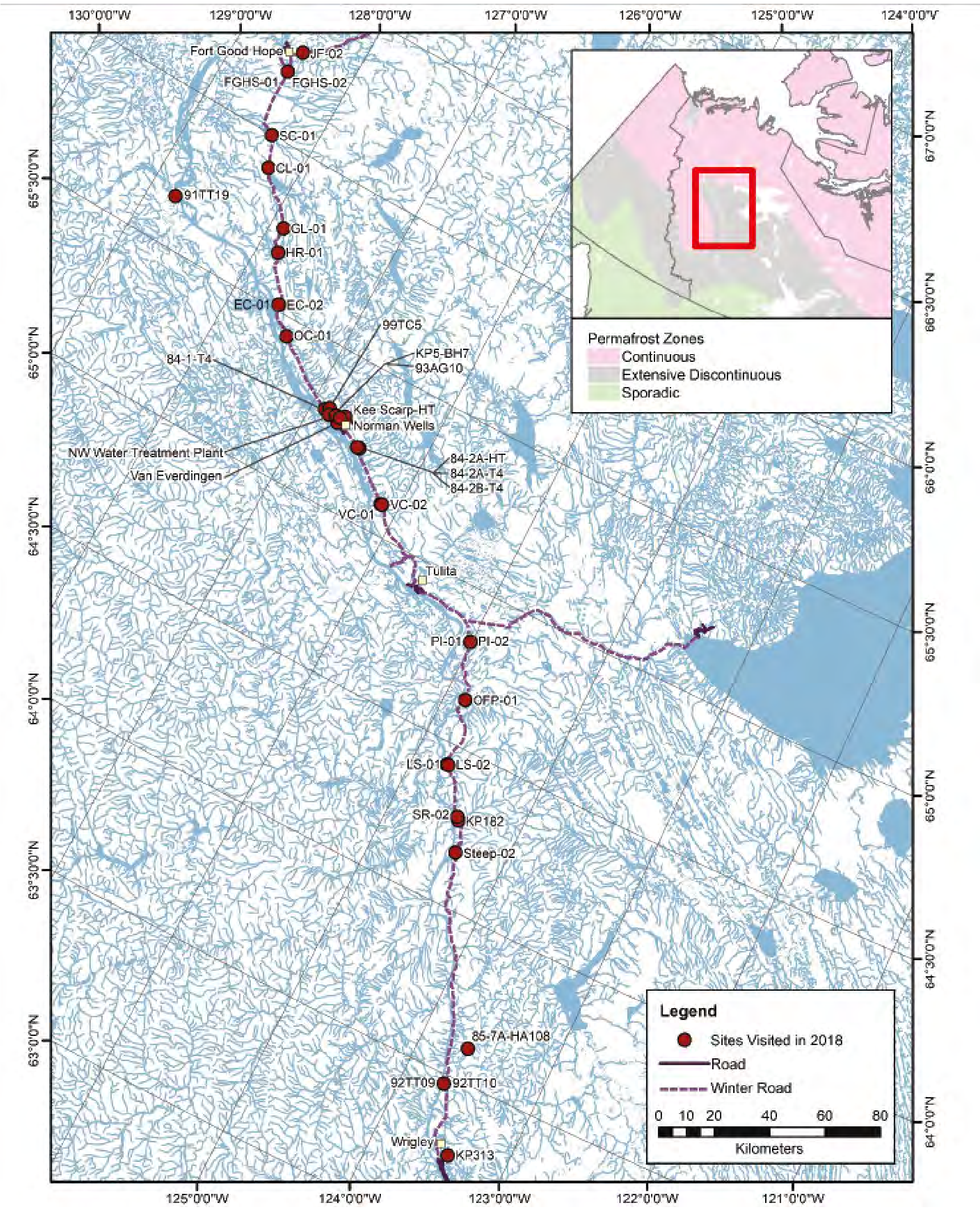
Key drivers of the variability of the active layer within Mackenzie Valley include climate, vegetation and soil condition factors. Published studies indicate that there is significant inter-annual variability, likely driven by variation in thawing degree days (i.e., the cumulative annual measure of degrees above 0°C), and inter-annual variations in soil moisture content. Higher variability occurs where moisture content and organic cover are high and spatially variable. The active layer of thick organic soils is generally less than the surrounding mineral soils.

The GSC maintains a series of active layer monitoring sites within the Mackenzie Valley, several of which have been in operation since the early 1990s and data available from these locations contributed to numerous publications (e.g., Nixon, 2000; Smith et al., 2009b; Duchesne et al., 2015, Duchesne et al., 2020). At GSC monitoring sites, air and ground temperatures are being monitored and thaw tubes are used to determine the maximum thaw penetration during the period of maximum thaw. Review of available data indicates that 17 monitoring sites are located within the RSA (Figure 4.5). There is a general southward increase in active-layer thickness with increasing thawing degree days and recent data (summer 2017) indicate thaw depths ranging from 0.46 m to 7.68 m (Table 4.6). The absence of active layer values at several sites suggests absence of permafrost, or a thaw depth deeper than the depth of recording.

Researchers cited above have been able to document trends in the active layer over time and data available for sites in Mackenzie Valley shows that there is significant inter-annual variability. For example, Duchesne et al. (2015) note that there has been an increase of the active layer between 1991 and 1998 (maximum in 1998), a thinning between 1999 and 2005, then an increase up to 2012. Although records are too short to make inferences about temporal trends related to climate[2], there is a consensus that the active layer has generally increased at sites along the Mackenzie Valley over the last few decades, which was most likely in response to warmer air temperatures. It is anticipated that the active layer will increase with climate change.

[2] https://www.enr.gov.nt.ca/en/state-environment/132-trends-active-layer-thickness-nwt#:~:text=In%20the%20NWT%2C%20there%20is,soil%20moisture%20and%20snow%20cover.

Figure 4.5 GSC Active Layer Monitoring Sites from Wrigley to Fort Good Hope



Source: from Duchesne et al. (2020)

Table 4.6 Summary of 2017 Thaw Depth at Monitoring Sites Located Within the RSA

Site ID	Lat/Long (°)	Approx. MVWR KM	Thaw Depth (m)	Landform	Vegetation
KM313	63.26 N 123.43 W	694	1.0 to 3.62	Lacustrine plain	Moss cover and peat, forested, mix of birch and spruce
92TT09	63.46 N 123.70 W	723	0.46 (probed)	-	-
92TT10	63.47 N 123.69 W	724	0.78 (probed)	Low fluvial terrace cut into glaciolacustrine plain	moss and typical boreal vascular plants
85-7A-HA108	63.61 N 123.64 W	738	N/A	Ground moraine	Lichen, moss, ericaceous shrubs with black spruce and alder
Steep-02	64.18 N 124.38 W	816	N/A	Alluvial and colluvial	Mixed, white spruce, jackmine, aspen, birch
KM182	64.28 N 124.47 W	832	N/A	Lacustrine plain	Forested (burned 1994) – Aspen, willow, birch, tamarack and moss and peat ground cover (unburned)
SR-02	64.29 N 124.49 W	833	7.09	Glaciofluvial veneer over lacustrine	Burnt black spruce forest
LS-01	64.43 N 124.74 W	853	N/A	Alluvial flood plain	Open mature black spruce forest – cleared between 2015 and 2016.
LS-02	64.43 N 124.73 W	854	7.68	Glaciofluvial outwash plain	Tamarack birch poplar, and pine forest transition to spruce
OFP-01	64.65 N 124.84 W	881	3.12	Lacustrine plain	Open mixed spruce, pine deciduous forest adjacent to open, low-lying fen
PI-01	64.83 N 125.01 W	906	5.11	Lacustrine plain	Recovering burn (burnt black spruce forest)
PI-02	64.83 N 125.01 W	906	N/A	Lacustrine plain	Unburnt, black spruce forest with moss and lichen ground cover
VC-01	65.10 N 126.14 W	987	2.75	Moraine plain	NW side of creek, on top of ridge in black spruce forest
VC-02	65.10 N 126.13 W	987	1.73	Moraine plain	SE side of creek on plateau in area of burnt black spruce
84-2A-HT	65.23 N 126.50 W	1011	3.32	Ground moraine	Lichen, moss, ericaceous shrubs with black spruce and tamarack
84-2A-T4	65.23 N 126.50 W	1011	3.39	Ground moraine	Lichen, moss, ericaceous shrubs with black spruce and tamarack
84-2B-T4	65.23N 126.52 W	1011	1.47	Ground moraine	Moss with white spruce

Source: Modified from Duchesne et al. (2020)

4.5.5 Ground Thermal Regime

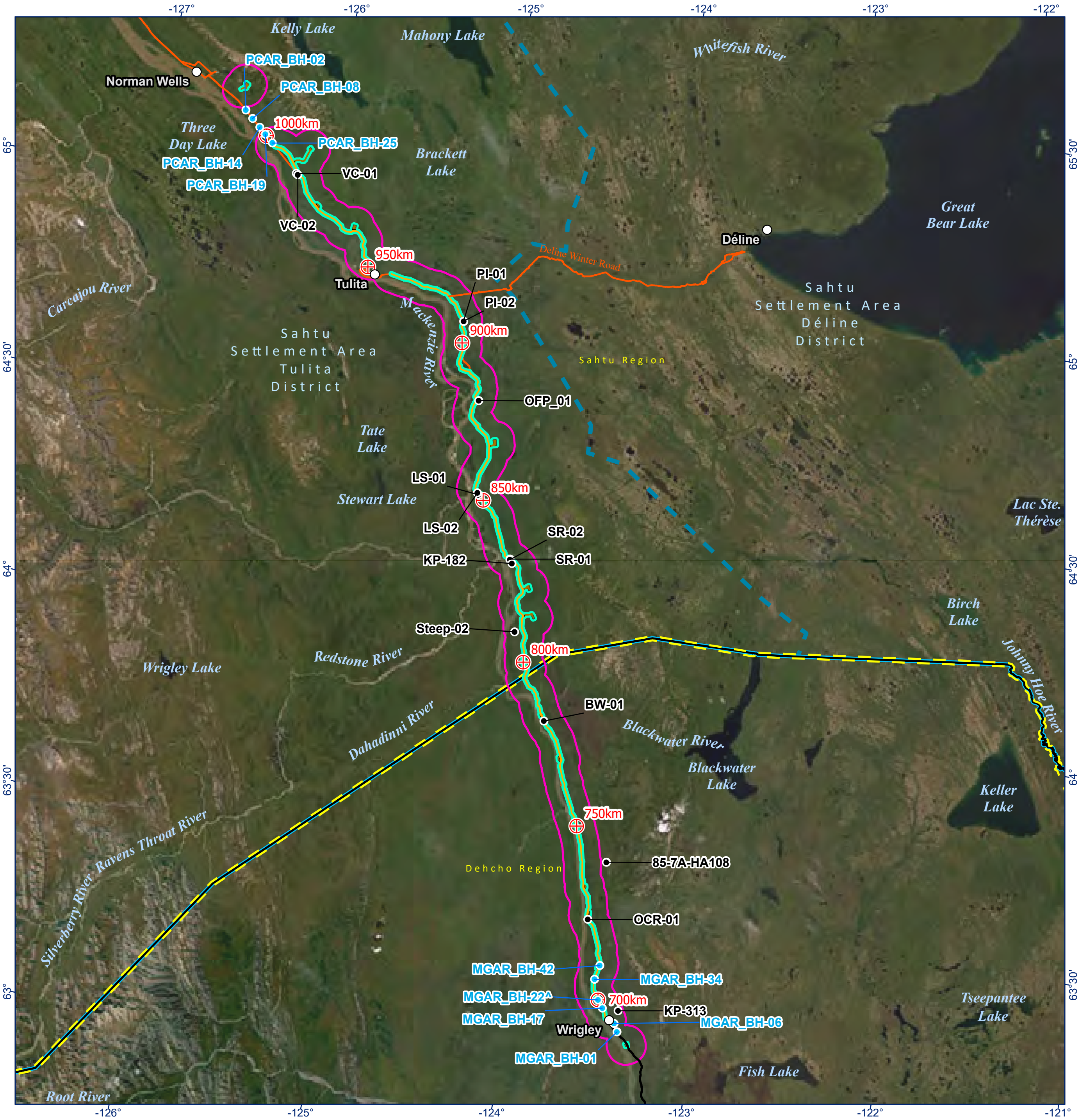
4.5.5.1 Monitoring by the Geological Survey of Canada

Historical information on ground thermal regime of the Mackenzie Valley is available from Judge (1973). Since the mid-1980s, the GSC has developed and maintained a permafrost monitoring network in the Mackenzie Valley, resulting in a suite of publications detailing permafrost conditions in the region (including but not limited to Smith and Burgess, 2000; Smith et al., 2004; Duchesne et al., 2014). A recent compilation of air temperature, ground-thermal and active-layer data acquired from these sites was released, including a summary of ground temperature records for the 2007–2018 period (Duchesne et al., 2020). That publication has tabulated summaries and thermal profiles at monitoring sites (trumpet curves).

Ground temperature monitoring sites within the RSA are presented in Figure 4.6. Recent data (summer 2017–2018) shows the annual mean ground temperatures at depth of zero annual amplitude (or deepest available measurements) range from above zero (i.e., absence of permafrost) to approximately -2°C. Ground temperature records for the 2007–2018 period indicated that permafrost is generally warming throughout the Mackenzie Valley and, for a majority of sites, permafrost is currently warmer than the baseline established during the International Polar Year (2007–2009) (Duchesne et al., 2020).

4.5.5.2 MGAR and PCAR Permafrost Assessments

A summary of key results obtained from the geotechnical, geophysical and thermal evaluations conducted by Tetra Tech along the PCAR and MGAR (Tetra Tech, 2020a, 2020b, 2020c, 2020d) are presented below.



- GSC ground temperature monitoring
- PCAR/MGAR ground temperature monitoring
- Mackenzie Valley Highway Kilometre Post
- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Granular Borrow / Rock Quarry Site and Access
- Local Study Area
- Regional Study Area
- Community
- All-Season Road (Hwy 1)
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

0 10 20 Kilometres

(At original document size of 8.5x11)
1:1,600,000

N

Kálo-Stantec

Notes
1. Coordinate System: NAD 1983 Northwest Territories Lambert
2. Data Sources: Centre of Geomatics of Government of NWT, Government of Canada, Stantec
3. Background: World Topographic Map: Esri, FAO, NOAA, USGS, NRCan
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 3/9/2023
TR by AJ on 3/9/2023

Client/Project
144903025-0073 REVB

Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
4.6

Title
RSA Ground Temperature Monitoring Sites

MGAR

- The MGAR project begins in Wrigley (MVWR KM 690) and extends to Mount Gaudet at (MVWR KM 709).
- A total of 42 boreholes at approximately 500 m spacing were drilled along the MGAR alignment. Drill depths ranged from 0.9 m to 8.1 m.
- Both unfrozen and frozen soils, including visible ground ice, were encountered in the boreholes, with a total 37 out of the 42 boreholes showing frozen soils.
- The southern portion of the MGAR (Wrigley to MVWR KM 692.5) consisted of frozen coarse-grained glaciofluvial sand and gravel to the depth of the borehole (based on 12 boreholes completed in this section, which depth ranged from 0.9 to 6.6 m).
- The middle portion of the MGAR (MVWR KM 692.5 to KM 703) consisted of lacustrine silty clay that was frozen with excess visible ground ice throughout the depth of borehole.
- The northern portion of the MGAR (MVWR KM 703 to KM 707.3) consisted of both unfrozen and frozen lacustrine silty clay.
- The seasonally frozen (interpreted as the active layer in Tetra Tech report)layer was estimated to range from 0.5 m to 2.0 m thick, based on five ground temperature monitoring locations along the MGAR.

In August 2020, multi-bead ground temperature cables were installed in six boreholes, all in fine-grained till deposits. Their locations are presented in Figure 4.6.

Summary data as presented by Tetra Tech is presented in Table 4.7. Refer to the original reports for tabulated summaries and graphs depicting temperature profiles.

Table 4.7 MGAR Ground Temperature Data Summary

Borehole Number	BH-01	BH-06	BH-17	BH-34	BH-42
MVWR Milepost (km)	686.4	688.8	694.8	703.3	707.3
Permafrost Encountered	No	No	Yes	Yes	No
Estimated Depth of Active Layer*	0.5 m	0.6 m	2.0 m	1.4 m	1.5 m
Minimum Temperature below Active Layer (November 2020)	1.3°C @ 1.0 m	0.1°C @ 8.0 m	-0.4°C @ 7.7 m	-0.2°C @ 7.7 m	1.9°C @ 6.0 m
Maximum Temperature below Active Layer (November 2020)	3.7°C @ 4.0 m	0.7°C @ 3.0 m	0.0°C @ 2.7 m	0.1°C @ 1.7 m	2.6°C @ 2.0 m

** Active layer is defined as the top layer of ground subject to annual thawing and freezing in areas underlain by permafrost.*

MGAR Section	MVWR Milepost (km)		Permafrost Conditions	GTCs within Section	Boreholes within Section
	From	To			
South (Wrigley to MVWR km 692.5)	686.4	692.5	Unfrozen Frozen, No Excess Ice	2 (BH-01, BH-06)	12 (BH-01 to BH-12)
Middle (MVWR km 692.5 to 703.0)	692.5	703.0	Frozen, Ice-Poor Frozen, Ice-Rich	1 (BH-17)	21 (BH-13 to BH-33)
North (MVWR km 703.0 to Mount Gaudet)	703.0	707.3	Unfrozen Frozen, Ice-Poor	2 (BH-34, BH-42)	9 (BH-34 to BH-42)

Source: Tetra Tech (2020a, 2020b)

PCAR

- The PCAR project begins at Canyon Creek (MVWR KM 1009) and extends to Prohibition Creek (MVWR KM 995).
- A total of 25 boreholes drilled to depth ranging from 5.5 m to 8.1 m showed both unfrozen and frozen soils.
- The alignment from KM 997 to KM 1009 consisted primarily of clay till with layers or pockets of silt, sand and gravel. KM 997 to KM 999.5 encountered highly weathered shale bedrock underlying the mineral soil.
- Permafrost was encountered in most of the boreholes, with ice contents generally ranging from no visible ice to around 20% visible ice.
- Active layer was observed in all 25 boreholes, at depths ranging from 0.6 m to 1.5 m.
- Ground ice contents were observed to be higher closer to the surface and decreasing with depth.
- No areas of massive ground ice were encountered.

In August 2020, multi-bead ground temperature cables were installed in five of the previously drilled boreholes, all in fine-grained till deposits (see location on Figure 4.6). A first complete set of readings were collected in October 2020. Summary data as presented by Tetra Tech are in Table 4.8.

Table 4.8 PCAR Ground Temperature Data Summary

Borehole Number	BH-02	BH-08*	BH-14	BH-19	BH-25
MVWR Milepost (km)	1008.2	1005.0	1001.8	999.2	996.0
Depth of Active Layer	0.8 m	-	0.6 m	1.2 m	1.5 m
Minimum Temperature below Active Layer (October 2020)	-1.0°C @ 7.8 m	4.4°C @ 8.0 m	-0.3°C @ 1.2 m	-1.9°C @ 7.3 m	-1.0°C @ 7.2 m
Maximum Temperature below Active Layer (October 2020)	-0.4°C @ 1.3 m	8.6°C @ 2.0 m	0.2°C @ 3.7 m	-0.3°C @ 1.3 m	-0.2°C @ 1.7 m

** Ground temperature readings incorrectly high in Borehole BH-08, likely due to Amphenol connector issue with GTC.*

PCAR Section	MVWR Milepost (km)		Permafrost Conditions	GTCs within Section	Boreholes within Section
	From	To			
South (Prohibition Creek to MVWR km 999)	995.3	999.2	Frozen, Ice-Poor Unfrozen	1 (BH-25)	6 (BH-20 to BH-25)
Middle (MVWR km 999 to Christina Creek)	999.2	1001.1	Frozen, Ice-Poor Frozen, Ice-Rich	1 (BH-19)	5 (BH-15 to BH-19)
North (Christina Creek to Canyon Creek)	1001.1	1009.3	Unfrozen Frozen, Ice-poor	3 (BH-02, BH-08, BH-14)	14 (BH-01 to BH-14)

Source: Tetra Tech (2020c, 2020d)

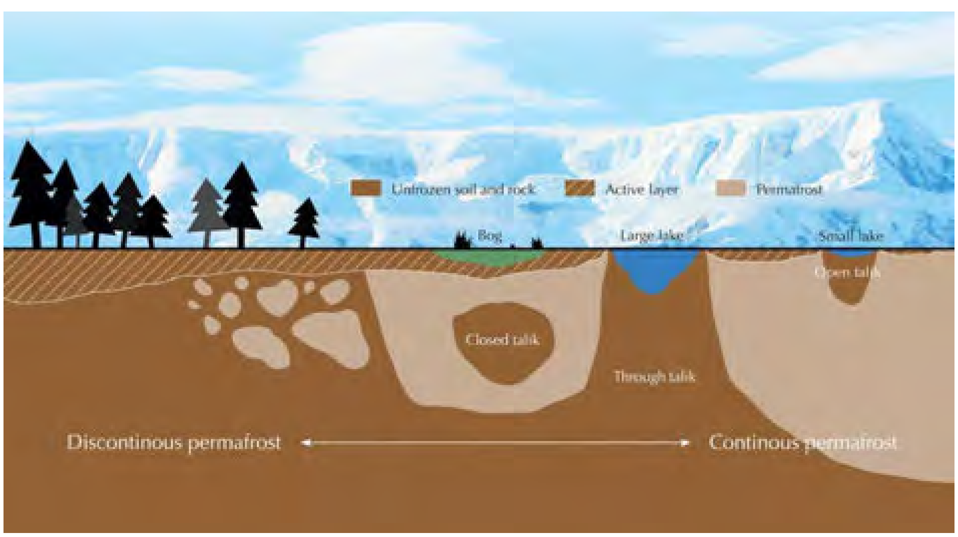
4.5.6 Permafrost, Surface Water and Groundwater Interactions

At the watershed scale, surface and subsurface runoff transports snowmelt and rainfall from hillslopes to numerous lakes and stream systems. In the Taiga Plains, drainage conditions are characterized by runoff peaks during spring snowmelt and are influenced by high surface water storage in waterlogged soils, wetlands, and ponds. A large portion of the RSA is characterized by the presence of wetlands (40% of the RSA in the Sahtu Region and approximately 30% in the Dehcho Region) (K'alo-Stantec, 2022c), with waterlogged soils influenced by the distribution of permafrost.

Water discharges in streams, mainly through river valleys that have developed along the main tributaries to the Mackenzie River. Within the LSA, the MVWR route often crosses these streams in areas of wide floodplains, opening onto even larger fans. Streams and water bodies are underlain by taliks, some contained within permafrost, others are interconnected through discontinuous permafrost (through taliks; Figure 4.7). In undulating terrain, surface drainage is often condensed into channels, some of the larger ones associated to post-glacial erosion. On moderately-steep to steep hillslopes and escarpments, surface runoff is directed into gullies, which often show signs of mass movement. Along low-angle hillslopes, areas affected by increased seepage and surface runoff often host distinct vegetation communities that facilitate their identification on air photos and satellite imagery.

Drainage patterns are seasonally controlled by the depth to the frost table and the presence of ephemeral drainage channels. In continuous permafrost terrain, the presence of frozen ground limits groundwater flow, and surface runoff and seepage occur through the active layer. In discontinuous permafrost or areas characterized by interconnected taliks, near-surface drainage can interact with a deeper aquifer. Local groundwater quantity and flow patterns are influenced by the presence of permafrost.

Figure 4.7 Simplified Schematic Representation of Continuous/Discontinuous Permafrost and Taliks (from PhysicalGeography.net)



Poor drainage conditions along a road in permafrost terrain may cause surface water ponding, thermal erosion, thermokarst and/or the formation of icings (see Section 4.6.4). To facilitate the identification of potential drainage flow intersecting the MVH alignment, apparent drainage flow paths were delineated as part of the LSA terrain mapping (Section 5).

4.6 Geomorphological Processes and Geological Hazards

Geomorphological processes are natural mechanisms of weathering, erosion, transport and deposition that result in the modification of the surficial materials and landforms at the Earth's surface (Howes and Kenk, 1997. The terrain within the RSA is influenced by several geomorphological processes, many of which are directly related to the presence of permafrost.

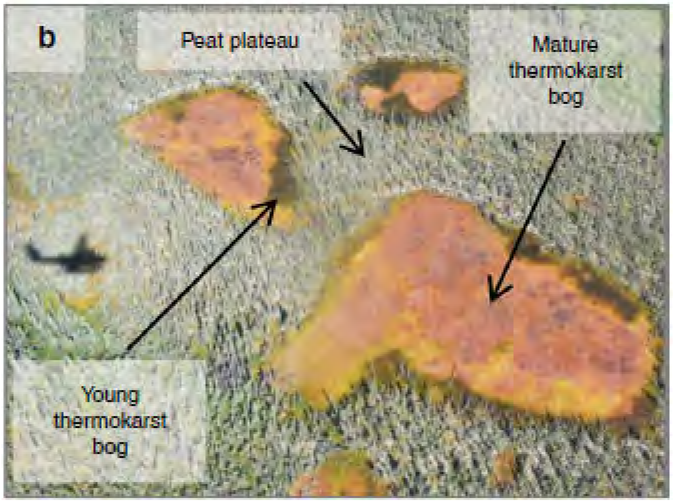
4.6.1 Thermokarst

Thermokarst features ("Xt" in the LSA terrain mapping) are topographic depressions created in a variety of shapes and sizes as a result of thawing ground ice. These features occur in terrain where the near-surface thermal regime has changed, allowing for the active layer to increase and ground ice to thaw. Processes triggered by thermokarst include the transformation of frozen peatlands to collapsed wetlands, lake expansion and localized flooding, and the initiation or reactivation of shallow landslides.

Within the RSA, visual indicators of thermokarst are prevalent in low-lying terrain associated with thick organic soils, especially in peat plateaus where the distinct signature of collapse scars or "thermokarst bogs" are often visible on the ground surface. These features generally initiate as small, water-saturated depressions that progressively expand as circular features, often coalescing with each other by lateral expansion. In their young stage, the depressions or collapse portions of the plateaus present distinctive drainage patterns when compared to the generally dry surface of the peat plateaus (Figure 4.8). Soils will be saturated and surface water may accumulate. Affected areas initially dominated by black spruce and Labrador tea will transition to vegetation cover initially dominated by sphagnum and sedges, then progressively by shrubs. Forest fires affecting peat plateaus are known to increase the rate of formation and magnitude of thermokarst.

On hillslopes, the increased input of water from melting ground ice can alter the water quality of lakes and streams with implications for aquatic ecosystems (Kokelj and Jorgenson, 2013). This increased water input can also lead to mass movements (e.g., active layer detachments).

Figure 4.8 Example of a Peatland Impacted by Thermokarst (from Gibson et al., 2018)



4.6.2 Landslides

Landslides within the RSA are of a variety of forms and types. The landslide types listed below are documented in landslide inventory databases produced by Couture and Riopel (2008a, 2008b) and Aylsworth and Traynor (2001). These inventories took place in the Mackenzie Valley and adjacent areas; they include the mapped locations of numerous landslides with baseline characteristics tabulated in databases. The portion of the RSA covered by these landslide inventories includes the MVH alignment sections from Wrigley (KM 696) to KM 790 (Aylsworth and Traynor, 2001), and from KM 910 to Norman Wells (KM 1010).

The information below describes the various landslide types previously identified in the RSA and briefly characterizes the terrain as observed in the RSA. The authors of these studies describe relative landslide ages as recent, intermediate, and ancient. In general, with this type of study, the older the mapped landslide feature the less reliable the data. Many of the mapped landslides appear well vegetated or forested on the orthophoto imagery reviewed, making identification and classification by type more difficult. It is important to note that the RSA and LSA are susceptible to both permafrost and non-permafrost related landslides: active layer detachments and retrogressive thaw slumps are associated with permafrost however, debris flows or debris slides are not.

Active layer detachments (thaw flows, “Xf” in the LSA terrain mapping) are shallow landslides involving the detachment and downslope movement of the active layer sediment (peat, mixed fine, and coarse debris) and vegetation. They are initiated by the detachment of a thin veneer of vegetation and active layer materials and their subsequent movement occurs along an inclined surface matching the permafrost table (McRoberts and Morgenstern, 1974). They occur in soils characterized by moderate to high water content, with movement generally triggered by an event or condition that allowed for a progressive or sudden thickening of the active layer.

Active layer detachments are included in the mapping by Aylsworth et al. (2000b) along the right bank escarpments of the Mackenzie River, but also along the escarpments that define the channels of tributary streams and rivers. They are also mapped as occurring along gullied escarpments on some upland hillsides. When occurring on low-angled slopes above an escarpment, these landslides can be precursors to retrogressive thaw slumps (i.e., when ground ice is exposed in the headwall). Not all occurrences of active layer detachments are included in existing landslide databases; therefore, special attention was given to delineate landslides as part of the LSA terrain mapping.

Debris flows ("Rd" in the LSA terrain mapping) are very rapid to extremely rapid flows of saturated non-plastic sediment and debris in moderately-steep to steep gradient channels. Debris flows commonly travel down zero- and first-order incised channels (gullies) but can occur in second-order channels. However, the term, as used in the landslide inventory by Couture and Riopel (2008a, 2008b), may or may not infer containment within a channel. Debris flow deposits often take the form of lobate features on moderately-steeply sloping colluvial cones or gently-to-moderately sloping colluvial fans, but debris flows can also deposit in some confined, but wide, low-gradient stream channels (gullies) or rivers. There is typically limited or no particle-sorting within the deposition zone, but subsequent stream action may sort, transport, and re-deposit limited amounts of sediment and organic debris within and below the original deposition zone.

Debris flows that do not flow in channels are typically called debris avalanches, and they are defined as very rapid to extremely rapid, shallow flows of partially or fully saturated debris, usually on a moderate to steep sloping hillside, without confinement. Several such features, mapped as debris flows, occur along the steep escarpments of tributary streams and one or two occur along the right bank escarpments of the Mackenzie River. These would more appropriately be mapped as and termed debris avalanches.

Debris slides (or debris avalanche, "Rs" in the LSA terrain mapping) are shallow planar slides of deformed material (Huntley, 2008), likely involving siding of an intact, unfrozen mass on an underlying, frozen or unfrozen surface, without confinement. Where present within the RSA, these tend to be small features. Several features tabulated as debris slides in the landslide inventory by Couture and Riopel (2008a, 2008b) are located along the escarpments of the Mackenzie River and on the escarpments of tributary rivers (e.g., the Great Bear River) and tributary streams.

Retrogressive thaw flows (or rotational slump, "Ru" in the LSA terrain mapping) are landslides that occur in ice-rich terrain. These landslides have a somewhat circular or bowl-like shape, with a steep, near-vertical headscarp and a low-angle flow lobe. The landslide fails retrogressively with the headscarp retreating upslope as ground ice and/or ice within the soil thaws. The unfrozen, saturated surficial material flows downslope and typically has a high to very high water content (Aylsworth et al., 2000; Huntley, 2008). In the case of shallow translational lobate flow of surface earth materials, the thawed layer moves along a planar contact with the underlying permafrost or competent material. Retrogressive thaw flows are indicative of an ice-rich terrain. The features remain active as long as ice continues to be exposed, hence making potential mitigation difficult.

Retrogressive thaw flows are mapped along the escarpments of the Mackenzie River and the Great Bear River and along the escarpments and gully walls of incised tributary streams. There is also a small cluster of these features mapped on the level-to-gently sloping organic mantled-upland west of KM 910. In this case, several appear to have become debris flows, which ran into a small, incised stream tributary to the Mackenzie River. Several retrogressive thaw flows are also mapped (Aylsworth and Traynor, 2001) along the Mackenzie River escarpment between Wrigley and Blackwater River.

Rockfall (”Rb” in the LSA terrain mapping) is the detachment of individual rock fragments from a steep rock slope and their gravitational downhill transport by falling, bouncing, and rolling. Evidence for ongoing or periodic rockfall includes the presence of colluvial accumulations (talus or scree) or individual fragments of rock below a steep rock slope.

There are a few areas of rockfall mapped along the escarpments of small, incised tributaries to the Mackenzie River in locations where those streams intersect and cut through low, rounded bedrock (shale) ridges. Rockfall is also mapped in upland locations were major joints or small faults cut though bedrock ridges: this occurs, for example, along the southeast side of Bear Rock and along the low limestone and dolostone ridge that trends north-northwest from Bear Rock. At some of these locations, there is also evidence of debris flow and, possibly, debris avalanche activity.

Figure 4.9 Examples of Landslides along the LSA

Retrogressive landslide along the Mackenzie River south of Tulita

Post-fire debris flow along Prohibition Creek, a few kilometers upstream from the MVH.

Rockfall along a bedrock ridge near Bear Rock

Rockslide along a colluvial apron (southeast of Bear Rock)

Figure 4.10 LiDAR Hillshade View of Some Areas Impacted by Landslides

Gullying and retrogressive landslides between MVH KM 882 and KM 885

Landslides along the north bank of the Saline River (MVH KM 832)

Landslides upslope from the MVH alignment near Vermillion Creek South (MVH KM 752 to KM 754)

4.6.3 Forest Fire

Large portions of the LSA and RSA have burned in the past. Dyke (2004), in his investigation of frozen and thawing slopes along the Norman Wells pipeline, indicated that forest fire had probably reached every point in forested areas of the Mackenzie Valley at least once in the last 200 years. The frequency of forest fires and the proportion of area burned were determined by decade (1960 to 2019) as part of the Vegetation and Wetlands TDR (K'alo-Stantec, 2020c). Along both the LSA and RSA, a higher frequency of forest fires was observed in the Dehcho Region (MVWR KM 690 to KM 796), where portions of the LSA has burned each decade between 1960 and 2019. Fires are not as common in Sahtu Region portion of the LSA (MVWR KM 796 to KM 1011) where a maximum of 2 fires per decade have been recorded (1990-1999).

The implications of forest fires on terrain and permafrost stability are considerable and the importance of forest fires as a driver of permafrost thaw has been researched by several authors (e.g., Jafarov et al., 2013; Zhang et al., 2015; Gibson et al., 2018). The presence of an often thick, organic soil cover is an important factor controlling soil temperature and permafrost stability, especially in the discontinuous permafrost region. Permafrost, at the same time, preserves the carbon in a frozen state and, as a result, protects it from decomposition. The primary effect of the forest fire is to reduce or eliminate the insulative quality of surface vegetation, causing great influences on the dynamic of the active layer and near-surface permafrost. The impact of forest fire on the thermal regime will generally depend on the thickness of organic soils remaining after the fire: the greater the residual organic layer, the better it may still protect the underlying permafrost from thaw.

Comparison of thermal conditions before and after forest fire at sites located along the Norman Wells Pipeline showed annual mean surface temperatures at burned sites that were generally 1 °C to 2 °C warmer than at the unburnt site (Smith et al., 2015; Smith and Bonaventure, 2016). Ground warming at burned sites was accompanied by an increase in active layer thickness. Although a decrease in ground temperature can occur following regrowth, recovering forest fire sites located in mineral soils generally host degrading permafrost.

Permafrost degradation and landslides are known to be initiated following forest fire in the Mackenzie Valley (e.g., Harry and MacInnes, 1988; Savigny et al., 1989; Burn, 1998; Dyke, 2004). In 1986, the occurrence of a forest fire about 250 km north of Norman Wells resulted in the development of extensive active layer detachments within one year from the forest fire event (Harry and MacInnes, 1988). The mass movements were predominant in silt-rich soils rich in ground ice. Small thaw slides were also observed to have evolved into retrogressive thaw flows (Dyke, 2004). Forest fires that occurred south of Norman Wells during the summers of 1994 and 1995 appear to have affected terrain stability along the Norman Wells Pipeline. These situations included observations of shallow active layer detachments on burned areas immediately adjacent to the pipeline right-of-way (Hanna et al., 1998). Investigations along the pipeline indicated that these landslides had mainly formed within weak colluvial deposits found along most valley walls and were generally absent from areas underlain by more competent clay till. Intentional clearing of vegetation for a fire line could have an impact on permafrost stability in the long run, potentially contributing to the initiation of landslides.

4.6.4 Other Potential Geohazards or Constraints

Karst landforms and associated groundwater systems refer to features created by bedrock dissolution. Karst forms in carbonate rocks such as limestone, dolomite or other highly soluble evaporite rocks such as gypsum and anhydrite; all are lithologies that are present in bedrock formations found in the Norman Wells region. The weathering and dissolution processes can result in distinctive features ranging from irregular topography, sinkholes and vertical shafts, dry valleys, and gorges, disappearing and reappearing streams, and caves.

The occurrence of karst in the central portion of the Mackenzie Valley is well documented (e.g., Ford, 1982, 1987, 2004; Hamilton, 1995; Hamilton and Ford, 2002; Ford, 2008), including karst landforms located within the LSA and RSA. Couture and Riopel (2008a) have identified a series of karst depressions approximately 5 km east of the MVWR KM 983 as part of the landslide inventory described above. This includes the 120 m x 60 m x 40 m deep “Bear Rock sinkhole” (see Figure 4.11) which is thought to be the largest simple cylindrical collapse landform known anywhere in Canada (Ford, 2008). The sinkhole is located approximately 325 m east from the Prohibition Creek quarry (reference number 7.083).

Figure 4.11 Bear Rock Sinkhole Near Prohibition Creek (4 km northeast from MVH KM 977)

Further south, just before the confluence of Great Bear River with Mackenzie River at Tulita, the prominent Bear Rock is reported as "*an outstanding example of glaciokarstic landform development that includes many sinkholes and larger closed depressions, some with permanent lakes that are drained underground at their overflow points, plus some striking pinnacle clusters, and a major group of perennial springs that display big ice build-up (icings) in winter*" (Ford, 2008). A portion of the RSA at the northern limit of Bear Rock near MVWR KM 961. No distinct karst features are visible within the RSA at that location. With the exception of Mount Gaudet, a few locations along the base of the western side of the Franklin Mountains, and Bear Rock, most of the MVWR is located in terrain where a thick cover of surficial materials is present. Karst features may be present in bedrock-controlled terrain found in the southern portion of the alignment; however, if present, these features are often too small to be visible on the imagery and LiDAR reviewed as part pf the assessment.

Gully erosion refers to the modification of surficial materials and bedrock by processes such as running water, mass movement (e.g., debris flows) and snow avalanching. These processes result in the formation of parallel and sub-parallel, long, V- and U-shaped channels (modified from Howes and Kenk, 1997).

Extensive areas of gully erosion (gullies) are present along many of the escarpments that bound the Mackenzie River and the escarpments along tributary rivers and streams that are incised into the uplands of the Mackenzie Plain. Many of the gullied areas will experience periodic landslide events over time. For example, there are debris avalanches on gully sidewalls and debris flows that travel down the gully channels and runout, depositing on the terrain (often fans) at the base of the gullies.

Gullies were delineated as part of the LSA terrain mapping. Their identification is based on distinctive morphology visible on the LiDAR hillshade data.

Inundation refers to terrain seasonally under standing water. The term is commonly applied to ephemeral lakes and ponds and to surficial materials (e.g., organic terrain) with seasonally high-water tables that result in local flooding for a continuous and significant time period (Howes and Kenk, 1997). Within the RSA, inundation will most likely occur in terrain dominated by organic deposits.

Areas interpreted as susceptible to inundation or seasonal flooding were identified as part of the LSA terrain mapping.

Surface seepage is the movement of surface water discharge, where evidence of substantial seasonal seepage is provided by physical and vegetative indicators (Howes and Kenk, 1997). The process is often associated with low soil-infiltration rates and high water-storage capacity. In northern regions, the process is influenced by the presence of permafrost. The existing surficial geology mapping does not document the presence of surface seepage; however, examination of the orthophoto imagery provided for this assessment suggests that extensive areas of surface seepage may occur where long, gently sloping toe slopes are located below the escarpments along the Mackenzie River (for example, between KM 723 and KM 754). Surface seepage, if present, may be a constraint on constructability .

Terrain polygons interpreted to be subject to seasonal seepage were part of the LSA terrain mapping.

Icings are sheet-like masses of layered ice that form during the winter by freezing of successive flows of water on the ground surface, or on top of river or lake ice (ACGR, 1988). The feature generally forms when water in a stream channel becomes pressurized because of ice buildup, then flows onto existing ice cover or the ground surface. This winter hydrological phenomenon is influenced by severe continental climate, cold winters with low snow cover, the presence of groundwater springs or unfrozen, water bearing layers (taliks), and highly permeable materials such as deposits of sand or gravel, organic matter, or karst terrain (Romanovskii et al., 1996).

Icings have been reported to negatively impact the performance of seasonal and all-season roads, with adverse effects on bridges and culverts; therefore, they are a transportation risk in the Arctic (Carey, 1973).

No spatial data is currently available on the occurrence and distribution of icings along the MVWR route, LSA, or RSA.

Frost heave is the upward/outward movement of the ground surface caused by the formation of ice in the soil. Frost susceptibility is a concept widely used in cold-region geotechnical design to quantify the capacity of a soil in generating frost heave. Soil texture does affect the degree of seasonal frost heave (and subsequent thaw) of local soils. Clayey silty-sand materials are generally classified as frost susceptible because they contain fine particles allowing for the formation of ice lenses when exposed to moisture and freezing temperature. Other soils containing organic layers and peat that are exposed to a high level of moisture may also undergo frost heaving when freezing occurs. In comparison, granular materials are generally classified as low to non-frost susceptible.

4.7 Climate Change Considerations

Warming in the North has triggered changes that are affecting both infrastructure and the livelihood of communities. Terrain hazards, especially permafrost degradation, are anticipated to be exacerbated by the effects of climate change. Available records show long-term trends in temperature increase and precipitation increase across most northern regions, and climate models suggest that warming over much of the North will continue at a rate that may increase. Similarly, it is anticipated that active-layer thicknesses will increase with climate warming. The Canadian Standards Association (CSA) provides guidance for screening the sensitivity of permafrost and the consequence of its degradation due to climate change (CSA, 2019). This risk-based approach requires site-specific information to be collected (e.g., ground material, ice content, and an estimate of the ground temperature), which is then used to determine the level of risk of the permafrost to a specific project. More specifically, the following three main factors are considered to assess permafrost sensitivity:

- likelihood of thaw settlement due to the active layer deepening
- potential for a reduction in bearing strength and creep resistance due to warming of the frozen ground
- potential for accentuated frost heaving

As stated previously, Tetra Tech (2020a, 2020b, 2020c, 2020d) completed geotechnical, geophysical and thermal assessments to support the design and engineering of the MGAR and PCAR, which are subsets of the MVH (i.e., it is expected that these two road sections will be upgraded to highway standard and integrated to the MVH alignment). Key findings of these assessments indicated that 1) local materials were predominantly silts and clays (i.e., clay-till near Norman Wells and glaciolacustrine silts and clays near Wrigley and Mount Gaudet), 2) permafrost was generally present but discontinuous (37 of 42 boreholes along the MGAR and 23 of 25 for the PCAR), and 3) where recorded, permafrost is warm with a mean annual ground temperature above -2°C. Accounting for these conditions, the permafrost sensitivity of the MGAR /PCAR was characterized as high (see Table 5.3 in CSA, 2019). However, the sensitivity of permafrost is expected to vary when evaluated along the remaining sections of the MVH alignment, especially in coarse-grained materials such as colluvial, glaciofluvial or alluvial deposits. The reduced presence of permafrost and ice-rich soils in these materials is expected to result in a medium-to-low permafrost sensitivity.

Considering ground conditions encountered as part of recent geotechnical investigations along the MGAR and PCAR sections, it is expected that climate warming will increase ground temperatures and cause a deepening of the active layer. Thawing permafrost may also generate changes in soil moisture, resulting in ground subsidence where ice-rich soils are located.

Permafrost degradation is expected to result in a loss of soil strength over time (e.g., as the heat is absorbed by the road surface and ground temperature rises), This may then result in ground surface deformation on flat terrain (i.e., as ground ice melts and the soil consolidates), to progressive deformation (creep), and the occurrence of landslides on sloping ground.

Climate change also has the potential to accentuate frost heave where the deepening of the active layer and greater availability of groundwater may lead to greater frost heave potential (CSA, 2019). During the winter months, the moisture in the ground freezes and expends. In the spring, the active layer melts and the subgrade condition may provide limited support. The repeated freeze-thaw cycles may destabilize frost-susceptible soils, causing heaving and deformation of the roadway surface.

4.7.1 Forest Fires

A predicted increase in forest fires frequency and severity with climate change will most likely accelerate the degradation of permafrost in burned areas. Empirical models of forest fires frequency and severity in Alaska and Canada suggest that the average area burned per decade will double by 2041–2050 and will increase on the order of 3.5 to 5.5 times by 2100 (Balshi et al., 2009). Soil types and near-surface ice content are expected to influence the distribution of landslides in permafrost terrain, where the sudden thickening of the active layer can cause the melting of excess ice, triggering the downslope movement of water-saturated soils.

The destabilization of slopes showing previous signs of landslides, particularly through the occurrence of active layer detachments, could occur following forest fires. This includes sections of the escarpment marking the edge of the main fluvial terrace on the southern portion of the route (MVWR KM 725 to KM 788). In this area, dozens of shallow landslides (mainly thaw flow and debris flows) are located within a few hundred metres from the MVWR, hidden under a well grown forest cover.

5 LSA Terrain Mapping

The following sections provide a summary and description of findings from terrain mapping. The goal of terrain mapping was to compile a map-based inventory of terrain conditions in the LSA. Of interest is the recorded occurrence of terrain constraints and geomorphological processes and other landscape hazards that are important to consider in the design and operations of the Project.

5.1 Surficial Material Distribution

The following section describes the spatial and, to some extent, the topographical distribution of the surficial materials, by dominance, in the RSA and LSA (see Table 5.1, Table 5.2 and Table 5.3). The spatial distribution of surficial materials using the MVWR route as the basis for the study areas. When interpreting spatial extent and tabulated statistical summaries of percent cover, it is important to acknowledge that these statistics and descriptions are based on two separate scales of mapping (greater than 1:100,000 for the RSA and 1:10,000 for the LSA); also, the LSA terrain mapping has not been ground-truthed by K'alo-Stantec.

Table 5.1 Distribution of Surficial Materials Within the RSA

Dominant Surficial Geology	Area (ha)	Percent of Area (%)
Glaciolacustrine (GL)	117,165	38.3
Till (T)	57,948	18.9
Alluvial (A)	41,739	13.6
Colluvium (C)	25,468	8.3
Glaciofluvial (FG)	16,174	5.3
Organic (Ob) - bog	4,072	1.3
Organic (Of) - fen	1,748	0.6
Bedrock (R)	7,461	2.4
Eolian (E)	497	0.2
Waterbody (W)	33,936	11.1
Total	**306,208**	**100**

Table 5.2 Distribution of Dominant Surficial Materials Within the LSA

Dominant Surficial Geology	Area (ha)	Percent of Area (%)
Morainal Material (M)	7,406	23.3
Glaciolacustrine Material (LG)	6,535	20.6
Organic Material (O)	4,855	15.3
Glaciofluvial Material (FG)	4,469	14.1
Colluvium (C)	3,485	11.0
Eolian (E)	1,952	6.1
Fluvial Materia (F)	1,559	4.9
Bedrock (R)	177	0.6
Anthropogenic Material (A)	58	0.2
Not Classified (N)	1,068	3.4
Total	**31,752**	**100**

Table 5.3 Distribution of Dominant Surficial Materials Along the MVH

Dominant Surficial Geology	Length (km)	Percent Length (%)
Glaciolacustrine Material (LG)	79.1	25.8
Morainal Material (M)	65.1	21.3
Glaciofluvial Material (FG)	59.6	19.5
Organic Material (O)	39.0	12.7
Eolian (E)	23.3	7.6
Fluvial Materia (F)	19.6	6.4
Colluvium (C)	17.8	5.8
Anthropogenic Material (A)	2.1	0.7
Not Classified (N)	0.6	0.2
Grand Total	**306.2**	**100.0**

The surficial geology mapping used to characterize the RSA includes regional work initiated in the 1970s and often presented at a scale of 1:100,000 or smaller. The interpretation would have been carried out using an optical stereoscope and stereo air photos, without the aid of LiDAR data. It is likely that on these regional maps, smaller deposits of some surficial materials would be under-represented; for example, small bogs and fens, bedrock outcrops, and eolian deposits of limited extent would not have been mapped. Similarly, many of the surficial material map units include more than one surficial material type; but in this summary, only the dominant surficial material in each map unit is considered. Two small areas of the RSA recently mapped at scales of 1:20,000 and 1:30,000 near the north and south ends of the RSA (i.e., MGAR and PCAR) have been inserted to replace the original regional mapping in those areas.

Detailed mapping conducted for the LSA allowed for more precise characterization of terrain conditions. Glaciolacustrine materials are dominant in the LSA, followed by till, alluvial, colluvial and glaciofluvial materials. Organic deposits (fens, bogs) and bedrock exposures are all mapped as minor components of the landscape. Eolian deposits are rare.

Available borehole data shows the depth to bedrock to vary greatly; however, it does suggest that most of the MVH alignment is covered by thick mantle of unconsolidated materials (generally over 5 m). Bedrock is absent in a significant portion of the boreholes compiled as part of historical database (e.g., Smith et al., 2005). Shallow (less than 2 m from ground surface) or exposed bedrock is present locally, but overall, is expected to be present along only limited sections of the MVH.

Glaciolacustrine materials are present as extensive deposits covering flat-to-gently undulating terrain throughout the LSA. Geotechnical investigation along the MGAR (Tetra Tech, 2020a, 2020b) confirmed the presence of lacustrine (glaciolacustrine) silty clay along the section of road between MVWR KM 692.5 to KM 707.3. The material extends farther north, that is part of the Mackenzie Plain.

Except for a few locations, till is absent in the southern portion of the LSA up to about the MVWR KM 800. It is present in the upland areas farther east into the RSA and occasionally interspersed with glaciolacustrine materials (exposed till likely occupies slightly higher elevations and is otherwise buried at depth under glaciolacustrine materials). Till is generally present on the uplands along the MVWR route until MVWR KM 867 with a break near Big Smith Creek. Till is generally present within the LSA from MVWR KM 952 and on the uplands east of the MVWR to near the base of the Discovery Ridge of the Norman Wells Range. In some areas, the till is overlain by glaciolacustrine materials. Geotechnical investigation along the PCAR (Tetra Tech, 2020c, 2020d) confirmed the presence of clay till with layers or pockets of sand, silt, and gravel along the section of road between MVWR KM 997 to KM 1,009. Permafrost was encountered in most boreholes, with ice content generally ranging from no visible ice to about 20% visible ice.

Alluvial materials are dominant along the sides of the Mackenzie River where the river is not confined by steep riverside escarpments. Alluvial materials are also mapped along the lower reaches of the tributary rivers and larger streams along the east side of the Mackenzie River, including large fans where some tributaries join the Mackenzie River. Along some incised tributary rivers and streams, the alluvial map units include portions of the steep colluvial escarpments that bound the river and stream channels. In some areas along the Mackenzie River, wide alluvial terraces are mapped along the river above steep, right bank escarpments.

Colluvial materials are common along the steep, often gullied escarpments that bound the Mackenzie River and along the gorge and gully walls that bound tributary rivers and streams that flow into the Mackenzie River. Colluvial materials also occur along steeper uplands slopes (hills and ridges and gullies on these features) to the east of the Mackenzie River, often in association with overlying bedrock slopes. Fine-grained colluvial materials derived from glaciolacustrine deposits are common on low-lying to moderately steep slopes.

Glaciofluvial materials occur as occasional large terraces along the Mackenzie River and at the confluences with some larger tributaries formed in part as deltas building into Glacial Lake Mackenzie (e.g., the Great Bear River). Geotechnical investigation along the MGAR (Tetra Tech, 2020c, 2020d) confirmed glaciofluvial sands and gravels reaching over 10 m in thickness between Wrigley and MVWR KM 692.5.

Organic veneers (less than 1 m thick) and blankets (greater than 1 m thick) are present throughout the low-lying landscape that marks the Mackenzie Valley. In the southern part of the LSA, wetlands have mostly formed on top of level or very gently sloping glaciolacustrine surfaces and farther north on both glaciolacustrine and till surfaces. Areas mapped as organic range from well-defined wetlands marked by distinct low-lying vegetation, and also more densely forested terrain where available field data indicates the presence of a significant accumulation of organic material (greater than 30 cm).

Eolian materials are restricted in extent, occurring primarily as low elongated ridges found above the glaciolacustrine plain extending from Big Smith Creek (MVWR KM 873) to the Great Bear River area (MVWR KM 950).

5.2 Terrain Constraints and Geomorphological Processes

As part of the LSA terrain mapping, special attention was given to the identification of potential terrain constraints or terrain hazards found close to the MVWR route. For the MVH Project, terrain constraints are interpreted as naturally occurring features having the potential to negatively affect the design, construction, and maintenance of the road infrastructure. Examples of this are steep slopes, poor drainage conditions, occurrence of thick organic soils, and ice-rich permafrost. Terrain hazards consist primarily of features or geomorphological processes having the potential to lead to localized or widespread damage to property and pose a threat to personal safety. Examples of this are landslides, gully erosion, and thermokarst.

Tabulated statistics performed on LSA terrain polygons intersected by the MVWR route indicated that surface seepage is the dominant geomorphological process occurring along the route (Table 5.4). The identification of areas where seepage is believed to be present is based on a combination of distinctive topography (e.g., gullies and rills) and vegetation communities. Seepage was mapped in areas of non-channelized flow where excess water is expected to concentrate. Seepage was also mapped in areas containing thick organic soils and in areas characterized by fine-grained till and glaciolacustrine silt and clay. The occurrence of a shallow permafrost table (i.e., upper limit of the permafrost) in several of these areas is likely, resulting in surface flow and shallow sub-surface seepage.

Table 5.4 Key Constraints and Geomorphological Processes Along the MVH

	Length (km)	Percent Length (%)
Seepage	43.5	14.2
Gullying	12.9	4.2
Landslides	4.5	4.5
Thermokarst	3.8	1.2

The overall location of the MVH along the east bank of the Mackenzie River means that its alignment will cross numerous tributaries rivers, drainage channels and gully systems routing surface water towards the river. Deep gullies have developed in a variety of materials; however, the most active and potentially unstable ones are likely to have developed along the east bank escarpments in glaciolacustrine materials and fine-grained till. Well-developed "V"-shaped gullies (e.g., MVWR KM 787 and KM 814) appear to grow by basal incision, headward erosion as well as by small landslides along the gully sidewalls. "U"-shaped gully cross-sections are often indicative of debris flow travel down the gullies. Landslides initiating in or entering these gullies may pose a hazard to roadway infrastructure constructed across, or downstream of, gully channels.

5.2.1 Landslide Hazard Summary

The largest and apparently most active landslides observed from the LiDAR and satellite imagery are a series of retrogressive thaw flows located along the Mackenzie River (MVWR KM 854 to KM 855, KM 874 to KM 878, KM 886 to KM 889). Most of these landslides occupy the western limit of LSA, downslope from the MVH alignment (i.e., 300 m west of the MVWR route). Although no recent landslides were observed to intersect the MVWR, the retrogression of some of these landslides remains a possibility in the future.

At large river crossings, the terrain mapping suggests that landslides are more prevalent on south-facing slopes than on north-facing slopes. The increase in landslide activity is sometimes identified by distinct topography and vegetation. As with the northern portion of the MVH Project Area, the southern section of the alignment intersects a moderate number of incised river and stream gorges. Landslides occur periodically along the steep, sometimes discontinuous escarpments that border these streams. There are also several locations along the southern portion of the alignment where the MVWR route runs along the base of an escarpment marked by old landslides. There was no clear evidence of recent forest fires resulting in permafrost degradation or landslide initiation in the imagery used for the LSA terrain.

A summary of the main locations where landslides were observed is presented in Table 5.5. Additional landslides are also present, as indicated in the LSA terrain mapping.

Table 5.5 Main Landslide Occurrence Along the MVWR

MVWR KM	Description
694	Shoreline erosion and landslides at Hodgson Creek
724	Shoreline erosion and landslides at Ochre Creek
725 to 748	Old landslides along terrace escarpment from Ochre River to Strawberry Creek
751	Old and recent landslides along terrace escarpment surrounding Vermillion Creek South
754	Recent erosion and landslides along escarpment north of Bob's Canyon Creek
765	Old and recent landslides along terrace escarpment near Dam Creek
788	Old and recent landslides along terrace escarpment north of Blackwater River
816	Old retrogressive landslide along terrace escarpment
833	Landslides along south facing slope at Saline River
845	Landslides along south facing slope at unnamed tributary
853	Landslides at Little Smith Creek
874	Retrogressive landslides along Big Smith Creek (right bank)
876-877, 883-887	Retrogressive landslides along Mackenzie River

Note:

Landslides described as “old” appear completely re-vegetated on available imagery. No indicators of recent movement were observed; however, could still be slow-moving or dormant. Other landslides were observed to be devoid of vegetation, partly re-vegetated or re-vegetated with pioneer species only or were displaying morphology indicative of recent movements. Depending on subsurface conditions old “stable” retrogressive thaw slumps may reactivate in the future (landslide should not be assumed to be stable forever, regardless of their vegetated status).

5.2.2 Permafrost Distribution

Landscape features can be indicative of the presence (or absence) of permafrost. Patterned ground and other periglacial landscape features are also indicative of the presence of permafrost. Ice wedge polygons are expected to be rare along the MVH. Only two general locations displaying the distinctive polygonal pattern were identified from the LiDAR data (i.e., MVWR KM 800 and KM 812). Ice wedges could be present locally even if not readily visible; however, their overall limited occurrence is not expected to cause major permafrost stability concerns. Other features indicative of permafrost include peat plateaus and palsas (i.e., peat mounds with permanently frozen peat and mineral soil cores), formed by the expansion of freezing peat as segregated ice lenses form to create an ice-rich permafrost. These features are generally elevated in comparison to the surrounding low-lying and poorly-drained ground. Although no distinct palsas were identified as part of the LSA terrain mapping, extensive areas of black spruce bogs where identified (including areas of peat plateaus). Several of these bogs show the distinctive morphology (e.g., pits and irregular depressions), drainage conditions (e.g., localized flooding and pooling of water), and vegetation characteristics (e.g., “drunk forest” and other areas of impacted vegetation) often associated with thermokarst.

The use of geomorphic site characteristics to assess the presence or absence of permafrost is helpful; however, site characteristics provide only limited evidence to characterize or map permafrost distribution within the LSA. Geotechnical investigations (including geophysical and thermal evaluations) like those carried out along the MGAR and PCAR sections of the MVH Project, conducted in conjunction with desktop terrain analysis, are the most appropriate method to obtain precise, site-specific information on permafrost.

6 Borrow Sources and Access Roads

An extensive number of desktop evaluations, field reconnaissance and geotechnical field investigations have been completed in relation to the availability of borrow sources along the Mackenzie Valley over the last 50 years. In the early 1970s, the Department of Indian and Northern Development (DIAND); now Crown-Indigenous Relations and Northern Affairs Canada (CIRNAC)) first attempted to establish a comprehensive inventory of granular resources present within the Mackenzie Valley. These efforts were in anticipation of an increase in demands due to hydrocarbon exploration activity in the Mackenzie Delta, completion of the Mackenzie Highway, and competing proposals for large diameter gas transmission facilities.

During the 1980s and 1990s, additional investigations of potential borrow sources were conducted, which included a compilation of over 50 granular resource studies conducted in the Lower Mackenzie Valley by Hardy Associates (1986), as well as a similar compilation produced for the Upper Mackenzie Valley by EBA (1988). In the early 2000s and 2010s, lists of potential borrow sources were presented as part of environmental assessment studies and PDRs developed in support of the proposed routes developed for oil and gas pipelines (e.g., Mackenzie Gas Project) and for the MVH Project.

Using existing data listed above, K’alo-Stantec, supported by Tetra Tech, conducted a desktop and reconnaissance field evaluation of prospect granular and quarry sites between Wrigley and Norman Wells, NT (K’alo-Stantec, 2020e). Selection criteria used for initial borrow source screening focused predominantly on technical considerations (e.g., material quality and quantity, relative proximity to the Project, absence of major terrain-related constraints) although it also considered environmental, archeological/cultural and land use and land ownership factors.

Following the background data review and a field reconnaissance visit, a list of prospective borrow sources was identified (K’alo-Stantec, 2021). As part of the assessment, the sources were subdivided into “primary” versus “secondary”, where the primary sources were considered as having the greatest potential for future development and should be prioritized during the field reconnaissance and follow-up geotechnical investigations. The secondary sources could be considered later if the primary sources are discarded based on technical, economic, social and/or environmental considerations.

The list of prospective borrow sources was refined over time, resulting in a shortlist of 15 primary sources to be part of the Project and assessed (7 borrow sources and 8 quarries, see Table 6.1). Nine (9) of the 15 Primary sources were identified for permanent use (including highway construction and long-term operations) and 6 were identified for temporary use (i.e., highway construction only). Another 10 alternate sources were identified in case additional sources were required (see Table 6.2).

Table 6.1 MVH Primary Borrow Sources and Quarries

Source ID[1]	Source Type	Planned Usage	MVWR KM	Access Road Length (km)	Borrow Pit/Quarry Description	Overburden Type and Thickness (m):	Development Considerations
10.043	Borrow Pit	Temporary	683		• Existing borrow source located approximately 6 km southeast of Wrigley, adjacent to the west side of Highway 1. • Deposit consists of a large glaciofluvial terrace (approximately 2.5 km in length and 0.75 km in width) and is adjacent and parallel to the east bank of the Mackenzie River.	• Coarse-grained material observed at ground surface throughout the site. • Organic silty topsoil layer in undisturbed terrain supporting dense growth of spruce with occasional clusters of birch poplar and pine. • Good overall drainage conditions with exception of localized areas of poorly drained soils.	• Existing borrow source • Existing access (HWY 1) • Wetland present south of existing borrow site (<1 m of organic expected). Respect of 300 m buffer around airport VOR Station (Crown Lands) and 65 m buffer for MVWR.
10.028	Quarry	Permanent	709		• Bedrock ridge (N-NE/S-SW orientation) associated with medium to thick bedded grey limestones of the Nahanni Formation and with dolomite and limestone of the Bear Rock Formation. • An existing pit is located approximately 3 km north from the current prospect area (MVWR KM 710).	• Thick colluvial and till along the base of the ridge, with discontinuous veneer of weathered bedrock and/or till on the ridge. • Good overall drainage conditions.	• Potential limitation associated to steep slopes. Reported thermal springs and rare plant in the area (9). Respect of 65 m buffer for MVWR.
10.020	Borrow Pit	Temporary	725	0.1	• Flat to gently undulating glaciofluvial terrace alongside the north bank of the Ochre River at its confluence with the Mackenzie River. • Large laydown clearing area served as a borrow source in the past.	• Thin layer of peat or organic topsoil and silt generally less than 0.5 m in thickness • Overall good drainage with localized fair drainage in low-lying areas. Poor drainage in the wetlands to the north.	• Deposit intersected by MVWR, development buffer needs to be respected. Respect 100 m buffer with watercourse and 65 m buffer with MVWR. Cleared area used as pullout for people travelling on the MVWR.
10.014A	Borrow Pit	Permanent	733	0.2	• Flat to gently undulating glaciofluvial terrace alongside north bank of Whitesand Creek at its confluence with the Mackenzie River.	• Shallow organic topsoil development (< 0.3 m). Potential for organic veneers in low-lying terrain north of the site. • Good drainage toward Whitesand Creek and Mackenzie River. • Fair to poor drainage to the west and north of the site.	• Respect 100 m buffer with watercourse and 65 m buffer with MVWR. • Potential for seasonal groundwater seepage along northwestern corner of prospect area.
10.007	Borrow Pit	Permanent	751		• Flat to gently undulating fluvial terrace alongside the east bank of the Mackenzie River, north from the confluence of Vermillion Creek South. The terrace is approximately 0.4 km wide and 2.5 km in length, with a flat to gently inclined surface sloping towards the Mackenzie River. • Some organic materials have accumulated over the terrace in some areas; for example, near the central portion of the terrace.	• Organic topsoil, peat and/or silt ranging in thickness from 0.3 m to a maximum of approximately 2 m. • Permafrost observed during site reconnaissance (active layer between 0.8 m and 1.85 m)	• The portion of the terrace located south from Vermillion Creek is not recommended for development due to environmental (watercourse) and infrastructure buffers. • Respect 100 m buffer with watercourse and respect 65 m buffer with MVWR
10.004	Borrow Pit	Temporary	770	0.2	• Located approximately 16 km south of the Blackwater River bridge. The site consists of a glaciofluvial terrace (approximately 1.0 km in length and 0.5 km in width) and is adjacent and parallel to the east bank of the Mackenzie River.	• Shallow organic topsoil layer (0 to 0.3 m deep) that supports dense growth of spruce and birch. An area with up to 1.4 m of silt was also observed overlying the gravel deposit (4). • Good overall drainage conditions, except for the wetlands observed to the north and east of the prime prospect area. • Small drainage channels observed both north and south of the target deposits	• Direct access from MVWR • Respect 100 m buffer with watercourse and 64 m buffer with MVWR

Source ID[1]	Source Type	Planned Usage	MVWR KM	Access Road Length (km)	Borrow Pit/Quarry Description	Overburden Type and Thickness (m):	Development Considerations
9.043	Borrow Pit	Permanent	783	0.1	• Glaciofluvial terrace located just south of the Blackwater River and Mackenzie River confluence. • Two distinct gravel pits observed at the site. Historical borrow source east of MVWR is generally open with scattered bushes and few young trees.	• Exposed material consisted of sand and gravel with variable cobble content. Existing pits were estimated to be 8 m to 10 m deep • Good drainage conditions. • Organic topsoil general under 0.3 m thick, which supports moderate to dense growths of spruce, birch, and poplar	• Existing access by the MVWR • Respect 100 m buffer with watercourse and 65 m buffer with MVWR
9.025B	Quarry	Temporary	813	2.4	• Located approximately 10 km southeast of the Steep Creek bridge. The site encompasses a bedrock ridge approximately 3.0 km in length and 0.5 km in width.	• Bedrock ridge is mostly exposed and includes only minor shallow glacial drift cover. A veneer of glacial drift and slope wash overlying undulating bedrock covers the area west of the ridge	• New access required • Area toward MVWR is heavily treed. Includes some low-lying wetland terrain
9.019	Quarry	Permanent	822	1.7	• Located approximately 5 km north of the Steep Creek bridge. The site encompasses a bedrock ridge (approximately 1.5 km in length and 0.7 km in width) that consists of Ordovician and Silurian dolomite with minor shale inclusion. • Steep slope on western ridge. Gently sloping to the east. • Dense tree coverage. Moderately dense surrounding bedrock exposure areas. Mostly mature spruce, pine, some areas with younger forest with birch.	• Shallow glacial drift cover and slope wash material with few exposures of weathered dolomite. • Drainage channels or creek to the north and south	• Seepage
9.002	Borrow Pit	Permanent	851	0.9	• Site consists of a large glaciofluvial terrace (approximately 2.4 km in length and 0.7 km in width) southeast of the Little Smith Creek, 2 km upstream from the east bank of the Mackenzie River. • Existing granular borrow source on site; 1 m to 2 m depth of excavation with material stockpiles.	• A thin topsoil layer (approximately 0.2 m thick) overlay the sand and gravel deposit and supports dense growths of spruce and birch.	• Potentially unstable moderate sloping colluvium ravine located on the northern end of the deposit. • Respect of 65 m buffer with MVWR and 300 m buffer with the Norman Wells to Zama Lake Pipeline.
8.039	Quarry	Permanent	867	1.3	• Bedrock hills comprised of dolomite of the Franklin Mountain Formation. Mix of exposed bedrock and undulating till veneer overlying shallow bedrock	• Variable. Some exposed bedrock. Thin layer of topsoil and discontinuous veneer of till and/or weathered bedrock. Blanket of till in topographic depressions. • Good drainage on the bedrock hill. Apparent fair to poor drainage along the lower access to the MVWR.	• New access required
7.109	Quarry	Permanent	962	0.5	• Exposed bedrock approximately 16 km northwest from Tulita. Bedrock surface is undulating with outcrop extending up to 500 m west at the northern portion of the prospect.	• Variable. Topsoil and discontinuous veneer of till and/or weathered bedrock. Blanket of till in topographic depressions. Some colluvial in areas characterized by steep bedrock escarpments.	• New access required. • Norman Wells to Zama Lake Pipeline crossing. • Respect of 100 m buffer with waterbody and 300 m buffer with the Norman Wells to Zama Lake Pipeline.
7.090	Quarry	Temporary	975	0.5	• Northwest/southeast oriented bedrock ridge. The ridge is approximately 3.5 km in length and 0.4 km in width. The southwest facing slope is covered with till (Mv to Mb), while the northwest-facing slope consists of a bedrock escarpment and colluvial deposit. Competent bedrock confirmed at shallow depth.	• Topsoil and clay till overlying bedrock. The thickness of the overburden decreases at the upper limit of the ridge (approximately 2 m thick within the middle section of the ridge, near the crest of the slope).	• Norman Wells to Zama Lake Pipeline crossing. • Respect of 100 m buffer with watercourse and waterbody and 300 m buffer with the Norman Wells to Zama Lake Pipeline
7.083 (Prohibition Creek Quarry)	Quarry	Permanent	990	6.6	• Area consists of an NW-SE oriented bedrock ridge overlain by till. Bedrock exposures of blocky and fractured limestone are noted in the area. • Existing bedrock quarry.	• Vegetation is cleared up to northeast extent of prospect	
Edie Lake Quarry	Quarry	Temporary	1013	2.2	• Active bedrock quarry. Area consists of an NW-SE oriented bedrock ridge.	• Topsoil and organic silt (generally under 0.6 m in thickness) overlying till veneer.	• Respect 100 m buffer with watercourse and waterbody.

Table 6.2 MVH Alternate Borrow Sources and Quarries

Source ID[1]	MVWR KM Access	Distance from Alignment (km)	Ownership	Material Type
10.041	683	Intersected by MVWR route	Crown/Territorial	Granular
10.037	709	0.1 km W	Territorial	Quarry
10.001	725	50 m E	Territorial	Granular
9.044B	733	0.1 km E	Territorial	Granular
9.037	751	50 m E	Territorial	Granular
9.010	770	50 m W	Territorial	Granular
9.002A	783	Intersected by MVWR route	Territorial	Granular
7.155A	813	2.6 km E	Private (Sahtu)	Quarry
Dhu1	822	1.6 km E	Territorial	Quarry
Dhu2	851	Intersected by MVWR route	Private (Sahtu)	Granular

7 Closure

This TDR was prepared for the sole benefit of GNWT to describe existing conditions related to soils, terrain and permafrost within the soils LSA and soils RSA. If you have any questions, please do not hesitate to contact the undersigned.

Respectfully submitted,

K'alo-Stantec Limited

8 References

8.1 Literature Cited

AAFC (Agriculture and Agri-Food Canada). 1996. The National Soil Database. Agriculture and Agri-Food Canada. Downloaded from: https://open.canada.ca/data/en/dataset/7ed13bbe-fbac-417c-a942-ea2b3add1748.

AAFC (Agriculture and Agri-Food Canada). 1998. The Canadian System of Soil Classification. Third Edition. Soil Classification Working Group. Research Branch. Agriculture and Agri-food Canada. Publication 1646. Ottawa, Ontario.

Aitken, J.D., and D.G. Cook. 1976. Geology, Norman Wells, Mahoney Lake, District of Mackenzie; Geological Survey of Canada, Open File 304, scale 1:250,000.

ACGR (Associate Committee on Geotechnical Research). 1988. Canadian Glossary of Permafrost and Related Ground-Ice Terms, Technical Memorandum No. 142. National Research Council of Canada: Ottawa, Ontario. 156 p.

Aylsworth, J.M. and J.A. Traynor. 2001. Geological Survey of Canada Open File 3915: “Landslide inventory, Mackenzie corridor (southern part) covers the region from 60˚-64˚N and includes NTS map sheets 85 D to E and 95 A to C, F to K, N to O. Database is accompanied by a map depicting landslide location, differentiated by type.

Aylsworth, J.M., M.M. Burgess, D.T. Desrochers, A. Duk-Rodkin, T. Robertson, and J.A. Traynor. 2000a. Surficial geology, subsurface materials, and thaw sensitivity of sediments; in The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change. Geological Survey of Canada, Bulletin 547, p. 41-48.

Aylsworth, J.M., A. Duk-Rodkin, T. Robertson, and J.A. Traynor. 2000b. Landslides of the Mackenzie valley and adjacent mountains and coastal regions; in The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change. Geological Survey of Canada, Bulletin 547, p. 167-176.

Balshi, M.S., A.D. McGuire, P. Duffy, M. Flannigan, J. Walsh, and J. Melillo. 2009. Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach Glob. Change Biol. 15 578–600

Burgess, M.M., and C. Tarnocai. 1997. Peatlands in the Discontinuous Permafrost Zone Along the Norman Wells Pipeline: Their Characteristics and Response to Pipeline Environmental change. In Proceedings of the International Symposium on Physics, Chemistry and Ecology of Seasonally Frozen Soils. Fairbanks, Alaska, June 10–12, 1997. United States Cold Regions Research and Engineering Laboratory, Report 197- 10.

Burgess, M.M., and D.E. Lawrence. 2000. Permafrost and surficial materials along a north–south transect: observations from the Norman Wells Pipeline. Cited in L.D. Dyke and G.R. Brooks (ed.). The Physical Environment of the Mackenzie Valley, Northwest Territories: A Base Line for the Assessment of Environmental Change. Geological Survey of Canada, Bulletin 547. 127-142.

Burgess, M.M., and S.L. Smith. 2000. Shallow ground temperatures; in The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547, p. 89-103.

Burn, C.R. 1998. The response (1958e1997) of permafrost and near-surface ground temperatures to forest fire, Takhini River valley, southern Yukon Territory. Can. J. Earth Sci. 35 (2), 184e199.

CSA (Canadian Standards Association). 2019. Technical Guide: Infrastructure in permafrost: A guideline for climate change adaption (CSA Plus 4011:19). Technical guide prepared by the Canadian Standards Association. May 2019. ISBN 978-1-4883-2163-4.

Carey, K.L. 1973. Icings developed from surface water and ground water. Cold Regions Research and Engineering laboratory Monograph III-D3, U.S. Army Corps of Engineers, Hanover, NH.

Chartrand, J., K. Lysyshyn, R. Couture, S. Robinson, and M. Burgess. 2002. Digital geotechnical borehole databases and viewers for Norman Wells and Tuktoyaktuk, Northwest Territories; Geological Survey of Canada, Open File 3912, CD-ROM.

Côté, M.M., C. Duchesne, J.F. Wright, and M. Ednie. 2013. Digital compilation of the surficial sediments of the Mackenzie Valley corridor, Yukon Coastal Plain, and the Tuktoyaktuk Peninsula; Geological Survey of Canada, Open File 7289. doi:10.4095/292494.

Couture, R., and S. Riopel. 2008a. Regional Landslide Susceptibility Mapping and Inventorying in the Mackenzie Valley, Northwest Territories. In : J. Locat, D. Perret, D. Turmel, D. Demers et S. Leroueil, (2008). Proceedings of the 4th Canadian Conference on Geohazards: From Causes to Management. Presse de l'Université Laval, Québec, 594 p.

Couture, R., and S. Riopel. 2008b. Landslide Inventory along a Proposed Gas Pipeline between Inuvik and Tulita, Mackenzie Valley, Northwest Territories, Geological Survey of Canada, Open File 5740, 1 DVD-ROM.

Dehcho First Nations. 2011. Traditional Knowledge Assessment of Boreal Caribou (Mbedzih) in the Dehcho Region. Prepared by Dehcho First Nations for the Canadian Wildlife Service. Published by the Dehcho First Nations Fort Simpson, Northwest Territories.

Dessau. 2012. Mackenzie Valley Highway Extension Pehdzeh Ki Ndeh – Dehcho Region, Project Description Report (PDR). 004-P037500-0200-EI-R200-00. Prepared for the Government of the Northwest Territories and the Department of Transport. (Dessau report 004-P037500-0200-EIR200- 00).

Duchesne, C., D. Riseborough, and S.L. Smith. 2014. Air and near surface ground temperatures, indices and summary statistics from 1994 to 2011 for the Mackenzie Valley corridor, N.W.T.; Geological Survey of Canada, Open File 7392, 85 p., doi:10.4095/292675.

Duchesne, C., S.L. Smith, and M. Ednie. 2015. Active Layer Variability and Change in the Mackenzie Valley, Northwest Territories. GeoQuebec 2015.

Duchesne, C; J. Chartrand, and S.L. Smith. 2020. Report on 2018 field activities and collection of ground-thermal and active-layer data in the Mackenzie corridor, Northwest Territories. Geological Survey of Canada, Open File 8707, 84 pages.

Duk-Rodkin, A. 2002. Surficial geology, Norman Wells, District of Mackenzie, Northwest Territories; Geological Survey of Canada, Map 1989A, scale 1:250,000. doi:10.4095/213617.

Duk-Rodkin, A., and A. Couch. 2004. Surficial Geology, Fort Norman, Northwest Territories; Geological Survey of Canada, Open File 4662, Scale 1: 100,000.

Duk-Rodkin, A., and D. Huntley. 2009. Surficial Geology, Wrigley (95O/SW), Northwest Territories; Geological Survey of Canada, Open File 6014, Scale 1: 100,000.

Duk-Rodkin, A., and D.S. Lemmen. 2000. Glacial history of the Mackenzie region; in The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change. Geological Survey of Canada, Bulletin 547, p.11-20.

Dyke, L.D., 2004. Stability of frozen and thawing slopes in the Mackenzie valley, northwest territories. Proceedings, 57th Canadian Geotechnical Society Annual Conference, Quebec City, Canada, 1, pp. 31-38.

EBA (EBA Engineering Consultants Ltd.) 1988. Summary of Granular Resource Data for the Upper Mackenzie Valley Fort Providence to Norman Wells, Volume I-II. Prepared for Indian and Northern Affairs Canada. 0306-34395.

EBA. 1989. ESEBase borehole/testpit database, north Alaska Highway corridor (km 1748 - km 1966, Alaska Highway, Yukon). Indian and Northern Affairs Canada [Sponsor]. 600 p. Available at: http://pubs.aina.ucalgary.ca/gran/33585.pdf.

EBA. 2011. Project Description Report for Construction of the Mackenzie Valley Highway Tulita District, Sahtu Settlement Area. Report prepared by EBA, A Tetra Tech Company for Government of the Northwest Territories. October 2011. EBA File: Y22101155.

Fallas, K.M., and R.B. McNaughton. 2013. Geology, Norman Wells (southeast), Northwest Territories; Geological Survey of Canada, Canadian Geoscience Map 100, scale 1:100 000. doi:10.4095/292292.

Fallas, K.M., B.C. MacLean, and T. Proks. 2013. Geology, Fort Norman (Northwest), Northwest Territories. Geological Survey of Canada, Canadian Geoscience Map 92.

Ford, D.C. 1982. Karst groundwater activity in the modern permafrost regions of Canada, in R. LaFleur (Ed.) Groundwater Weathering in Geomorphology, George Allen and Unwin, London, 1984, pp. 340-350.

Ford, D.C. 1987. Effects of Glaciations and Permafrost upon the Development of Karst in Canada. Earth Surface Processes and Landforms, 12(5), pp. 507-522.

Ford, D.C. 2004. Bear Rock Karst, Canada. in John Gunn (Editor) Encyclopedia of Caves and Karst Science. New York, Fitzroy Dearborn; pages 137-138.

Ford, D.C. 2008. Report upon a Survey of Karst Landforms around Norman Wells, Northwest Territories for the NWT Protected Areas Strategy Department of Environment and Natural Resources Government of the Northwest Territories March 2008.

French, H. 2007. The Periglacial Environment. Third Edition. Hugh M. French. John Wiley and Sons Ltd, Chichester, UK, 2007. xviii + 458 pp.

Gibson, C.M., L.E. Chasmer, D.K. Thompson, W.L. Quinton, M.D., Fannigan and D. Olefeldt. 2018. Wildfire as a major driver of recent permafrost thaw in boreal peatlands. Nature communications 9, 3041.

GNWT (Government of the Northwest Territories). 2003. Minutes of Public Consultation in Fort Good Hope, NWT Held in Support of Applications for Land Use Permits/Water Licences for the Permanent Bridge Installations at Hanna Creek, KM 1184.4; Elliot Creek, KM 1072.4; Oscar Creek, KM 1054.4; Francis Creek, KM 1005.0; Helava Creek, KM 1002.7; Christina Creek, KM 1001.7; Notta Creek, KM 982.3; Jungle Ridge Creek, KM 978.5 of the MVWR. TEK Interview: Francis, Helava, Christina, Notta, and Jungle Ridge Creeks Bridge Installation Projects. In Water Licence Application S03L8-004. Prepared for Sahtú Land and Water Board by the Government of the Northwest Territories Department of Transportation. Yellowknife, NT.

GNWT-DOT (Government of the Northwest Territories – Department of Transportation). 2014. Mackenzie Valley Highway - Updated Project Description. August 2014, Department of Transportation, Government of the NWT. Yellowknife, Northwest Territories.

Golder Associates. 2015. Central Mackenzie Surface Water and groundwater Baseline Assessment. Report 1: Technical State of Knowledge. Submitted to: Bruce Hanna, Regional Science Coordinator. Government of the Northwest Territories Report Number: 1401835.

Government of Canada. 2020. Climatology of Temperature and Precipitation. Available at: https://weather.gc.ca/saisons/clim_e.html. Accessed October 2020.

GSC (Geological Survey of Canada). 2019a. Reconnaissance surficial geology, Wrigley Lake, Northwest Territories, NT S95-O; Geological Survey of Canada, Canadian Geoscience Map 371 (Surficial Data Model v.2.3.14 conversion of Map 13-1978), scale 1:125 000.

GSC. 2019b. Reconnaissance surficial geology, Dahadinni River, Northwest Territories, NT S95-N; Geological Survey of Canada, Canadian Geoscience Map 375 (Surficial Data Model v.2.3.14 conversion of Map 18-1979), scale 1:125 000.

G.V.M. Geological Consultants Ltd. 2016. MACKENZIE HIGHWAY TERRAIN ANALYSIS – CANYON CREEK TO GREAT BEAR RIVER. Prepared for Government of the NWT, Public Works and Services, January 2016.

G.V.M. Geological Consultants Ltd. 2019. MACKENZIE HIGHWAY TERRAIN ANALYSIS – WRIGLEY TO MT. GAUDET. Prepared for Government of the NWT, Department of Infrastructure, Strategic Planning, Policy & Communications, December 19, 2019.

Hamilton, J.P. 1995. Karst Geomorphology and Hydrogeology of the Northeastern Mackenzie Mountains, District of Mackenzie, N.W.T., Canada. PhD thesis, McMaster University. xvi, 532 p.

Hamilton, J., and D.C. Ford. 2002. Karst geomorphology and hydrogeology of the Bear Rock formation – a remarkable dolostone and gypsum megabreccia in the continuous permafrost zone of Northwest Territories, Canada. Carbonates and Evaporites, 17(2).

Hanley, P.T. 1973. Surficial Geology and Geomorphology Maps of Fort Norman, Carcajou Canyon, Norman Wells and Sans Sault Rapids, Mackenzie Valley, District of Mackenzie, Northwest Territories. Geological Survey of Canada, Open File 155, Scale 1:125,000.

Hanley, P.T., S.C. Chatwin, O.L. Hughes, and J. Pilon. 1975. Surficial Geology and Geomorphology of Norman Wells, Mahoney Lake and Canot Lake, District of Mackenzie, Northwest Territories. Geological Survey of Canada, Open File 294, Scale 1:125,000.

Hanna, A.j., D. McNeill, A. Tchekhovski, T. Friel, and C. Babkirk. 1998. The effect of the 1994 and 1995 forest fires on the slopes of the Norman Wells Pipeline. Permafrost. Seventh International Conference Proceedings. Yellowknife Canada. Collection Nordicana No 55.

Hardy Associates (Hardy Associates (1978) LTD.). 1986. Granular Resource Potential. Lower Mackenzie Valley. March 1986. Prepared for Indian and Northern Affairs Canada.

Harry, D.G., and K. MacInnes. 1988. The effect of forest fires on terrain stability, Little Chicago-Travaillant Lake area, Mackenzie Valley, N.W.T.; in Current Research, Part D, Geological Survey of Canada, Paper 88-1D, p. 91-94.

Heginbottom, J.A. 2000. Permafrost Distribution and Ground Ice in Surficial Materials. In L.D. Dyke and G.R. Brooks (ed). The Physical Environment of the Mackenzie River Valley, Northwest Territories: A Base Line for the Assessment of Environmental Change. Geological Survey of Canada, Bulletin 547:31–40.

Heginbottom, J.A., M.A. Dubreuil, and P.T. Harker. 1995. Canada: Permafrost. National Atlas of Canada Fifth Edition. Natural Resources Canada, MCR 4177. Scale 1:7,500,000, Department of Energy, Mines and Resources Canada. Available at: https://doi.org/10.4095/294672.

Howes, D.E., and E. Kenk. 1997. Terrain Classification System for British Columbia, Version 2. Ministry of Environment and Ministry of Crown Lands Province of British Columbia MOE Manual 10.

Huntley, D.H. 2008. Landslide Geohazard Mapping in complex Terrains. Geological Survey of Canada, Open File 5747.

Imperial Oil Resources Ventures Limited. 2004. Mackenzie Gas Project (MGP) Environmental Impact Statement (EIS) Volume 3: Biophysical Baseline Part A Environmental Setting, Soils, Landforms and Permafrost. Report submitted to National Energy Board and the Joint Review Panel.

Imperial Oil Resources Ventures Limited. 2006. Updated Preliminary Engineering Alignment Sheets. Submitted to National Energy Board. IPRCC.PR.2006.05. May 2006.

Jafarov, E.E., V.E. Romanovsky, H. Genet, A.D. McGuire, and S.S. Marchenko. 2013. The effects of fire on the thermal stability of permafrost in lowland and upland black spruce forests of interior Alaska in a changing climate. Environ. Res. Lett. 8, 03503.

Judge, A.S. 1973. The thermal regime of the Mackenzie Valley: observations of the natural state; Environmental-Social Committee Northern Pipelines Task Force on Northern Oil Development, Report No. 73–38, 177 p.

K'alo-Stantec (K'alo-Stantec Limited). 2022a. Mackenzie Valley Highway Extension Project - Technical Data Report (TDR). Cultural and Traditional Land Use. Draft report submitted for review.

K'alo-Stantec. 2022b. Tulita Renewable Resources Council Traditional Land and Resource Use Study for Tulita District Mackenzie Highway Project. Prepared for Tulita Renewable Resources Council by K'alo-Stantec Limited. 30 pp.

K'alo-Stantec. 2022c. Mackenzie Valley Highway Extension Project - Technical Data Report (TDR). Vegetation and Wetlands.

K'alo-Stantec. 2022d. Mackenzie Valley Highway Extension Project - Technical Data Report (TDR). Air Quality, Greenhouse Gases (GHG), and Climate TDR.

K'alo-Stantec. 2022e. Desktop Review of Prospect Borrow Sources (REVA). Submitted to the GNWT-INF on September 17, 2020.

K'alo-Stantec. 2021. Mackenzie Valley Highway – Prospective Borrow Sources Assessment Report. Submitted to the GNWT-INF on February 19, 2021.

Kokelj and Jorgenson. 2013. Advances in Thermokarst Research. Permafrost and Periglacial Processes. Special Issue: Transactions of the International Permafrost Association. Vol. 24-2. Pages 108-119. Available at: https://doi.org/10.1002/ppp.1779

Lachenbruch, A.H. 1962. Mechanics of thermal contraction cracks and ice- wedge polygons in permafrost. Geological Society of America, Special Paper 70.

Lawrence, D.E., and D.A. Proudfoot. 1976. Mackenzie Valley geotechnical data bank - hard copy, Geological Survey of Canada Open Files 421 to 425.

Levson, V.M., Ferbey, T., Kerr, B., Johnsen, T., Bednarski, J., Smith, I.R., Blackwell, J. and Jonnes, S. 2004. Quaternary geology and aggregate mapping in northeast British Columbia: applications for oil and gas exploration and development. Summary of Activities, Resource Development and Geosciences Branch, British Columbia Ministry of Energy and Mines. 12 pp.

Mackay, J.R. 1971. The origin of massive icy beds in permafrost, western Arctic Coast, Canada. Canadian Journal of Earth Sciences, 8: 397-422.

Mackay, J.R., and S.R. Dallimore. 1992. Massive ice of the Tuktoyaktuk area, western Arctic coast, Canada. Canadian Journal of Earth Sciences, 29: 1235- 1249.

MVEIRB (Mackenzie Valley Review Board). 2015. Terms of Reference EA1213-02 Mackenzie Valley Highway Extension Project Wrigley to Norman Wells Government of Northwest Territories. February 13, 2015. PR#66.

McRoberts, E.C., and N.R. Morgenstern. 1974. The stability of thawing slopes; Canadian Geotechnical Journal, v. II, p. 447-469.

Nixon, F.M. 2000. Thaw-depth monitoring. In: The physical environment of the Mackenzie Valley, Northwest Territories: a baseline for the assessment of environmental change. L.D. Dyke and G.R. Brooks, Eds. Geological Survey of Canada, Natural Resources Canada, Bulletin 547, pp. 119-126.

Nixon, J.F., R. Saunders, and J. Smith. 1991. Permafrost and thermal interfaces from Norman Wells pipeline ditchwall logs. Canadian Geotechnical Journal, 28: 738-745.

Okulitch, A.V., and D. Irwin. 2014. Geological Compilation of the Western Mainland and Southern Arctic Islands Regions, Northwest Territories; Northwest Territories Geoscience Office, NWT Open File 2014-01.

O'Neill, H.B., Wolfe, S.A., Duchesne, C., 2019. New ground ice maps for Canada using a paleogeographic modelling approach. The Cryosphere 13, 753–773. Available at: https://doi.org/10.5194/tc-13-753-2019.

O'Neill, H.B., S.A. Wolfe, and C. Duchesne. 2020. Ground ice map of Canada. Geological Survey of Canada, Open File 8713, version 1, 2020, 7 pages (1 sheet). Available at: https://doi.org/10.4095/326885.

Permafrost Subcommittee. 1988. Glossary of Permafrost and Related ground ice Terms. National Research Council of Canada. Technical Memorandum. No. 142. p. 156.

Phillips, David. 1990. The Climates of Canada. Environment Canada. Canadian Government Publishing Centre, ISSN 0-660-13459-4.

Proudfoot, D.A., and D.E. Lawrence. 1976. Mackenzie Valley geotechnical data bank, tape description manual, Geological Survey of Canada Open File 350.

Resources Inventory Committee. 1996. Guidelines and Standards to Terrain Mapping in British Columbia. Surficial Geology Task Group, Earth Sciences Task Force, British Columbia.

Romanovskii, N.N., G.F. Gravis, E.S. Melnikov, and M.O. Leibman. 1996. Periglacial processes as geoindicators in the cryolithozone. In Geoindicators: Assessing Rapid Environmental Changes in Earth Systems, AR Berger, WJ Iams (eds.). A.A. Balkema: Rotterdam, Netherlands; 47-67.

Savigny, K.W. 1989. Engineering geology of the Great Bear River area, Northwest Territories. Geological Survey of Canada, Paper 88-23.

Sheng, D. 2021. Frost susceptibility of soils—A confusing concept that can misguide geotechnical design in cold regions. Sciences in Cold and Arid Regions, 2021, 13(2): 87-94.

Smith I.R. 2011. The seismic shothole drillers log database and GIS for NWT and Northern Yukon: An archive of near-surface lithostratigraphic and bedrock geology data. GSC Open File 6833

Smith, S.L., and P. Bonaventure. 2016. Investigations of effects of forest fires on the ground thermal regime and permafrost, Northwestern Canada. Proceeding of the XI. International Conference on Permafrost. JUNE 2016.

Smith, S.L., and M.M. Burgess. 2000. Ground temperature data- base for northern Canada; Geological Survey of Canada, Open File 3954, 28 p.

Smith, S.L., and M.M. Burgess. 2002. A digital database of permafrost thickness in Canada; Geological Survey of Canada, Open File 4173, 38 p.

Smith, S.L., and C. Duchesne. 2017. Thaw depth monitoring in the Mackenzie Valley, Northwest Territories. Yellowknife Geoscience Forum, abstract and summary volume; Northwest Territories Geological Survey, Yellowknife Geoscience Forum Abstract and Summary Volume 2017, 2017 p. 75.

Smith I.R. and K. Lesk-Winfield, 2012. An updated assessment of ground ice and permafrost geology-related observations based on seismic shothole drillers log records, NWT and Northern Yukon. GSC Open File 7061.

Smith, S.L., M.M. Burgess, D. Riseborough, T. Coultish, and J. Chartrand. 2004. Digital summary database of permafrost and thermal conditions – Norman Wells Pipeline study sites; Geological Survey of Canada, Open File 4635, 104 p.

Smith, S.L., M.M. Burgess, J. Chartrand, and D.E. Lawrence. 2005. Digital Borehole Geotechnical Database for the Mackenzie Valley/Delta Region. Geological Survey of Canada, Open File 4924, 2005, 30 pages; 1 CD-ROM. Available at: https://doi.org/10.4095/220383.

Smith I.R. Lesk-Winfield, K. and L.E. MacDonald., 2007. Seismic shothole lithology database and GIS for the Mackenzie Corridor, NWT and Northern Yukon. GSC Open File 5465.

Smith, S.L., J. Chartrand, T.N. Nguyen, D.W. Riseborough, M. Ednie, and S. Ye. 2009a. Geotechnical database and descriptions of permafrost monitoring sites established 2006-07 in the central and southern Mackenzie corridor; Geological Survey of Canada, Open File 6041, 183 p., doi:10.4095/226435.

Smith, S.L., D.W. Riseborough, F.M. Nixon, J. Chartrand, C. Duchesne, and M. Ednie. 2009b. Data for Geological Survey of Canada active layer monitoring sites in the Mackenzie valley, N.W.T., Geological Survey of Canada Open File 6287.

Smith, S.L., D.W. Riseborough, and P.P. Bonaventure. 2015. Eighteen-year record of forest fire effects on ground thermal regimes and permafrost in the Central Mackenzie Valley, NWT, Canada. Permafr. Periglac. Process. 26, 289e303.

Smith, S.L., H.B. O'Neill, S.A. Wolfe, P.D. Morse, D.E. Kerr, B. Brodaric, S.V. Kokelj, and K.C. Karunaratne. 2017. A pilot project to increase public accessibility of permafrost information. Yellowknife Geoscience Forum 2017; Yellowknife, NT; CA; 14-16 November 2017.

Tarnocai, C. 1973. *Soils of the Mackenzie River Area. Environmental – Social Program Northern Pipelines*. Task Force on Northern Oil Development, Report No. 73–26:136.

Tarnocai, C. and J. Bockheim. 2011. *Cryosolic soils of Canada: Genesis, distribution, and classification*. Canadian Journal of Soil Science, Report No. 5-91:749-762. Available at: https://cdnsciencepub.com/doi/full/10.4141/cjss10020.

Tarnocai, C. and S.C. Zoltai. 1978. Soils of Northern Canadian Peatlands: Their Characteristics and Stability. *In* Proceedings of the Fifth North American Forest Soils Conference. Ft. Collins, Colorado.

Tetra Tech (Tetra Tech Canada Inc.). 2020a. Geotechnical and Geophysical Evaluation for Mount Gaudet Access Road, Wrigley, NT. Report prepared for the Government of the Northwest Territories, Department of Infrastructure by Tetra Tech Canada Inc. August 6, 2020. Tetra Tech File: 704-ENG.YARC03329-01A.

Tetra Tech. 2020b. Mount Gaudet Access Road Thermal Assessment Report. MVWR km 687 to 708, Northwest Territories. Issued for Review. Report prepared for the Government of the Northwest Territories, Department of Infrastructure by Tetra Tech Canada Inc. November 24, 2020. Tetra Tech File: 704-ENG.YARC03354-02.

Tetra Tech. 2020c. Geotechnical and Geophysical Evaluation for Prohibition Creek Access Road, Near Norman Wells, NT. Issued for Use report prepared for the Government of the Northwest Territories, Department of Infrastructure by Tetra Tech Canada Inc. October 21, 2020. Tetra Tech File: 704-ENG.YARC03329-01A.

Tetra Tech. 2020d. Prohibition Creek Access Road Thermal Assessment Report. MVWR km 995.3 to km 1009.3. Northwest Territories. Issued for Review. Report prepared for the Government of the Northwest Territories, Department of Infrastructure by Tetra Tech Canada Inc. November 24, 2020. Tetra Tech File: 704-ENG.YARC03354-02.

TRRC (Tulita Renewable Resources Council). 2022. Tulita Renewable Resources Council traditional land and resource use study for Tulita District Mackenzie Highway Project, 2022. Tulita, NT.

Wolfe, S.A., S.L. Smith, J. Chartrand, S. Kokelj, M. Palmer, and C.W. Stevens. 2010. Geotechnical database and descriptions of permafrost monitoring sites established 2006-2010 in the northern Mackenzie Corridor, Northwest Territories. Geological Survey of Canada, Open File 6677, 2010, 81 pages; 1 CD-ROM. Available at: https://doi.org/10.4095/287167.

Wright, J.F., Smith, M.W., and Taylor, A.E., 2000. Potential changes in permafrost distribution in the Fort Simpson and Norman Wells regions; in The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547, p. 197–207.

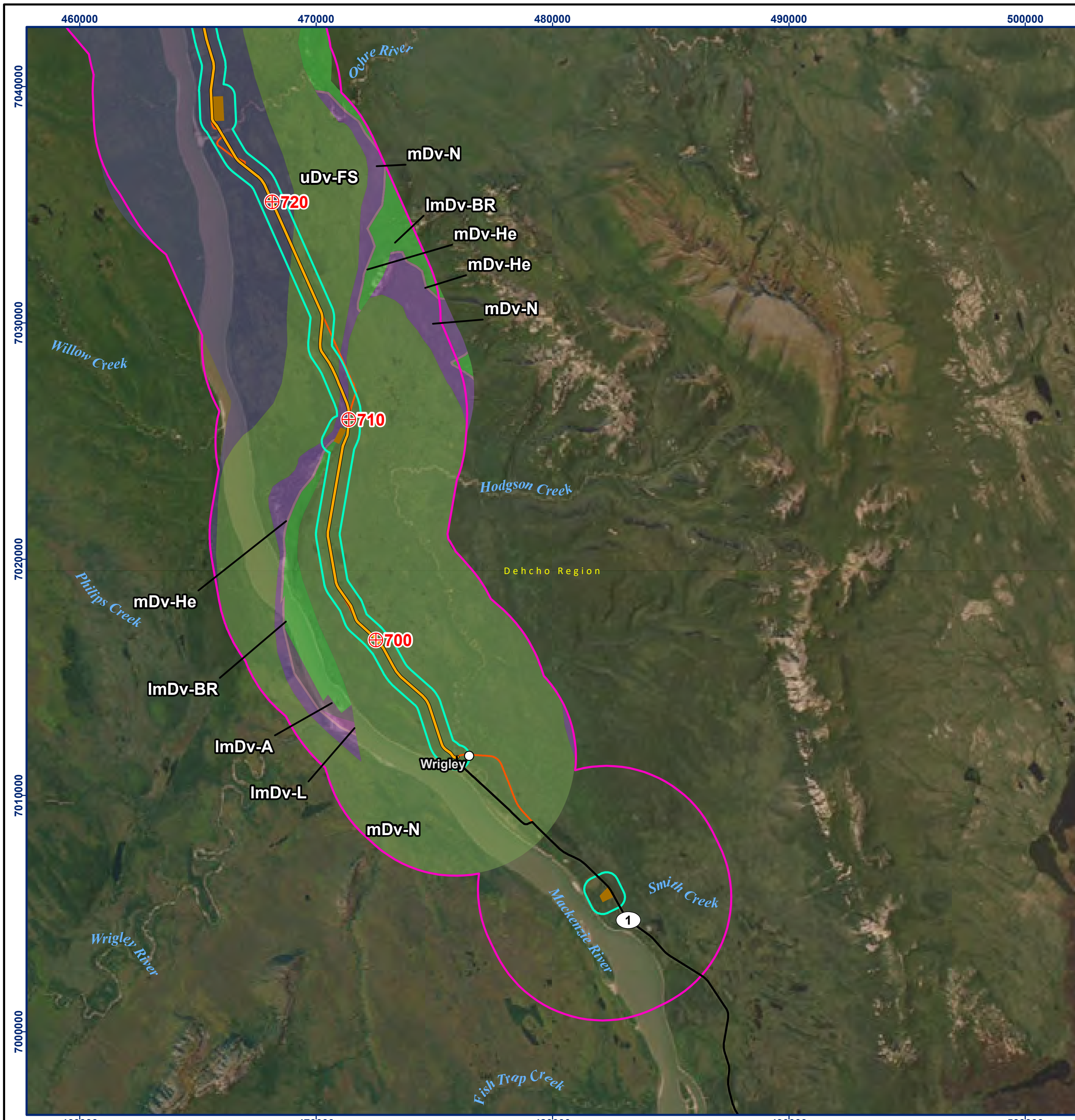
Zoltai, S.C., and W.W. Pettapiece. 1973. Studies of Vegetation, Landform and Permafrost in the MacKenzie Valley: Terrain, Vegetation, and Permafrost Relationships in the Northern part of the MacKenzie Valley and Northern Yukon. Prepared for the Environmental-Social Program Northern Pipelines. Available at: http://publications.gc.ca/collections/collection_2020/rcaanc-cirnac/R73-4-73-4-eng.pdf.

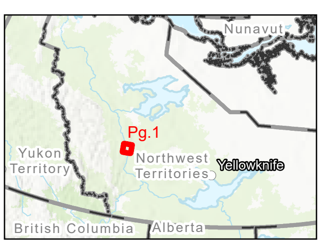
Zhang, Y., S.A. Wolfe, P.D. Morse, I. Olthof, and R.H. Fraser. 2015. Spatio-temportal impacts of wildfire and climate warming on permafrost across a subarctic region. J. Geophys. Res. Earth Surf. 120, 2338–2356.

Zoltai, S.C., C. Tarnocai, and W.W. Pettapiece. 1978. Age of Cryoturbated Organic Materials in Earth Hummocks from the Canadian Arctic. *In* Proceedings of the Third International Conference on Permafrost. Edmonton, Alberta.

Appendix A RSA Figures

Bedrock Geology	Figures A.1 to A.7
Surficial Geology	Figures A.8 to A.23
Soils	Figures A.24 and A.25





Bedrock Geology

- lmDv-A,dolostone, fine-crystalline, thick bedded, grey, finely porous, vuggy and brecciated in part; limestone
- lmDv-BR,dolostone; dolostone solution-breccia; anhydrite; gypsum; locally may include unit SlDv-T at base; marine
- lmDv-L,limestone, dark grey, thick-bedded, cryptogranular
- mDv-He,shale, grey; limestone, argillaceous, silty, thin to medium-bedded, nodular, bioclastic; minor dolostone; limestone, fine to crypto-crystalline, thin-bedded
- mDv-N,limestone, fine to coarse-grained, dark grey, medium to thick-bedded, bioclastic
- uDv-FS,shale, green and grey; siltstone; limestone; may include HORN RIVER fm or HARE INDIAN fm at base
- uDv-s,sandstone, greenish-grey, fine-grained, calcareous; mudstone, silty; shale, grey and greenish-grey; minor limestone
- Mackenzie Valley Highway Kilometre Post
- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Granular Borrow / Rock Quarry Site and Access
- Local Study Area
- Regional Study Area
- Community
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

0 2.5 5 Kilometres

N

(At original document size of 8.5x11)
1:250,000

Kálo-Stantec

Notes

1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada. Bedrock Geology source: Okulitch, A. V. and Irwin, D., 2016. Geological Compilation of the Western Mainland and Arctic Islands of the Northwest Territories; Northwest Territories Geological Survey, NWT Open File 2016-09
Esri, FAO, NOAA, USGS, NRCan, Earthstar Geographics, Esri, USGS

Project Location
Wrigley to Norman Wells, NWT

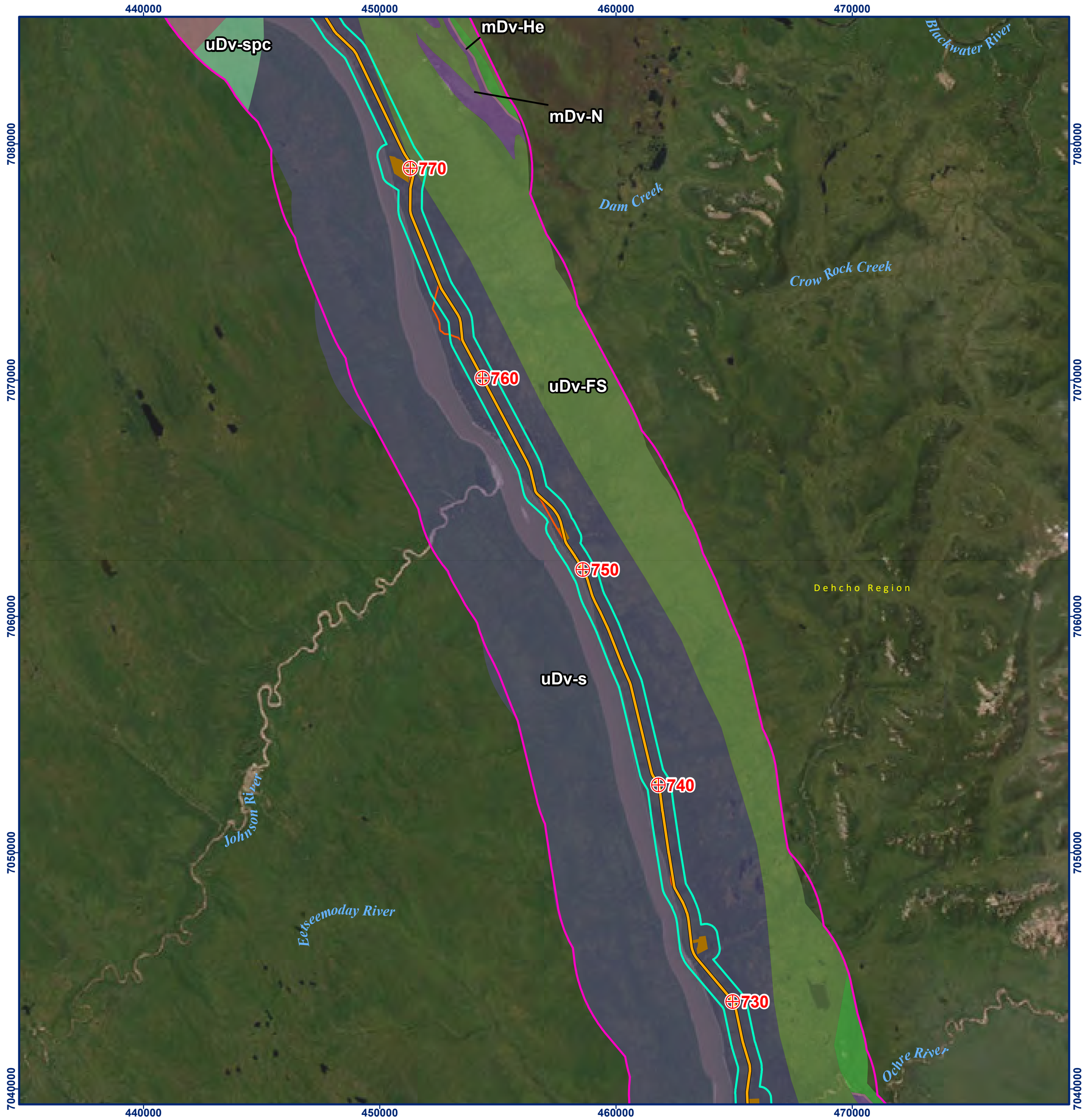
Prepared by AT on 3/9/2023
TR by AJ on 3/9/2023

Client/Project
144903025-0003 REVB

Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.1

Title
RSA Bedrock Geology



Bedrock Geology

- lmDv-BR,dolostone; dolostone solution-breccia; anhydrite; gypsum; locally may include unit SlDv-T at base; marine
- mDv-He,shale, grey; limestone, argillaceous, silty, thin to medium-bedded, nodular, bioclastic; minor dolostone; limestone, fine to crypto-crystalline, thin-bedded
- mDv-N,limestone, fine to coarse-grained, dark grey, medium to thick-bedded, bioclastic
- uCt-SR,BASAL: sandstone. UPPER: siltstone; shale, black and grey; bentonite interbeds; minor siltstone; sandstone, fine-grained
- uDv-FS,shale, green and grey; siltstone; limestone; may include HORN RIVER fm or HARE INDIAN fm at base
- uDv-s,sandstone, greenish-grey, fine-grained, calcareous; mudstone, silty; shale, grey and greenish-grey; minor limestone
- uDv-spc,shale, green, grey and red; siltstone and sandstone, fine-grained, greenish-grey; limestone, fossiliferous
- Mackenzie Valley Highway Kilometre Post
- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Granular Borrow / Rock Quarry Site and Access
- Local Study Area
- Regional Study Area
- Community
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

0 2.5 5 Kilometres

(At original document size of 8.5x11)
1:250,000

N

Kálo-Stantec

Notes

1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada. Bedrock Geology source: Okulitch, A. V. and Irwin, D., 2016. Geological Compilation of the Western Mainland and Arctic Islands of the Northwest Territories; Northwest Territories Geological Survey, NWT Open File 2016-09
Esri, FAO, NOAA, USGS, NRCan, Earthstar Geographics, Esri, USGS

Project Location
Wrigley to Norman Wells, NWT

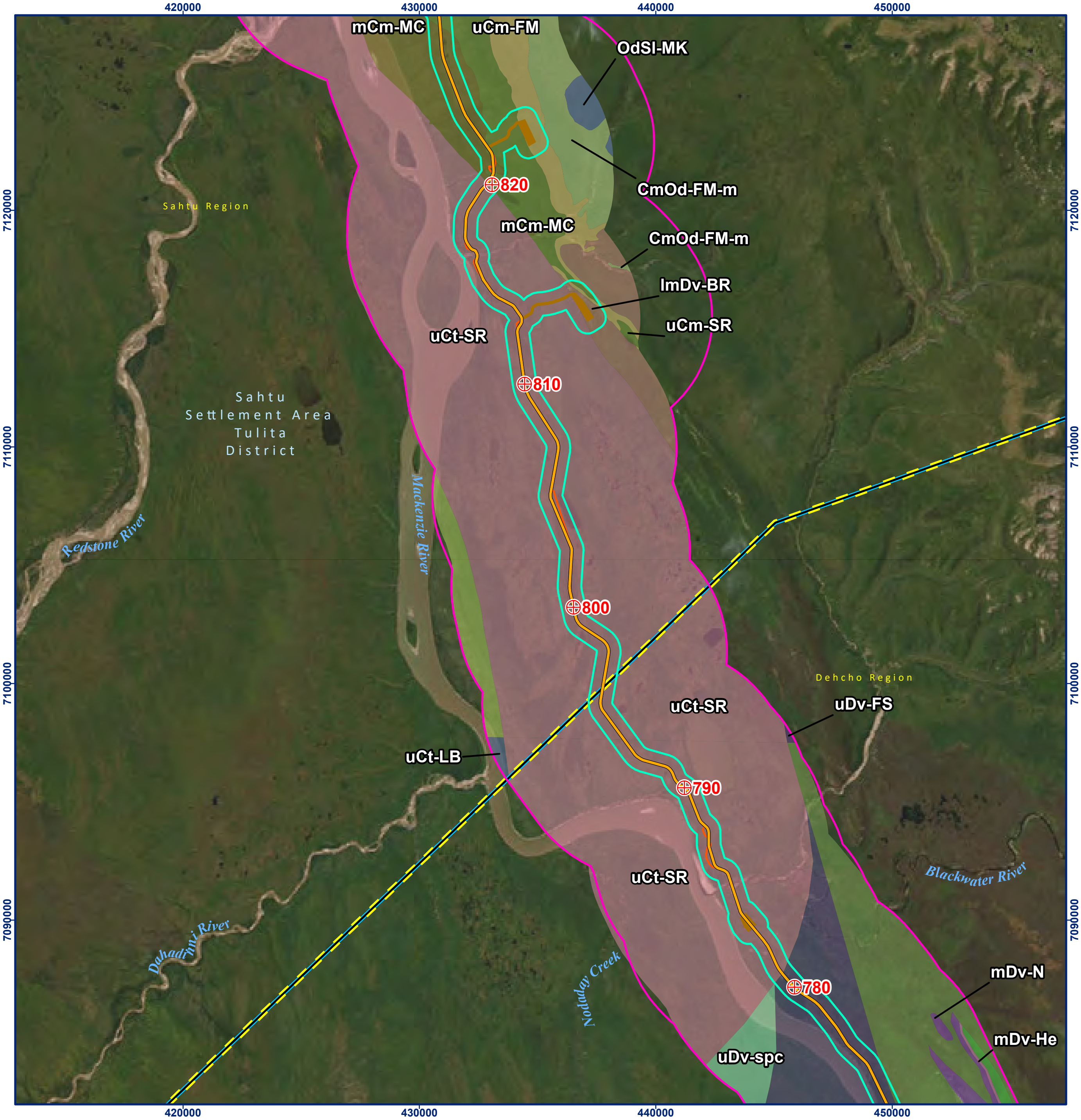
Prepared by AT on 3/9/2023
TR by AJ on 3/9/2023

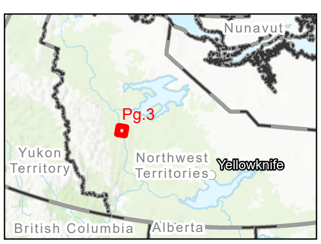
Client/Project
144903025-0003 REVB

Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.2

Title
RSA Bedrock Geology





Bedrock Geology

- CmOd-FM-m,dolostone, silty, very fine-crystalline alternating with dolostone, fine- to medium-crystalline, oolitic; locally quartzose; minor conglomerate, flat-pebble
- OdSl-MK,BASAL member: dolostone, argillaceous, silty, flaggy, nodular; shale, dolomitic; UPPER member: dolostone, cherty, medium to dark brownish-grey, fine- to medium crystalline, silicified corals, stromotoporoids, brachipods
- lmDv-BR,dolostone, dolostone solution-breccia, anhydrite, gypsum; locally may include unit SDT at base
- lmDv-BR,dolostone; dolostone solution-breccia; anhydrite; gypsum; locally may include unit SlDv-T at base; marine
- mCm-MC,shale, silty, black, red, green; limestone, pure, quartzose, glauconitic, thin-bedded; dolostone, grey, buff, brown, thin-bedded; sandstone, glauconitic, quartzose; siltstone

0 2.5 5 Kilometres

(At original document size of 8.5x11)
1:250,000

N

Kálo-Stantec

Notes

1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada. Bedrock Geology source: Okulitch, A. V. and Irwin, D., 2016. Geological Compilation of the Western Mainland and Arctic Islands of the Northwest Territories; Northwest Territories Geological Survey, NWT Open File 2016-09
Esri, FAO, NOAA, USGS, NRCan, Earthstar Geographics, Esri, USGS

Project Location
Wrigley to Norman Wells, NWT

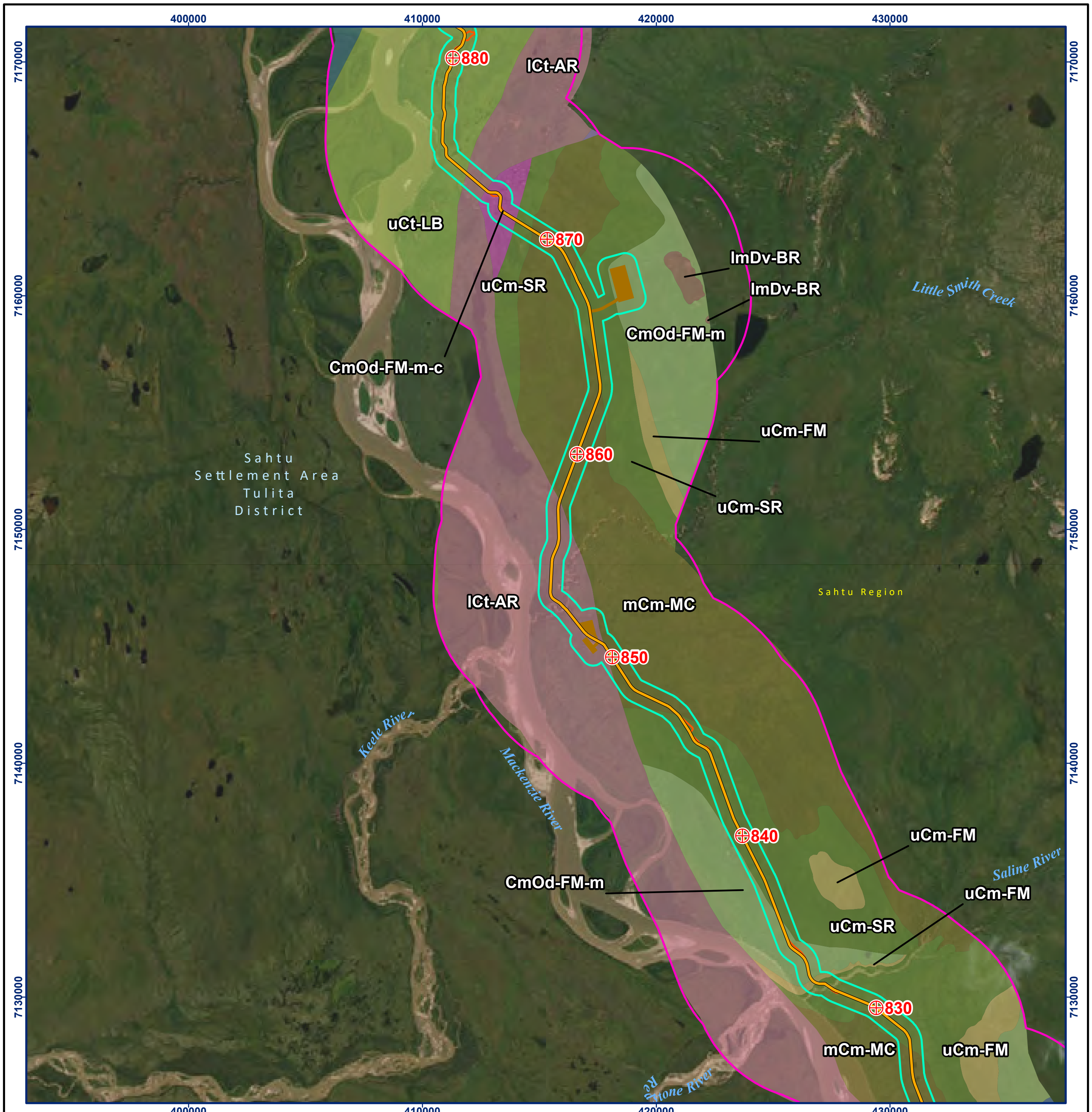
Prepared by AT on 3/9/2023
TR by AJ on 3/9/2023

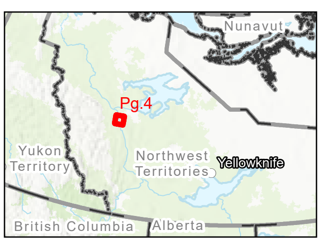
Client/Project
144903025-0003 REVB

Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.3

Title
RSA Bedrock Geology





Notes

1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada. Bedrock Geology source: Okulitch, A. V. and Irwin, D., 2016. Geological Compilation of the Western Mainland and Arctic Islands of the Northwest Territories; Northwest Territories Geological Survey, NWT Open File 2016-09
Esri, FAO, NOAA, USGS, NRCan, Earthstar Geographics, Esri, USGS

Bedrock Geology

- CmOd-FM-m,dolostone, silty, very fine-crystalline alternating with dolostone, fine- to medium-crystalline, oolitic; locally quartzose; minor conglomerate, flat-pebble
- CmOd-FM-m-c,limestone, silty, fine grained; minor conglomerate
- OdSl-MK,BASAL member: dolostone, argillaceous, silty, flaggy, nodular; shale, dolomitic; UPPER member: dolostone, cherty, medium to dark brownish-grey, fine- to medium crystalline, silicified corals, stromotoporoids, brachipods
- lCt-AR,shale, brownish-grey; minor radioactive shale
- lmDv-BR,dolostone, dolostone solution-breccia, anhydrite, gypsum; locally may include unit SDT at base
- mCm-MC,shale, silty, black, red, green; limestone, pure, quartzose, glauconitic, thin-bedded; dolostone, grey, buff, brown, thin-bedded; sandstone, glauconitic, quartzose; siltstone
- uCm-FM,dolostone, laminated, very thin-bedded, aphanocrystalline, oolitic; conglomerate, dolomitic, flat-pebble; dolostone, stromatolitic; shale, dolomitic, light green, maroon, thin-bedded
- uCm-SR,shale, red and green; siltstone, red, green; sandstone, red, green; salt; anhydrite; gypsum; dolostone
- uCt-EF,shale, siltstone; minor sandstone
- uCt-LB,LOWER shale, sandstone; UPPER sandstone, shale, coal
- uCt-SR,BASAL: sandstone. UPPER: siltstone; shale, black and grey; bentonite interbeds; minor siltstone; sandstone, fine-grained

- Mackenzie Valley Highway Kilometre Post
- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Granular Borrow / Rock Quarry Site and Access
- Local Study Area
- Regional Study Area
- Community
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

0 2.5 5 Kilometres

(At original document size of 8.5x11)
1:250,000

N

Kālo-Stantec

Project Location
Wrigley to Norman Wells, NWT

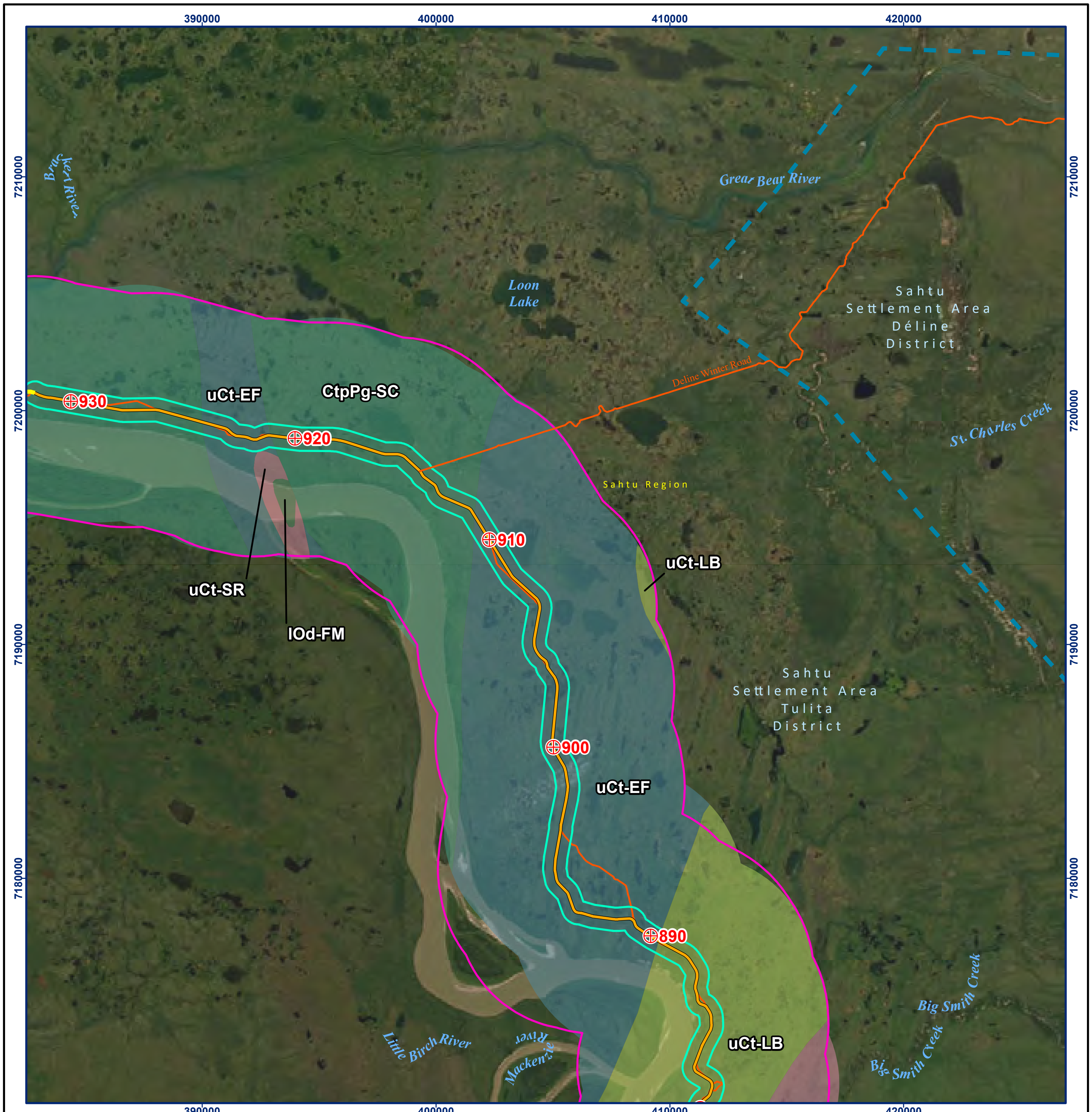
Prepared by AT on 3/9/2023
TR by AJ on 3/9/2023

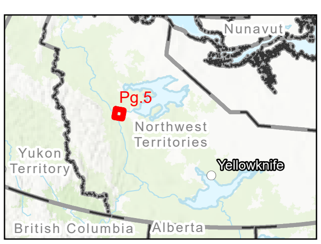
Client/Project
144903025-0003 REVB

Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.4

Title
RSA Bedrock Geology





Bedrock Geology

- CtpPg-SC,conglomerate, sandstone; coal, thin interbeds
- lOd-FM,dolostone, pale yellow-brown to pale grey, medium crystalline; chert, bedded, replacing stromatoporoids and oolites, white, yellowish-grey
- uCt-EF,shale, siltstone; minor sandstone
- uCt-LB,LOWER shale, sandstone; UPPER sandstone, shale, coal
- uCt-SR,BASAL: sandstone. UPPER: siltstone; shale, black and grey; bentonite interbeds; minor siltstone; sandstone, fine-grained
- Mackenzie Valley Highway Kilometre Post

- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Granular Borrow / Rock Quarry Site and Access
- Local Study Area
- Regional Study Area
- Community
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

0 2.5 5 Kilometres

(At original document size of 8.5x11)
1:250,000

N

Kálo-Stantec

Notes

1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada. Bedrock Geology source: Okulitch, A. V. and Irwin, D., 2016. Geological Compilation of the Western Mainland and Arctic Islands of the Northwest Territories; Northwest Territories Geological Survey, NWT Open File 2016-09
Esri, FAO, NOAA, USGS, NRCan, Earthstar Geographics, Esri, USGS

Project Location
Wrigley to Norman Wells, NWT

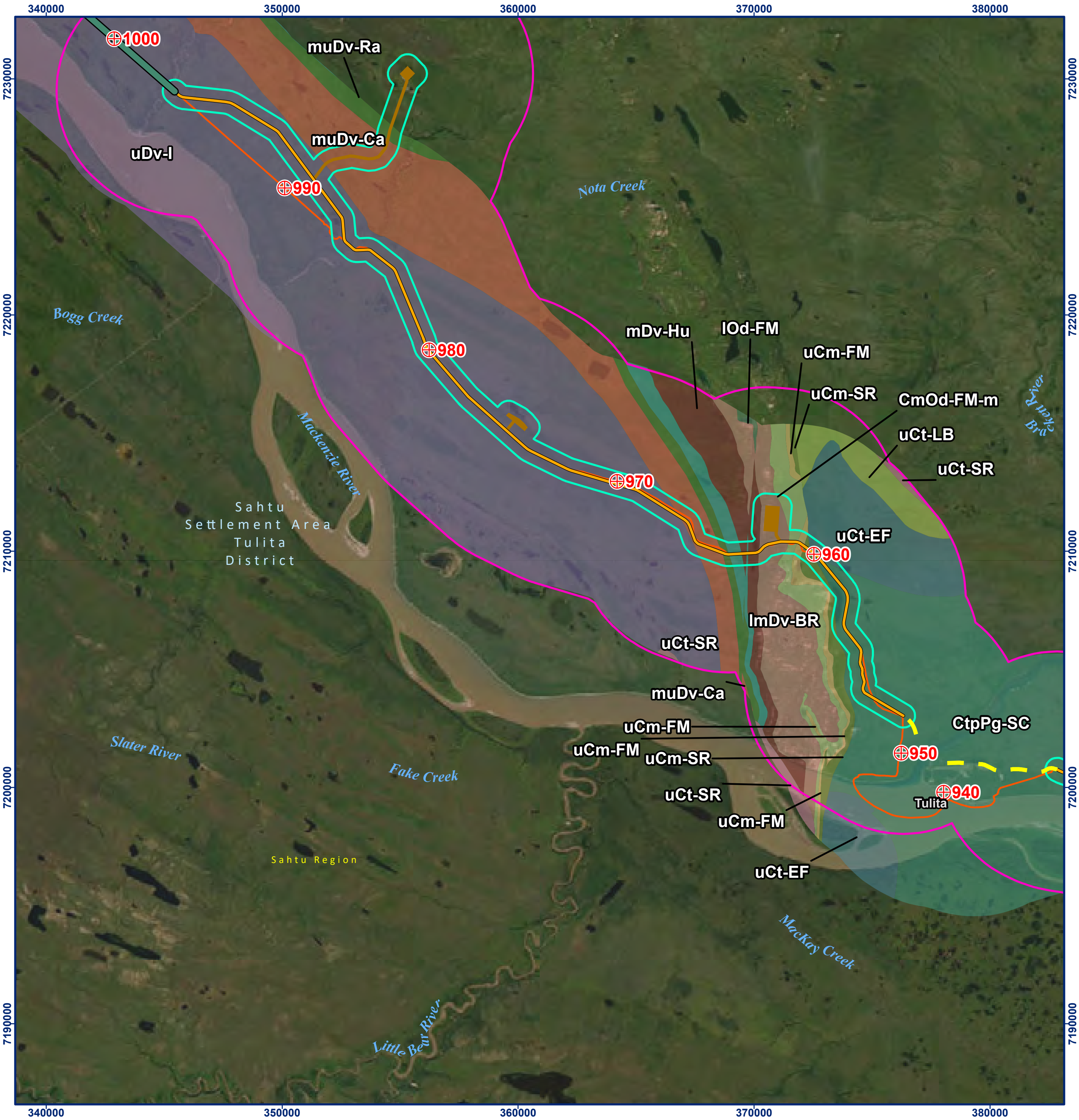
Prepared by AT on 3/9/2023
TR by AJ on 3/9/2023

Client/Project
144903025-0003 REVB

Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.5

Title
RSA Bedrock Geology



Bedrock Geology

- CmOd-FM-m,dolostone, silty, very fine-crystalline alternating with dolostone, fine- to medium-crystalline, oolitic; locally quartzose; minor conglomerate, flat-pebble
- CtpPg-SC,conglomerate, sandstone; coal, thin interbeds
- lOd-FM,dolostone, pale yellow-brown to pale grey, medium crystalline; chert, bedded, replacing stromatoporoids and oolites, white, yellowish-grey
- lmDv-BR,dolostone, dolostone solution-breccia, anhydrite, gypsum; locally may include unit SDT at base
- mDv-HI,basal BLUEFISH Member: shale, bituminous, dark grey, spore-bearing. UPPER member: shale, calcareous, bluish-grey, thin bedded; minor limestone, thin interbeds
- mDv-Hu,LOWER member: interbedded marlstone, dark grey and limestone, dark greyish brown, micro- to fine-fragmental, fossiliferous; MIDDLE member: interbedded limestone, argillaceous; marlstone; shale, silty
- mDv-Ra,limestone, largely skeltal-fragmental, fossiliferous
- muDv-Ca,shale, black, siliceous, rarely calcareous, platy; minor limestone, ironstone and barite nodules; sandstone; conglomerate
- uCm-FM,dolostone, laminated, very thin-bedded, aphanocrystalline, oolitic; conglomerate, dolomitic, flat-pebble; dolostone, stromatolitic; shale, dolomitic, light green, maroon, thin-bedded
- uCm-SR,shale, red and green; siltstone, red, green; sandstone, red, green; salt; anhydrite; gypsum; dolostone
- uCt-EF,shale, siltstone; minor sandstone
- uCt-LB,LOWER shale, sandstone; UPPER sandstone, shale, coal
- uCt-SR,BASAL: sandstone. UPPER: siltstone; shale, black and grey; bentonite interbeds; minor siltstone; sandstone, fine-grained
- uDv-I,shale; sandstone

- Mackenzie Valley Highway Kilometre Post
- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Granular Borrow / Rock Quarry Site and Access
- Local Study Area
- Regional Study Area
- Community
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

0 2.5 5 Kilometres

(At original document size of 8.5x11)
1:250,000

N

Kálo-Stantec

Notes

1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada. Bedrock Geology source: Okulitch, A. V. and Irwin, D., 2016. Geological Compilation of the Western Mainland and Arctic Islands of the Northwest Territories; Northwest Territories Geological Survey, NWT Open File 2016-09
Esri, FAO, NOAA, USGS, NRCan, Earthstar Geographics, Esri, USGS

Project Location
Wrigley to Norman Wells, NWT

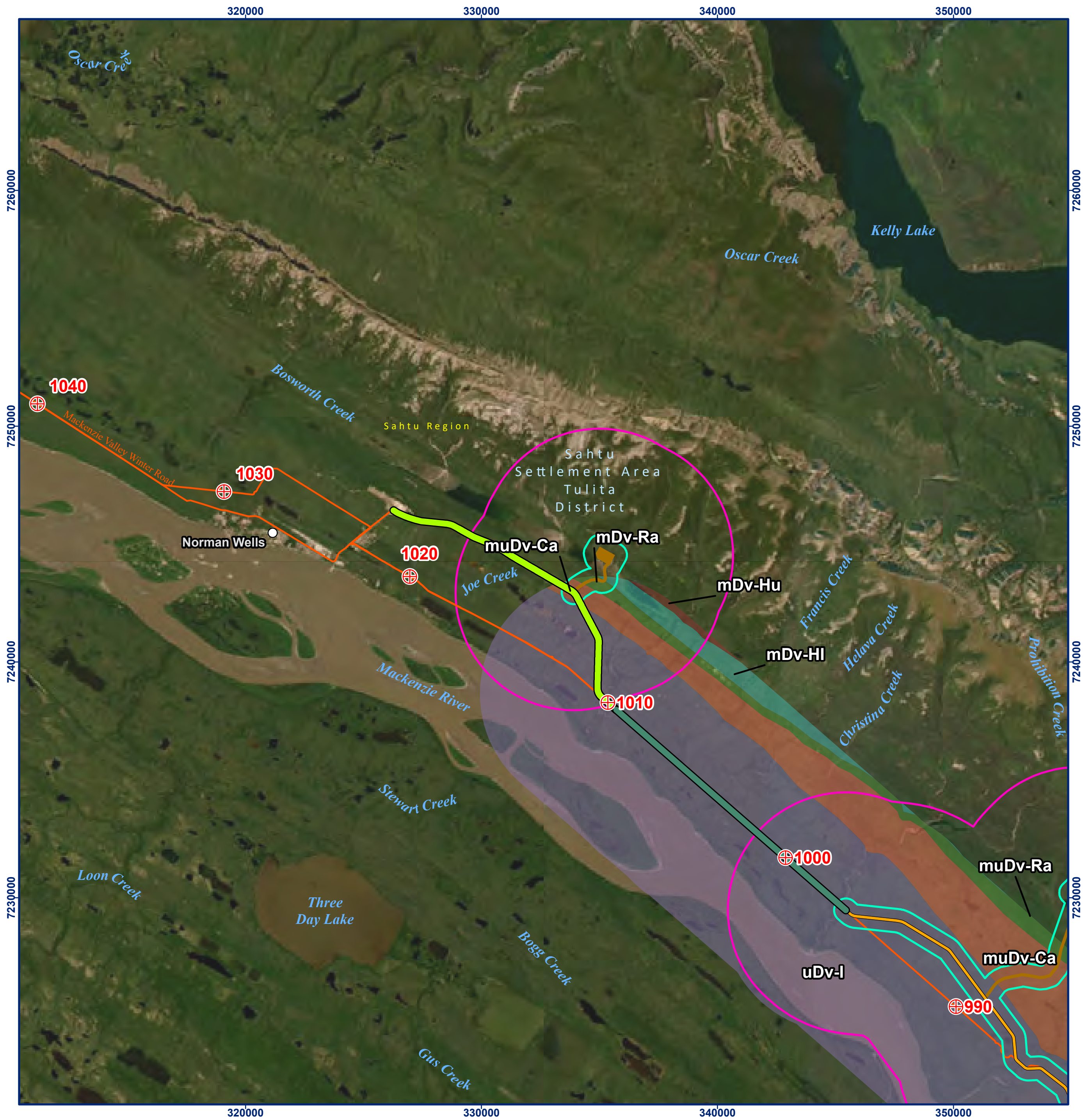
Prepared by AT on 3/9/2023
TR by AJ on 3/9/2023

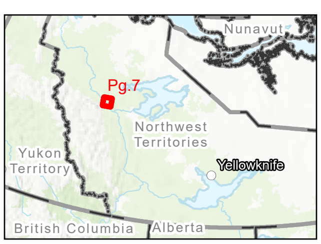
Client/Project
144903025-0003 REVB

Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.6

Title
RSA Bedrock Geology





Notes

1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada. Bedrock Geology source: Okulitch, A. V. and Irwin, D., 2016. Geological Compilation of the Western Mainland and Arctic Islands of the Northwest Territories; Northwest Territories Geological Survey, NWT Open File 2016-09
Esri, FAO, NOAA, USGS, NRCan, Earthstar Geographics, Esri, USGS

Bedrock Geology

- mDv-Hl,basal BLUEFISH Member: shale, bituminous, dark grey, spore-bearing. UPPER member: shale, calcareous, bluish-grey, thin bedded; minor limestone, thin interbeds
- mDv-Hu,LOWER member: interbedded marlstone, dark grey and limestone, dark greyish brown, micro- to fine-fragmental, fossiliferous; MIDDLE member: interbedded limestone, argillaceous; marlstone; shale, silty
- mDv-Ra,limestone, largely skeltal-fragmental, fossiliferous
- muDv-Ca,shale, black, siliceous, rarely calcareous, platy; minor limestone, ironstone and barite nodules; sandstone; conglomerate
- uDv-l,shale; sandstone

- Mackenzie Valley Highway Kilometre Post
- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Granular Borrow / Rock Quarry Site and Access
- Local Study Area
- Regional Study Area
- Community
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

0 2.5 5 Kilometres

(At original document size of 8.5x11)
1:250,000

N

Kálo-Stantec

Project Location
Wrigley to Norman Wells, NWT

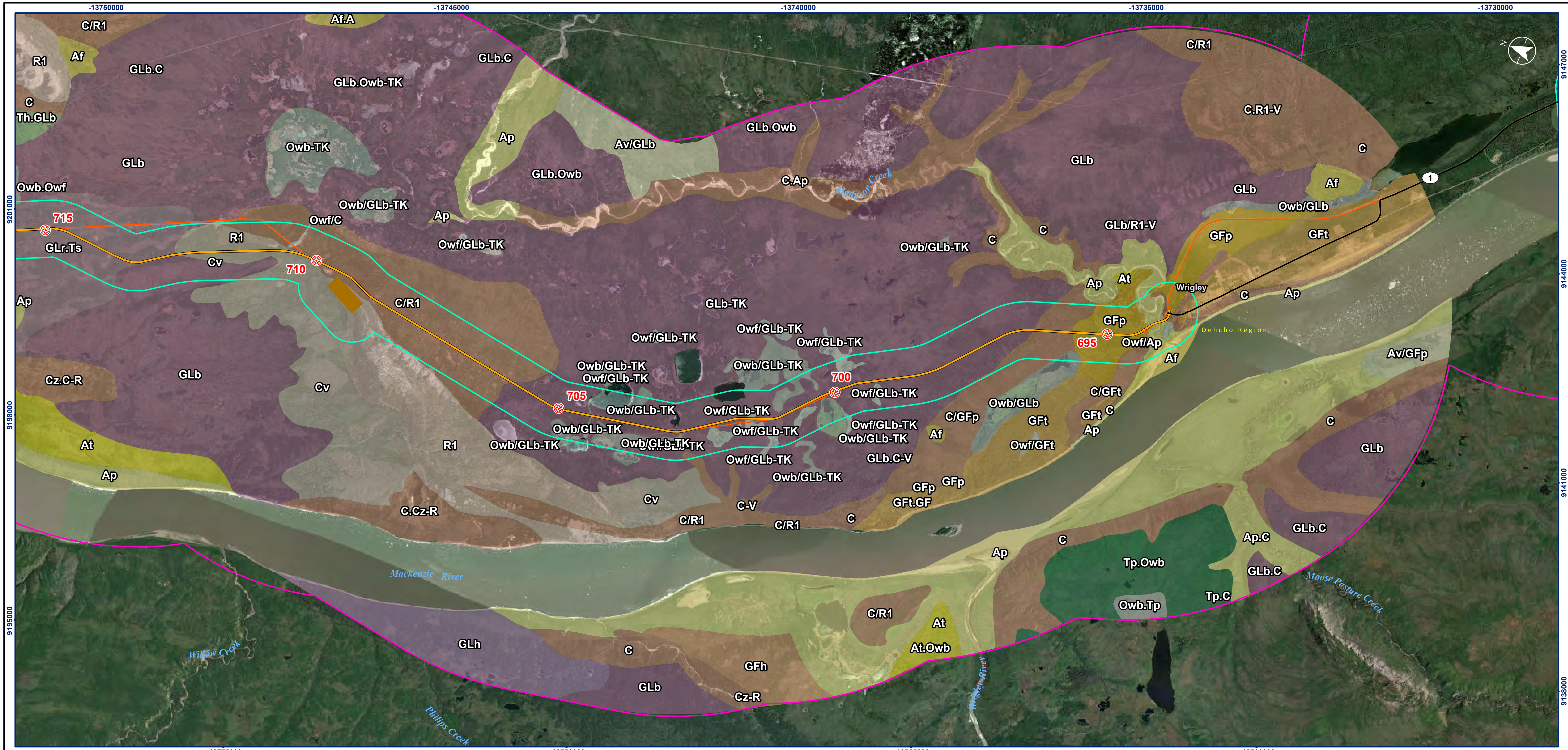
Prepared by AT on 3/9/2023
TR by AJ on 3/9/2023

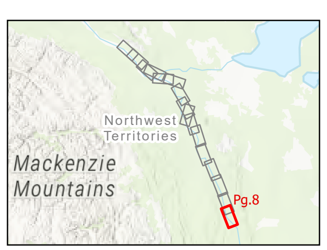
Client/Project
144903025-0003 REVB

Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.7

Title
RSA Bedrock Geology





Surficial Geology
- Af: Alluvial fan
- Ap: Alluvial floodplain sediment
- At: Alluvial terraced sediment
- Av: Alluvial veneer
- C: Colluvial deposit, undfferentiated
- Cv: Colluvial veneer
- Cz: Landslide deposit
- E: Eolian deposit, undifferentiated
- GFf: Glaciofluvial outwash-fan sediment
- GFh: Glaciofluvial hummocky sediment
- GFp: Glaciofluvial outwash-plain sediment
- GFr: Glaciofluvial esker sediment
- GFt: Glaciofluvial terraced sediment
- GFv: Glaciofluvial veneer
- GLb: Glaciolacustrine blanket
- GLh: Glaciolacustrine hummocky sediment
- GLr: Glaciolacustrine beach sediment
- GLv: Glaciolacustrine veneer
- Owb: Bog deposit
- Owf: Fen deposit
- R1: Sedimentary bedrock
- Tb: Till blanket
- Th: Hummocky till
- Tp: Till plain (all)
- Ts: Streamlined till
- Tv: Till veneer
- Mackenzie Valley Highway Kilometre Post

- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Local Study Area
- Regional Study Area
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- Granular Borrow / Rock Quarry Site and Access
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

Geomorphological Process
- R: Mass movement
- TK: Thermokarst
- V: Gullied

Example of terrain map unit symbol

Dominant surficial material and surface expression: Alluvial fan ⟹ AF/Tp - TK ⟸ Geomorphological process: Thermokarst (TK)

Dominant subsurface material and expression: till (M); plain (p)

Complex units
Two map-unit designators separated by a dot (.) are used where the surficial cover forms a complex area and the units are too small to be mapped individually (e.g. Ap.C designates an area of alluvial plain sediments with colluvial deposits).

Stratigraphic relationship
Two map-unit designators separated by a slash (/) are used where the stratigraphic relationship is observed or confidently inferred (e.g. GLv/T indicates glaciolacustrine veneer overlying till.)

0 1 2 Kilometres
1:70,000 (at original document size of 11x17)

Kálo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 2023-03-20
TR by AJ on 2023-03-20

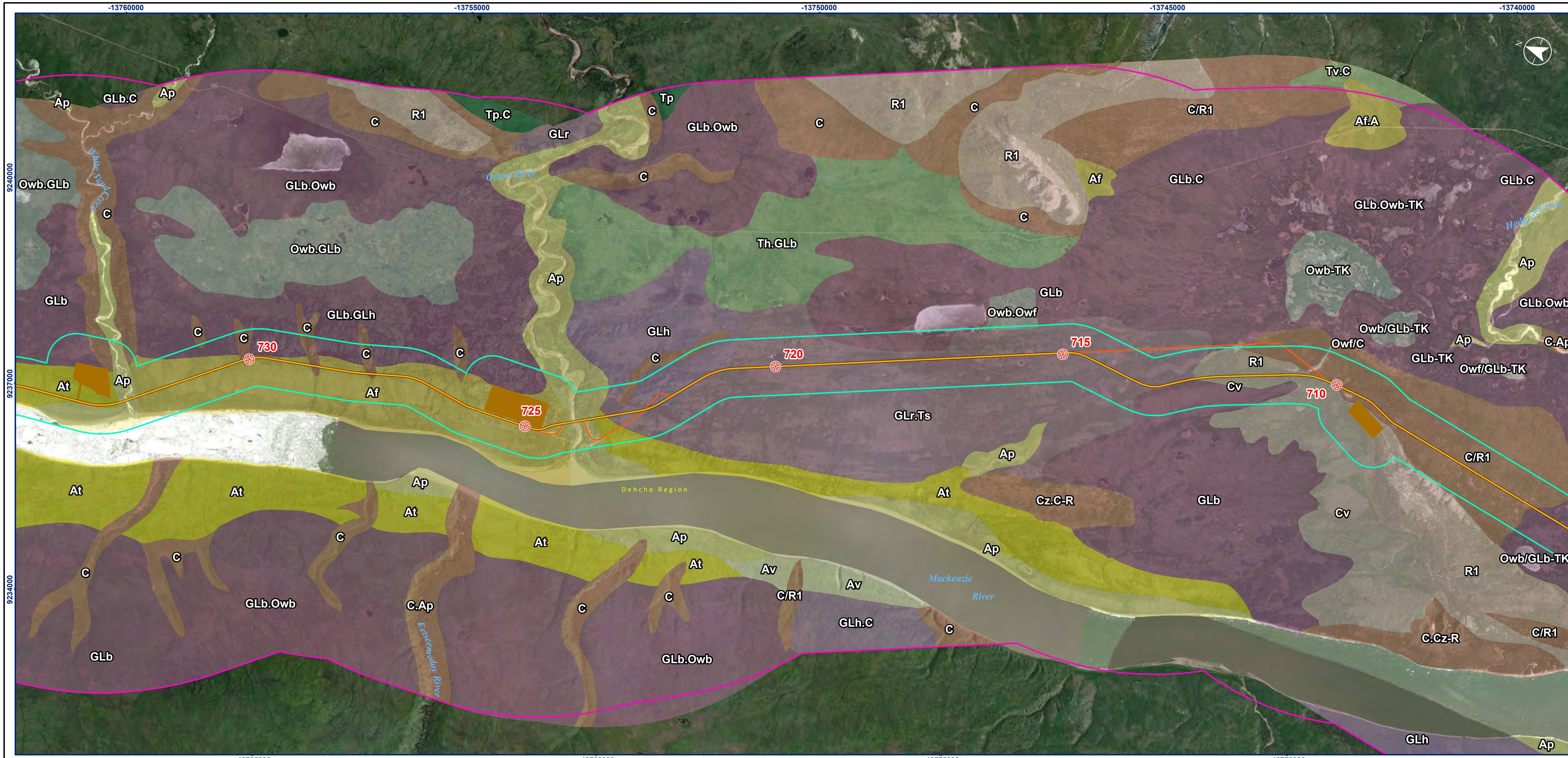
Client/Project
144903025-0020 REVB

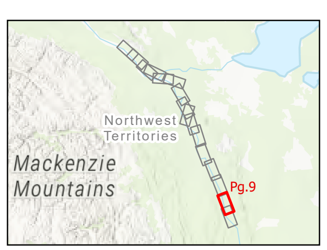
Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.8

Title
RSA Surficial Geology

Notes
1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada
3. Background: World Topographic Map: Northwest Territories, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Terrain mapping was compiled and modified based on a series of maps including OpenFile 7289 - middle east section from Côté et al. (2013), maps 371 and 375 from GSC (2019), and MGAR and Great bear prohibition mapping from G.V.M. Geological Consultant Ltd. (2016, 2019)





Surficial Geology

- Af: Alluvial fan
- Ap: Alluvial floodplain sediment
- At: Alluvial terraced sediment
- Av: Alluvial veneer
- C: Colluvial deposit, undffferentiated
- Cv: Colluvial veneer
- Cz: Landslide deposit
- E: Eolian deposit, undifferentiated
- GFf: Glaciofluvial outwash-fan sediment
- GFh: Glaciofluvial hummocky sediment
- GFp: Glaciofluvial outwash-plain sediment
- GFr: Glaciofluvial esker sediment
- GFt: Glaciofluvial terraced sediment
- GFv: Glaciofluvial veneer
- GLb: Glaciolacustrine blanket
- GLh: Glaciolacustrine hummocky sediment
- GLr: Glaciolacustrine beach sediment
- GLv: Glaciolacustrine veneer
- Owb: Bog deposit
- Owf: Fen deposit
- R1: Sedimentary bedrock
- Tb: Till blanket
- Th: Hummocky till
- Tp: Till plain (all)
- Ts: Streamlined till
- Tv: Till veneer
- Mackenzie Valley Highway Kilometre Post

- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Local Study Area
- Regional Study Area
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- Granular Borrow / Rock Quarry Site and Access
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

Geomorphological Process

R: Mass movement
TK: Thermokarst
V: Gullied

Example of terrain map unit symbol

Dominant surficial material and surface expression: Alluvial fan ⟹ AF/Tp - TK ⟸ Geomorphological process: Thermokarst (TK)

Dominant subsurface material and expression: till (M); plain (p)

Complex units
Two map-unit designators separated by a dot (.) are used where the surficial cover forms a complex area and the units are too small to be mapped individually (e.g. Ap.C designates an area of alluvial plain sediments with colluvial deposits).

Stratigraphic relationship
Two map-unit designators separated by a slash (/) are used where the stratigraphic relationship is observed or confidently inferred (e.g. GLv/T indicates glaciolacustrine veneer overlying till.)

0 1 2 Kilometres
1:70,000 (at original document size of 11x17)

Kálo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 2023-03-20
TR by AJ on 2023-03-20

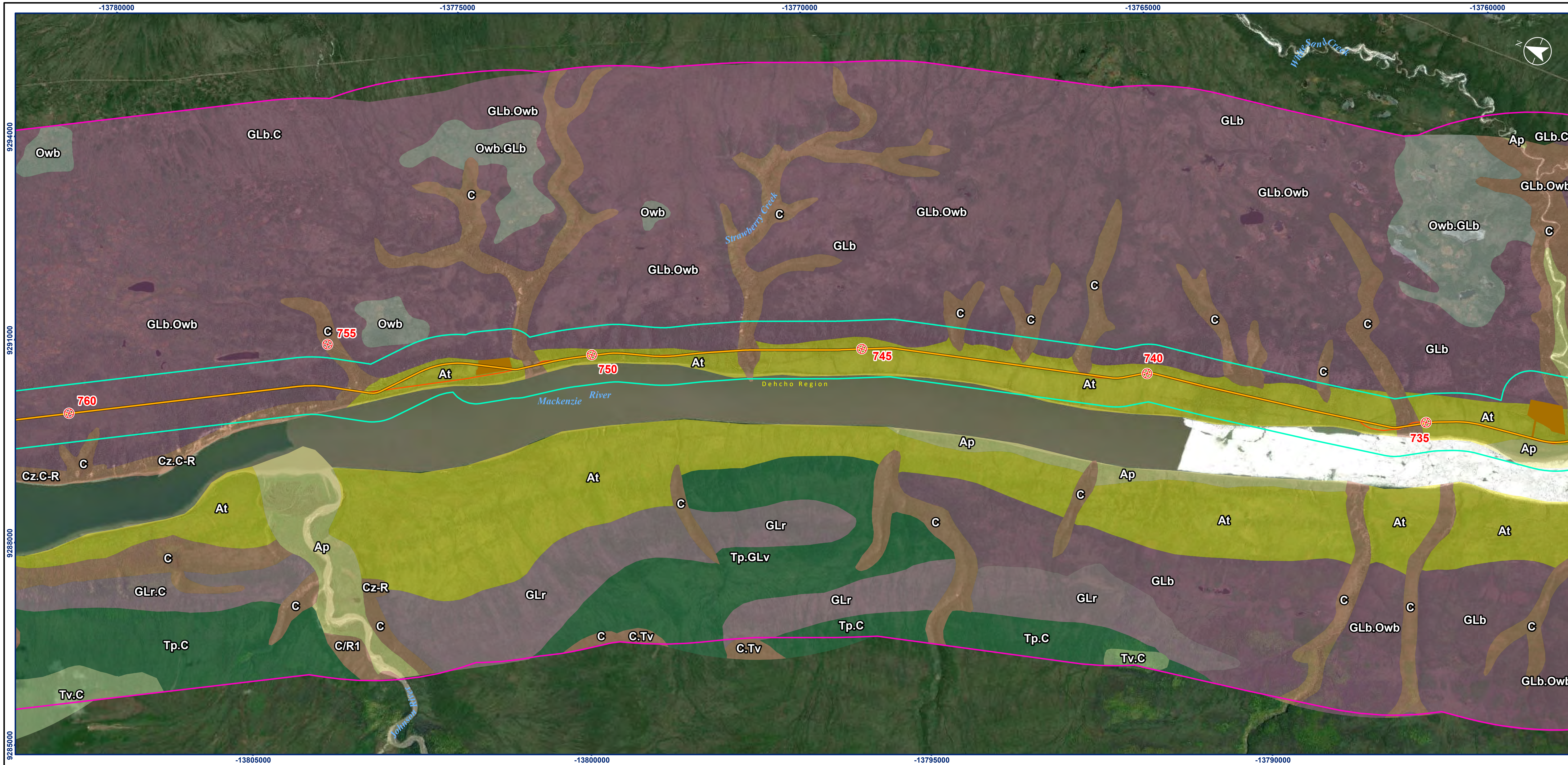
Client/Project
144903025-0020 REVB

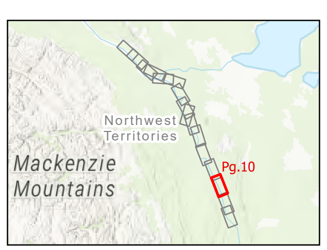
Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.9

Title
RSA Surficial Geology

Notes
1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada
3. Background: World Topographic Map: Northwest Territories, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Terrain mapping was compiled and modified based on a series of maps including OpenFile 7289 - middle east section from Côté et al. (2013), maps 371 and 375 from GSC (2019), and MGAR and Great bear prohibition mapping from G.V.M. Geological Consultant Ltd. (2016, 2019)





Surficial Geology

- Af: Alluvial fan
- Ap: Alluvial floodplain sediment
- At: Alluvial terraced sediment
- Av: Alluvial veneer
- C: Colluvial deposit, undfferentiated
- Cv: Colluvial veneer
- Cz: Landslide deposit
- E: Eolian deposit, undifferentiated
- GFf: Glaciofluvial outwash-fan sediment
- GFh: Glaciofluvial hummocky sediment
- GFp: Glaciofluvial outwash-plain sediment
- GFr: Glaciofluvial esker sediment
- GFt: Glaciofluvial terraced sediment
- GFv: Glaciofluvial veneer
- GLb: Glaciolacustrine blanket
- GLh: Glaciolacustrine hummocky sediment
- GLr: Glaciolacustrine beach sediment
- GLv: Glaciolacustrine veneer
- Owb: Bog deposit
- Owf: Fen deposit
- R1: Sedimentary bedrock
- Tb: Till blanket
- Th: Hummocky till
- Tp: Till plain (all)
- Ts: Streamlined till
- Tv: Till veneer
- Mackenzie Valley Highway Kilometre Post

- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Local Study Area
- Regional Study Area
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- Granular Borrow / Rock Quarry Site and Access
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

Geomorphological Process

R: Mass movement
TK: Thermokarst
V: Gullied

Example of terrain map unit symbol

Dominant surficial material and surface expression: Alluvial fan ⟹ AF/Tp - TK ⟸ Geomorphological process: Thermokarst (TK)

Dominant subsurface material and expression: till (M); plain (p)

Complex units
Two map-unit designators separated by a dot (.) are used where the surficial cover forms a complex area and the units are too small to be mapped individually (e.g. Ap.C designates an area of alluvial plain sediments with colluvial deposits).

Stratigraphic relationship
Two map-unit designators separated by a slash (/) are used where the stratigraphic relationship is observed or confidently inferred (e.g. GLv/T indicates glaciolacustrine veneer overlying till.)

0 1 2 Kilometres
1:70,000 (at original document size of 11x17)

Kálo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 2023-03-20
TR by AJ on 2023-03-20

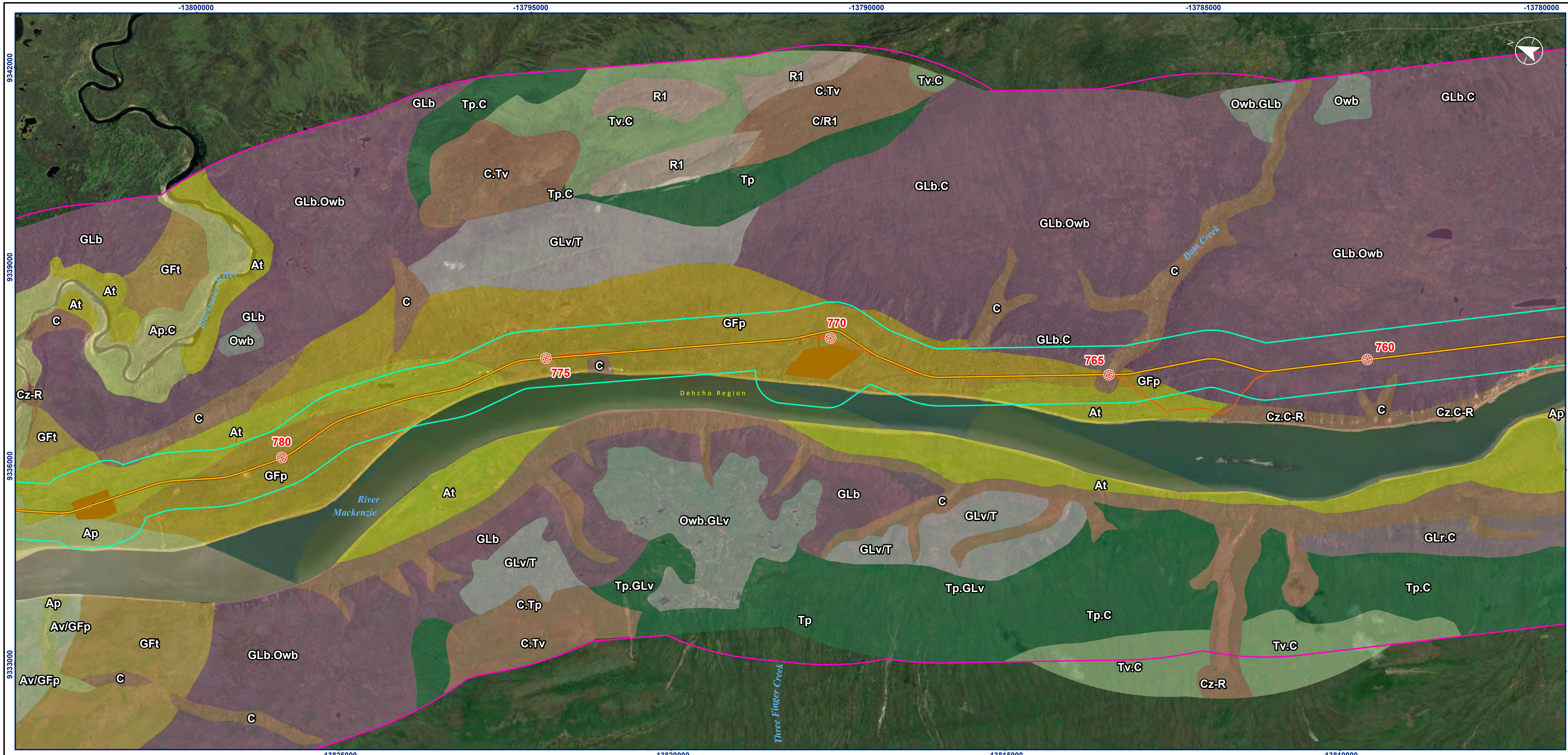
Client/Project
144903025-0020 REVB

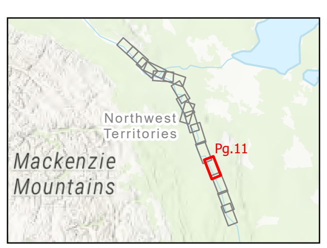
Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.10

Title
RSA Surficial Geology

Notes
1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada
3. Background: World Topographic Map: Northwest Territories, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Terrain mapping was compiled and modified based on a series of maps including OpenFile 7289 - middle east section from Côté et al. (2013), maps 371 and 375 from GSC (2019), and MGAR and Great bear prohibition mapping from G.V.M. Geological Consultant Ltd. (2016, 2019)





Surficial Geology

- Af: Alluvial fan
- Ap: Alluvial floodplain sediment
- At: Alluvial terraced sediment
- Av: Alluvial veneer
- C: Colluvial deposit, undfferentiated
- Cv: Colluvial veneer
- Cz: Landslide deposit
- E: Eolian deposit, undifferentiated
- GFf: Glaciofluvial outwash-fan sediment
- GFh: Glaciofluvial hummocky sediment
- GFp: Glaciofluvial outwash-plain sediment
- GFr: Glaciofluvial esker sediment
- GFt: Glaciofluvial terraced sediment
- GFv: Glaciofluvial veneer
- GLb: Glaciolacustrine blanket
- GLh: Glaciolacustrine hummocky sediment
- GLr: Glaciolacustrine beach sediment
- GLv: Glaciolacustrine veneer
- Owb: Bog deposit
- Owf: Fen deposit
- R1: Sedimentary bedrock
- Tb: Till blanket
- Th: Hummocky till
- Tp: Till plain (all)
- Ts: Streamlined till
- Tv: Till veneer
- Mackenzie Valley Highway Kilometre Post

- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Local Study Area
- Regional Study Area
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- Granular Borrow / Rock Quarry Site and Access
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

Geomorphological Process

R: Mass movement
TK: Thermokarst
V: Gullied

Example of terrain map unit symbol

Dominant surficial material and surface expression: Alluvial fan ⟹ AF/Tp - TK ⟸ Geomorphological process: Thermokarst (TK)

Dominant subsurface material and expression: till (M); plain (p)

Complex units
Two map-unit designators separated by a dot (.) are used where the surficial cover forms a complex area and the units are too small to be mapped individually (e.g. Ap.C designates an area of alluvial plain sediments with colluvial deposits).

Stratigraphic relationship
Two map-unit designators separated by a slash (/) are used where the stratigraphic relationship is observed or confidently inferred (e.g. GLv/T indicates glaciolacustrine veneer overlying till.)

0 1 2 Kilometres
1:70,000 (at original document size of 11x17)

Kálo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 2023-03-20
TR by AJ on 2023-03-20

Client/Project
144903025-0020 REVB

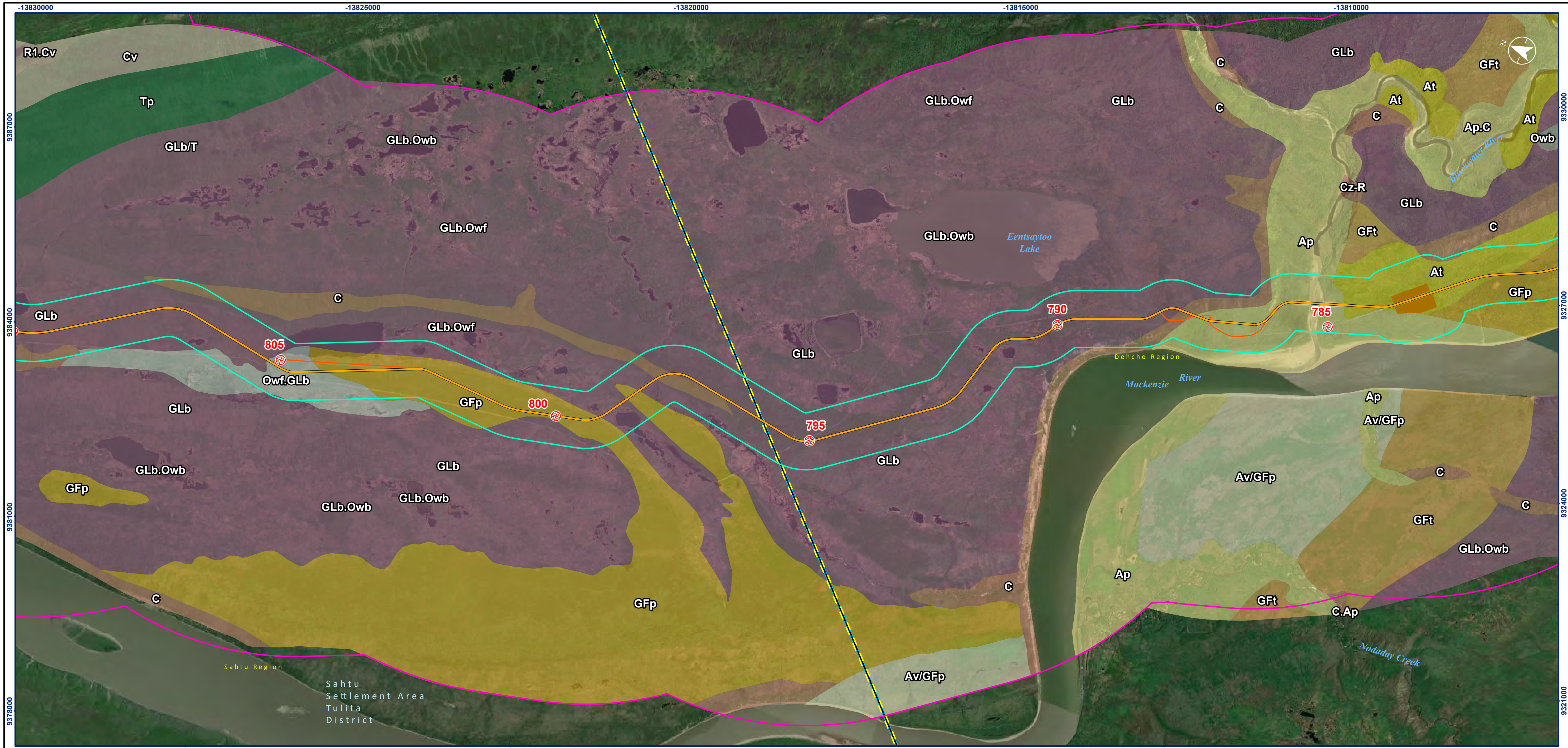
Government of Northwest Territories
Mackenzie Valley Highway Project

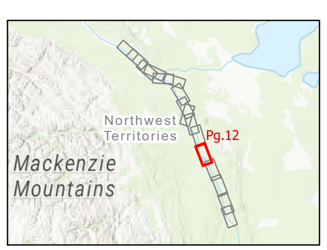
Figure No.
A.11

Title
RSA Surficial Geology

Notes

1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada
3. Background: World Topographic Map: Northwest Territories, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Terrain mapping was compiled and modified based on a series of maps including OpenFile 7289 - middle east section from Côté et al. (2013), maps 371 and 375 from GSC (2019), and MGAR and Great bear prohibition mapping from G.V.M. Geological Consultant Ltd. (2016, 2019)





Surficial Geology

- Af: Alluvial fan
- Ap: Alluvial floodplain sediment
- At: Alluvial terraced sediment
- Av: Alluvial veneer
- C: Colluvial deposit, undfferentiated
- Cv: Colluvial veneer
- Cz: Landslide deposit
- E: Eolian deposit, undifferentiated
- GFf: Glaciofluvial outwash-fan sediment
- GFh: Glaciofluvial hummocky sediment
- GFp: Glaciofluvial outwash-plain sediment
- GFr: Glaciofluvial esker sediment
- GFt: Glaciofluvial terraced sediment
- GFv: Glaciofluvial veneer
- GLb: Glaciolacustrine blanket
- GLh: Glaciolacustrine hummocky sediment
- GLr: Glaciolacustrine beach sediment
- GLv: Glaciolacustrine veneer
- Owb: Bog deposit
- Owf: Fen deposit
- R1: Sedimentary bedrock
- Tb: Till blanket
- Th: Hummocky till
- Tp: Till plain (all)
- Ts: Streamlined till
- Tv: Till veneer
- Mackenzie Valley Highway Kilometre Post

- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Local Study Area
- Regional Study Area
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- Granular Borrow / Rock Quarry Site and Access
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

Geomorphological Process

R: Mass movement
TK: Thermokarst
V: Gullied

Example of terrain map unit symbol

Dominant surficial material and surface expression: Alluvial fan ⟹ AF/Tp - TK ⟸ Geomorphological process: Thermokarst (TK)

Dominant subsurface material and expression: till (M); plain (p)

Complex units
Two map-unit designators separated by a dot (.) are used where the surficial cover forms a complex area and the units are too small to be mapped individually (e.g. Ap.C designates an area of alluvial plain sediments with colluvial deposits).

Stratigraphic relationship
Two map-unit designators separated by a slash (/) are used where the stratigraphic relationship is observed or confidently inferred (e.g. GLv/T indicates glaciolacustrine veneer overlying till.)

0 1 2 Kilometres
1:70,000 (at original document size of 11x17)

Kʼalo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 2023-03-20
TR by AJ on 2023-03-20

Client/Project
144903025-0020 REVB

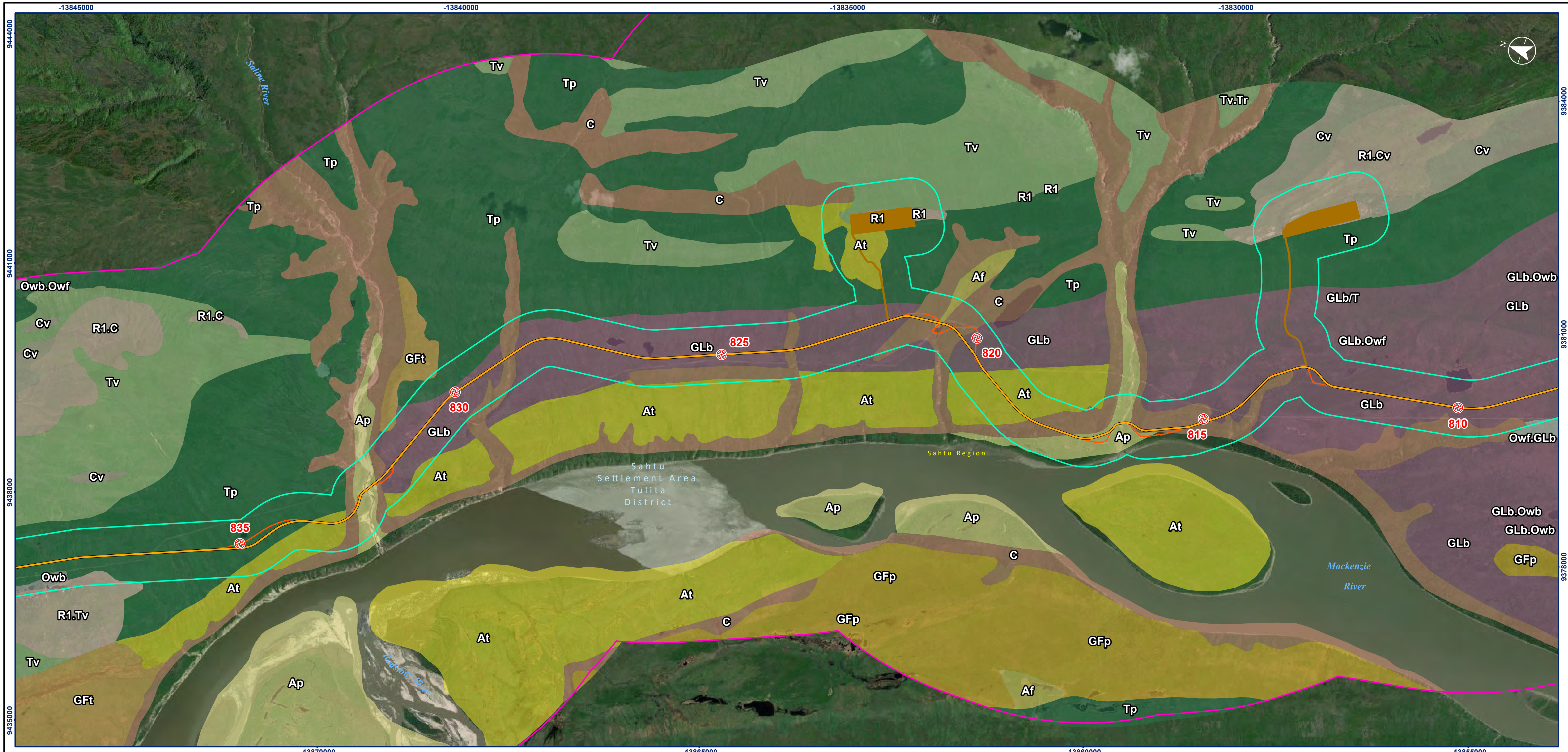
Government of Northwest Territories
Mackenzie Valley Highway Project

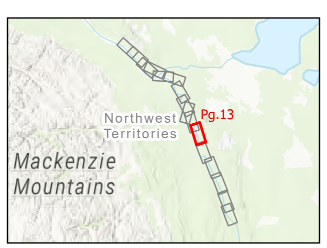
Figure No.
A.12

Title
RSA Surficial Geology

Notes

1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada
3. Background: World Topographic Map: Northwest Territories, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Terrain mapping was compiled and modified based on a series of maps including OpenFile 7289 - middle east section from Côté et al. (2013), maps 371 and 375 from GSC (2019), and MGAR and Great bear prohibition mapping from G.V.M. Geological Consultant Ltd. (2016, 2019)





Surficial Geology

- Af: Alluvial fan
- Ap: Alluvial floodplain sediment
- At: Alluvial terraced sediment
- Av: Alluvial veneer
- C: Colluvial deposit, undifferentiated
- Cv: Colluvial veneer
- Cz: Landslide deposit
- E: Eolian deposit, undifferentiated
- GFf: Glaciofluvial outwash-fan sediment
- GFh: Glaciofluvial hummocky sediment
- GFp: Glaciofluvial outwash-plain sediment
- GFr: Glaciofluvial esker sediment
- GFt: Glaciofluvial terraced sediment
- GFv: Glaciofluvial veneer
- GLb: Glaciolacustrine blanket
- GLh: Glaciolacustrine hummocky sediment
- GLr: Glaciolacustrine beach sediment
- GLv: Glaciolacustrine veneer
- Owb: Bog deposit
- Owf: Fen deposit
- R1: Sedimentary bedrock
- Tb: Till blanket
- Th: Hummocky till
- Tp: Till plain (all)
- Ts: Streamlined till
- Tv: Till veneer
- Mackenzie Valley Highway Kilometre Post
- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Local Study Area
- Regional Study Area
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- Granular Borrow / Rock Quarry Site and Access
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

Geomorphological Process

R: Mass movement
TK: Thermokarst
V: Gullied

Example of terrain map unit symbol

Dominant surficial material and surface expression: Alluvial fan ⟹ AF/Tp - TK ⟸ Geomorphological process: Thermokarst (TK)

Dominant subsurface material and expression: till (M); plain (p)

Complex units
Two map-unit designators separated by a dot (.) are used where the surficial cover forms a complex area and the units are too small to be mapped individually (e.g. Ap.C designates an area of alluvial plain sediments with colluvial deposits).

Stratigraphic relationship
Two map-unit designators separated by a slash (/) are used where the stratigraphic relationship is observed or confidently inferred (e.g. GLv/T indicates glaciolacustrine veneer overlying till.)

0 1 2 Kilometres
1:70,000 (at original document size of 11x17)

Kā'alo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 2023-03-20
TR by AJ on 2023-03-20

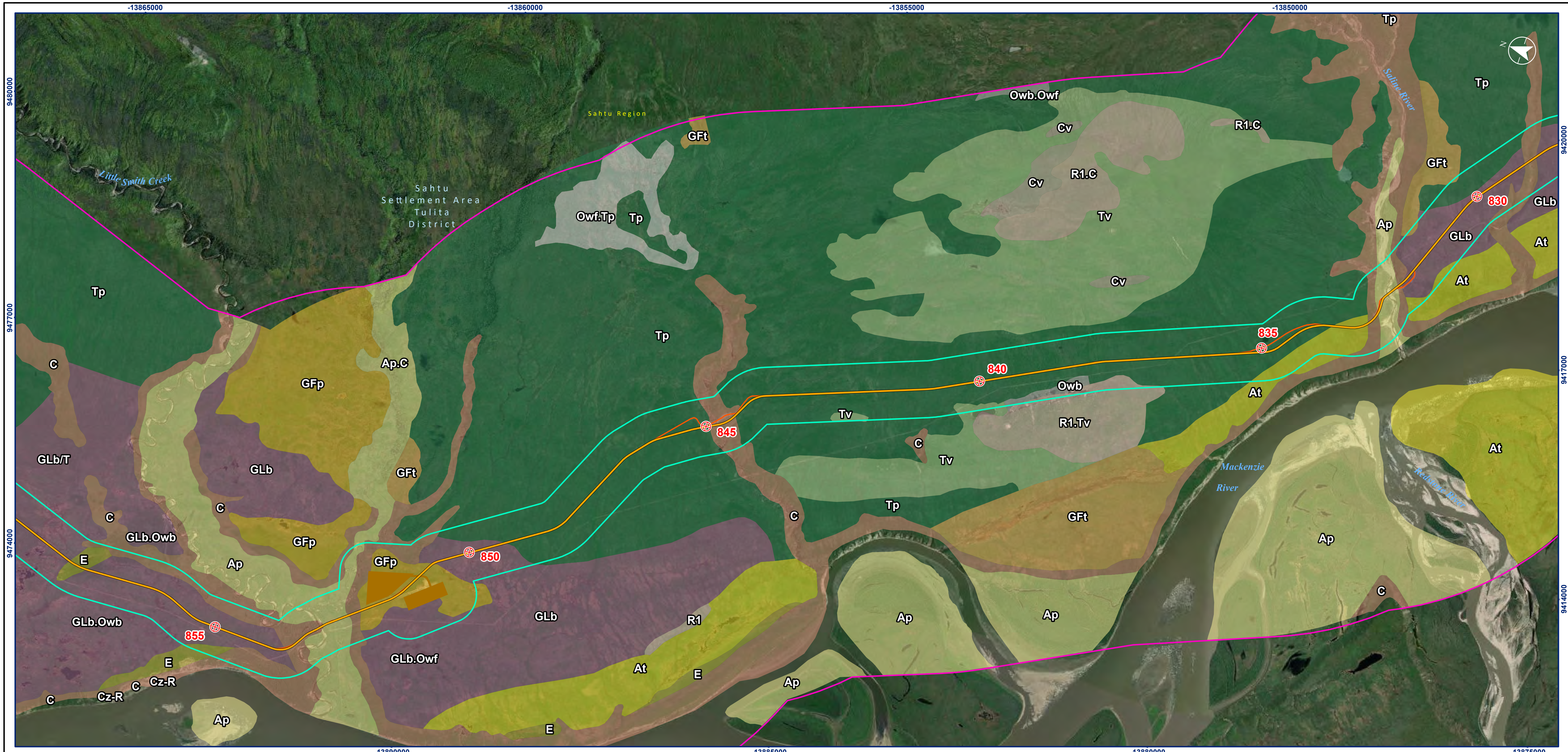
Client/Project
144903025-0020 REVB

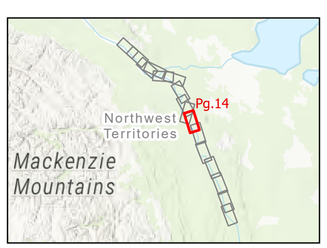
Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.13

Title
RSA Surficial Geology

Notes
1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada
3. Background: World Topographic Map: Northwest Territories, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Terrain mapping was compiled and modified based on a series of maps including OpenFile 7289 - middle east section from Côté et al. (2013), maps 371 and 375 from GSC (2019), and MGAR and Great bear prohibition mapping from G.V.M. Geological Consultant Ltd. (2016, 2019)





Surficial Geology

- Af: Alluvial fan
- Ap: Alluvial floodplain sediment
- At: Alluvial terraced sediment
- Av: Alluvial veneer
- C: Colluvial deposit, undfferentiated
- Cv: Colluvial veneer
- Cz: Landslide deposit
- E: Eolian deposit, undifferentiated
- GFf: Glaciofluvial outwash-fan sediment
- GFh: Glaciofluvial hummocky sediment
- GFp: Glaciofluvial outwash-plain sediment
- GFr: Glaciofluvial esker sediment
- GFt: Glaciofluvial terraced sediment
- GFv: Glaciofluvial veneer
- GLb: Glaciolacustrine blanket
- GLh: Glaciolacustrine hummocky sediment
- GLr: Glaciolacustrine beach sediment
- GLv: Glaciolacustrine veneer
- Owb: Bog deposit
- Owf: Fen deposit
- R1: Sedimentary bedrock
- Tb: Till blanket
- Th: Hummocky till
- Tp: Till plain (all)
- Ts: Streamlined till
- Tv: Till veneer
- Mackenzie Valley Highway Kilometre Post

- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Local Study Area
- Regional Study Area
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- Granular Borrow / Rock Quarry Site and Access
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

Geomorphological Process

R: Mass movement
TK: Thermokarst
V: Gullied

Example of terrain map unit symbol

Dominant surficial material and surface expression: Alluvial fan ⟹ AF/Tp - TK ⟸ Geomorphological process: Thermokarst (TK)

Dominant subsurface material and expression: till (M); plain (p)

Complex units
Two map-unit designators separated by a dot (.) are used where the surficial cover forms a complex area and the units are too small to be mapped individually (e.g. Ap.C designates an area of alluvial plain sediments with colluvial deposits).

Stratigraphic relationship
Two map-unit designators separated by a slash (/) are used where the stratigraphic relationship is observed or confidently inferred (e.g. GLv/T indicates glaciolacustrine veneer overlying till.)

0 1 2 Kilometres
1:70,000 (at original document size of 11x17)

Kálo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 2023-03-20
TR by AJ on 2023-03-20

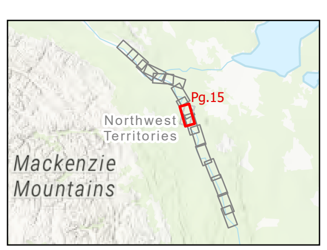
Client/Project
144903025-0020 REVB

Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.14

Title
RSA Surficial Geology

Notes
1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada
3. Background: World Topographic Map: Northwest Territories, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Terrain mapping was compiled and modified based on a series of maps including OpenFile 7289 - middle east section from Côté et al. (2013), maps 371 and 375 from GSC (2019), and MGAR and Great bear prohibition mapping from G.V.M. Geological Consultant Ltd. (2016, 2019)



Surficial Geology

- Af: Alluvial fan
- Ap: Alluvial floodplain sediment
- At: Alluvial terraced sediment
- Av: Alluvial veneer
- C: Colluvial deposit, undffferentiated
- Cv: Colluvial veneer
- Cz: Landslide deposit
- E: Eolian deposit, undifferentiated
- GFf: Glaciofluvial outwash-fan sediment
- GFh: Glaciofluvial hummocky sediment
- GFp: Glaciofluvial outwash-plain sediment
- GFr: Glaciofluvial esker sediment
- GFt: Glaciofluvial terraced sediment
- GFv: Glaciofluvial veneer
- GLb: Glaciolacustrine blanket
- GLh: Glaciolacustrine hummocky sediment
- GLr: Glaciolacustrine beach sediment
- GLv: Glaciolacustrine veneer
- Owb: Bog deposit
- Owf: Fen deposit
- R1: Sedimentary bedrock
- Tb: Till blanket
- Th: Hummocky till
- Tp: Till plain (all)
- Ts: Streamlined till
- Tv: Till veneer
- Mackenzie Valley Highway Kilometre Post

- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Local Study Area
- Regional Study Area
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- Granular Borrow / Rock Quarry Site and Access
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

Geomorphological Process

R: Mass movement
TK: Thermokarst
V: Gullied

Example of terrain map unit symbol

Dominant surficial material and surface expression: Alluvial fan ⟹ AF/Tp - TK ⟸ Geomorphological process: Thermokarst (TK)

Dominant subsurface material and expression: till (M); plain (p)

Complex units
Two map-unit designators separated by a dot (.) are used where the surficial cover forms a complex area and the units are too small to be mapped individually (e.g. Ap.C designates an area of alluvial plain sediments with colluvial deposits).

Stratigraphic relationship
Two map-unit designators separated by a slash (/) are used where the stratigraphic relationship is observed or confidently inferred (e.g. GLv/T indicates glaciolacustrine veneer overlying till.)

0 1 2 Kilometres
1:70,000 (at original document size of 11x17)

Kálo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 2023-03-20
TR by AJ on 2023-03-20

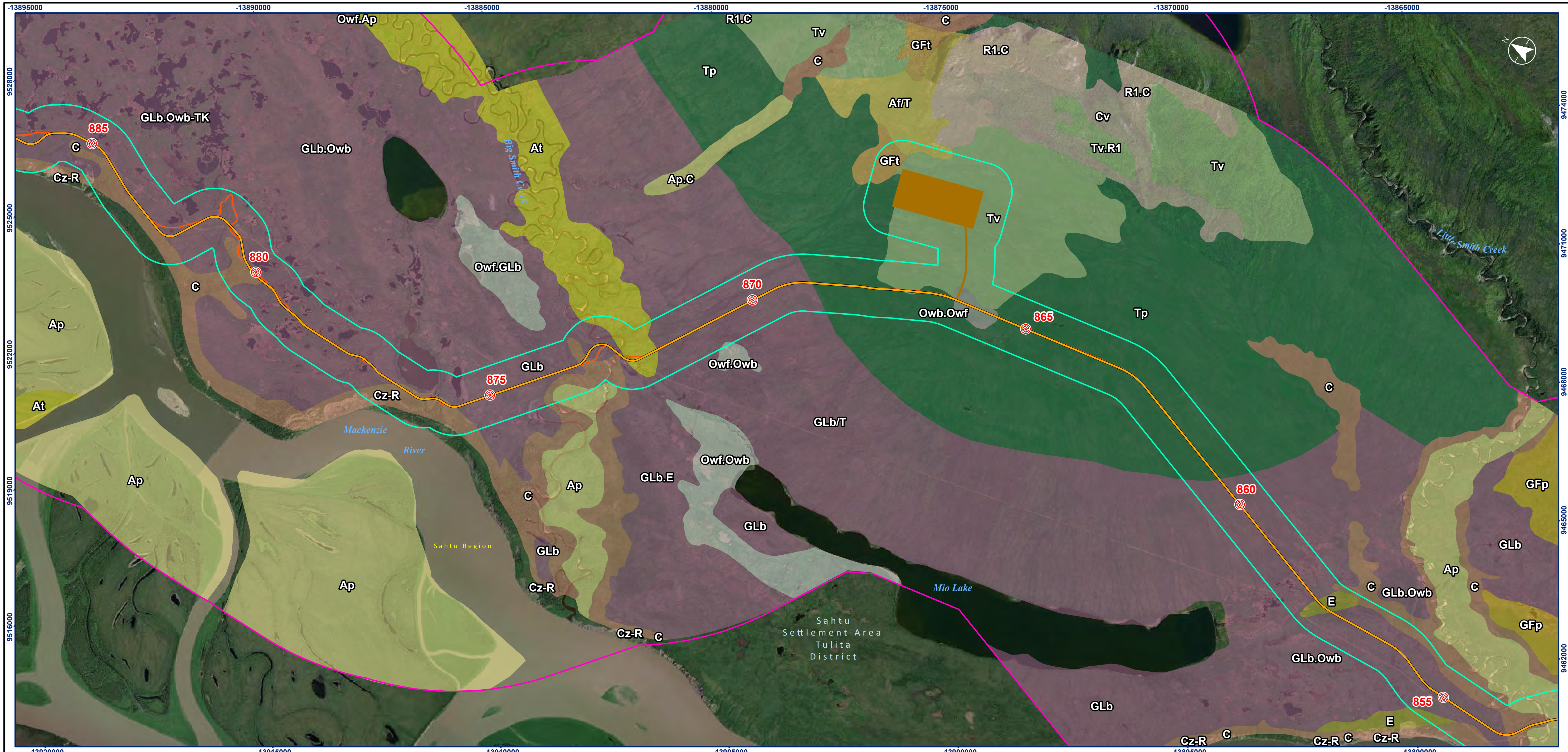
Client/Project
144903025-0020 REVB

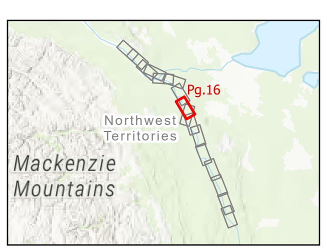
Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.15

Title
RSA Surficial Geology

Notes
1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada
3. Background: World Topographic Map: Northwest Territories, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Terrain mapping was compiled and modified based on a series of maps including OpenFile 7289 - middle east section from Côté et al. (2013), maps 371 and 375 from GSC (2019), and MGAR and Great bear prohibition mapping from G.V.M. Geological Consultant Ltd. (2016, 2019)





Surficial Geology

- Af: Alluvial fan
- Ap: Alluvial floodplain sediment
- At: Alluvial terraced sediment
- Av: Alluvial veneer
- C: Colluvial deposit, undfferentiated
- Cv: Colluvial veneer
- Cz: Landslide deposit
- E: Eolian deposit, undifferentiated
- GFf: Glaciofluvial outwash-fan sediment
- GFh: Glaciofluvial hummocky sediment
- GFp: Glaciofluvial outwash-plain sediment
- GFr: Glaciofluvial esker sediment
- GFt: Glaciofluvial terraced sediment
- GFv: Glaciofluvial veneer
- GLb: Glaciolacustrine blanket
- GLh: Glaciolacustrine hummocky sediment
- GLr: Glaciolacustrine beach sediment
- GLv: Glaciolacustrine veneer
- Owb: Bog deposit
- Owf: Fen deposit
- R1: Sedimentary bedrock
- Tb: Till blanket
- Th: Hummocky till
- Tp: Till plain (all)
- Ts: Streamlined till
- Tv: Till veneer
- Mackenzie Valley Highway Kilometre Post

- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Local Study Area
- Regional Study Area
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- Granular Borrow / Rock Quarry Site and Access
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

Geomorphological Process
R: Mass movement
TK: Thermokarst
V: Gullied

Example of terrain map unit symbol

Dominant surficial material and surface expression: Alluvial fan ⟹ AF/Tp - TK ⟸ Geomorphological process: Thermokarst (TK)

Dominant subsurface material and expression: till (M); plain (p)

Complex units
Two map-unit designators separated by a dot (.) are used where the surficial cover forms a complex area and the units are too small to be mapped individually (e.g. Ap.C designates an area of alluvial plain sediments with colluvial deposits).

Stratigraphic relationship
Two map-unit designators separated by a slash (/) are used where the stratigraphic relationship is observed or confidently inferred (e.g. GLv/T indicates glaciolacustrine veneer overlying till.)

0 1 2 Kilometres
1:70,000 (at original document size of 11x17)

Kạlo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 2023-03-20
TR by AJ on 2023-03-20

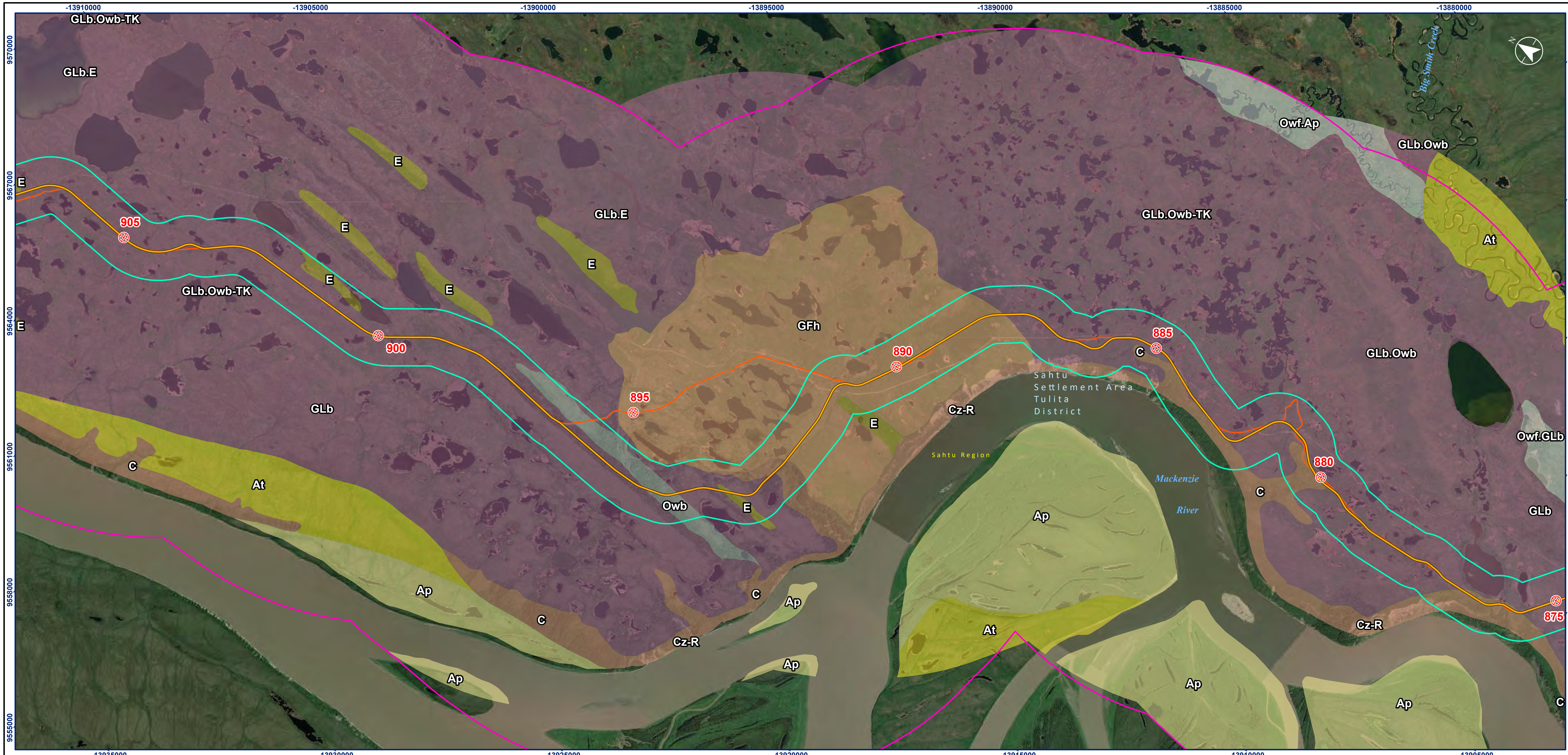
Client/Project
144903025-0020 REVB

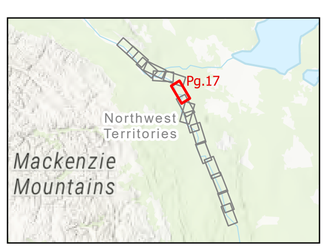
Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.16

Title
RSA Surficial Geology

Notes
1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada
3. Background: World Topographic Map: Northwest Territories, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Terrain mapping was compiled and modified based on a series of maps including OpenFile 7289 - middle east section from Côté et al. (2013), maps 371 and 375 from GSC (2019), and MGAR and Great bear prohibition mapping from G.V.M. Geological Consultant Ltd. (2016, 2019)





Surficial Geology

- Af: Alluvial fan
- Ap: Alluvial floodplain sediment
- At: Alluvial terraced sediment
- Av: Alluvial veneer
- C: Colluvial deposit, undfferentiated
- Cv: Colluvial veneer
- Cz: Landslide deposit
- E: Eolian deposit, undifferentiated
- GFf: Glaciofluvial outwash-fan sediment
- GFh: Glaciofluvial hummocky sediment
- GFp: Glaciofluvial outwash-plain sediment
- GFr: Glaciofluvial esker sediment
- GFt: Glaciofluvial terraced sediment
- GFv: Glaciofluvial veneer
- GLb: Glaciolacustrine blanket
- GLh: Glaciolacustrine hummocky sediment
- GLr: Glaciolacustrine beach sediment
- GLv: Glaciolacustrine veneer
- Owb: Bog deposit
- Owf: Fen deposit
- R1: Sedimentary bedrock
- Tb: Till blanket
- Th: Hummocky till
- Tp: Till plain (all)
- Ts: Streamlined till
- Tv: Till veneer
- Mackenzie Valley Highway Kilometre Post

- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Local Study Area
- Regional Study Area
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- Granular Borrow / Rock Quarry Site and Access
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

Geomorphological Process

R: Mass movement
TK: Thermokarst
V: Gullied

Example of terrain map unit symbol

Dominant surficial material and surface expression: Alluvial fan ⟹ AF/Tp - TK ⟸ Geomorphological process: Thermokarst (TK)

Dominant subsurface material and expression: till (M); plain (p)

Complex units
Two map-unit designators separated by a dot (.) are used where the surficial cover forms a complex area and the units are too small to be mapped individually (e.g. Ap.C designates an area of alluvial plain sediments with colluvial deposits).

Stratigraphic relationship
Two map-unit designators separated by a slash (/) are used where the stratigraphic relationship is observed or confidently inferred (e.g. GLv/T indicates glaciolacustrine veneer overlying till.)

0 1 2 Kilometres
1:70,000 (at original document size of 11x17)

K'alo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 2023-03-20
TR by AJ on 2023-03-20

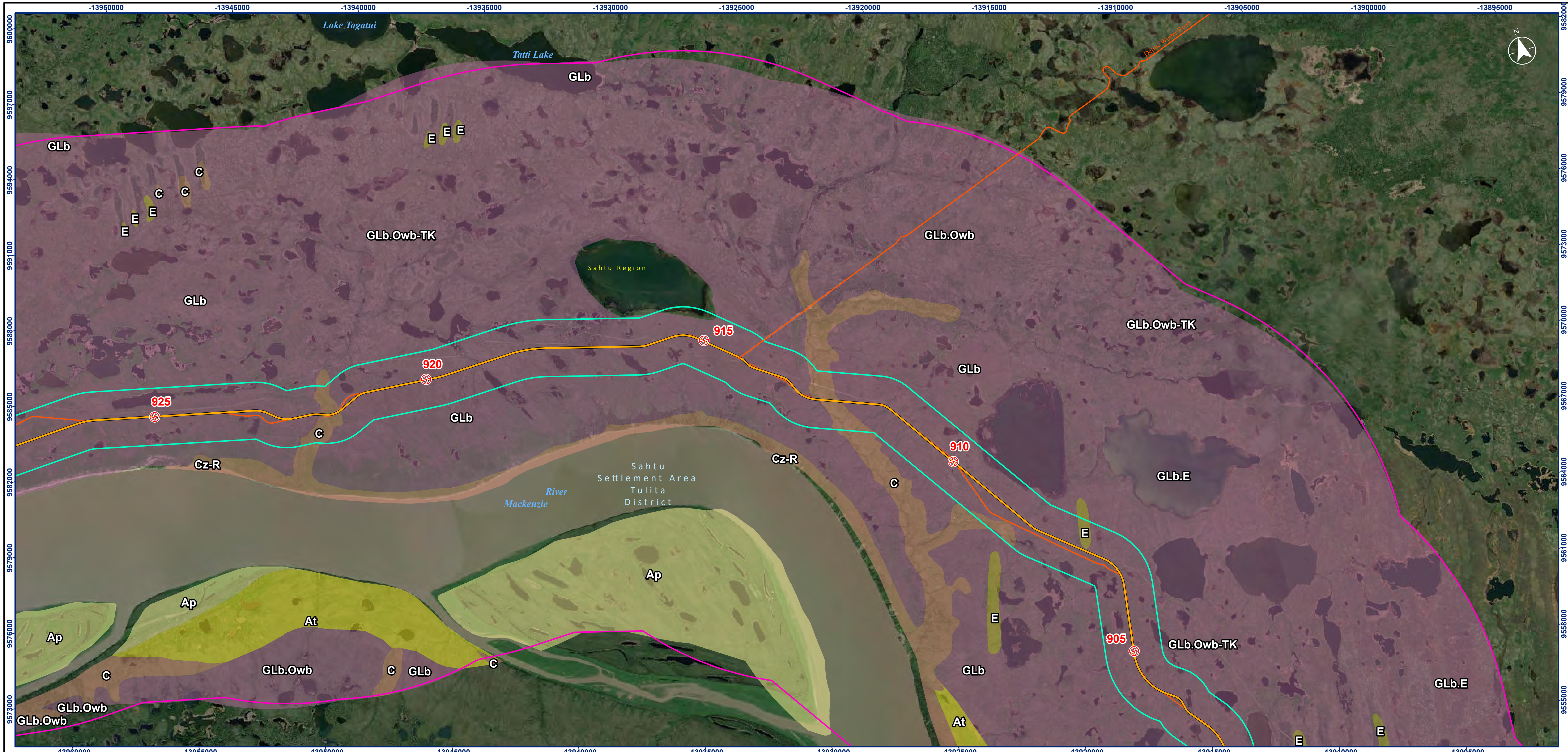
Client/Project
144903025-0020 REVB

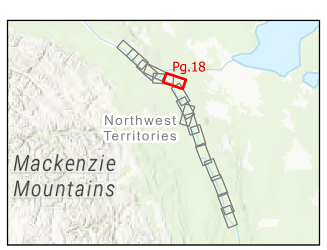
Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.17

Title
RSA Surficial Geology

Notes
1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada
3. Background: World Topographic Map: Northwest Territories, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Terrain mapping was compiled and modified based on a series of maps including OpenFile 7289 - middle east section from Côté et al. (2013), maps 371 and 375 from GSC (2019), and MGAR and Great bear prohibition mapping from G.V.M. Geological Consultant Ltd. (2016, 2019)





Surficial Geology

- Af: Alluvial fan
- Ap: Alluvial floodplain sediment
- At: Alluvial terraced sediment
- Av: Alluvial veneer
- C: Colluvial deposit, undfferentiated
- Cv: Colluvial veneer
- Cz: Landslide deposit
- E: Eolian deposit, undifferentiated
- GFf: Glaciofluvial outwash-fan sediment
- GFh: Glaciofluvial hummocky sediment
- GFp: Glaciofluvial outwash-plain sediment
- GFr: Glaciofluvial esker sediment
- GFt: Glaciofluvial terraced sediment
- GFv: Glaciofluvial veneer
- GLb: Glaciolacustrine blanket
- GLh: Glaciolacustrine hummocky sediment
- GLr: Glaciolacustrine beach sediment
- GLv: Glaciolacustrine veneer
- Owb: Bog deposit
- Owf: Fen deposit
- R1: Sedimentary bedrock
- Tb: Till blanket
- Th: Hummocky till
- Tp: Till plain (all)
- Ts: Streamlined till
- Tv: Till veneer
- Mackenzie Valley Highway Kilometre Post

- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Local Study Area
- Regional Study Area
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- Granular Borrow / Rock Quarry Site and Access
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

Geomorphological Process

R: Mass movement
TK: Thermokarst
V: Gullied

Example of terrain map unit symbol

Dominant surficial material and surface expression: Alluvial fan ⟹ AF/Tp - TK ⟸ Geomorphological process: Thermokarst (TK)

Dominant subsurface material and expression: till (M); plain (p)

Complex units
Two map-unit designators separated by a dot (.) are used where the surficial cover forms a complex area and the units are too small to be mapped individually (e.g. Ap.C designates an area of alluvial plain sediments with colluvial deposits).

Stratigraphic relationship
Two map-unit designators separated by a slash (/) are used where the stratigraphic relationship is observed or confidently inferred (e.g. GLv/T indicates glaciolacustrine veneer overlying till.)

0 1 2 Kilometres
1:70,000 (at original document size of 11x17)

Kálo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 2023-03-20
TR by AJ on 2023-03-20

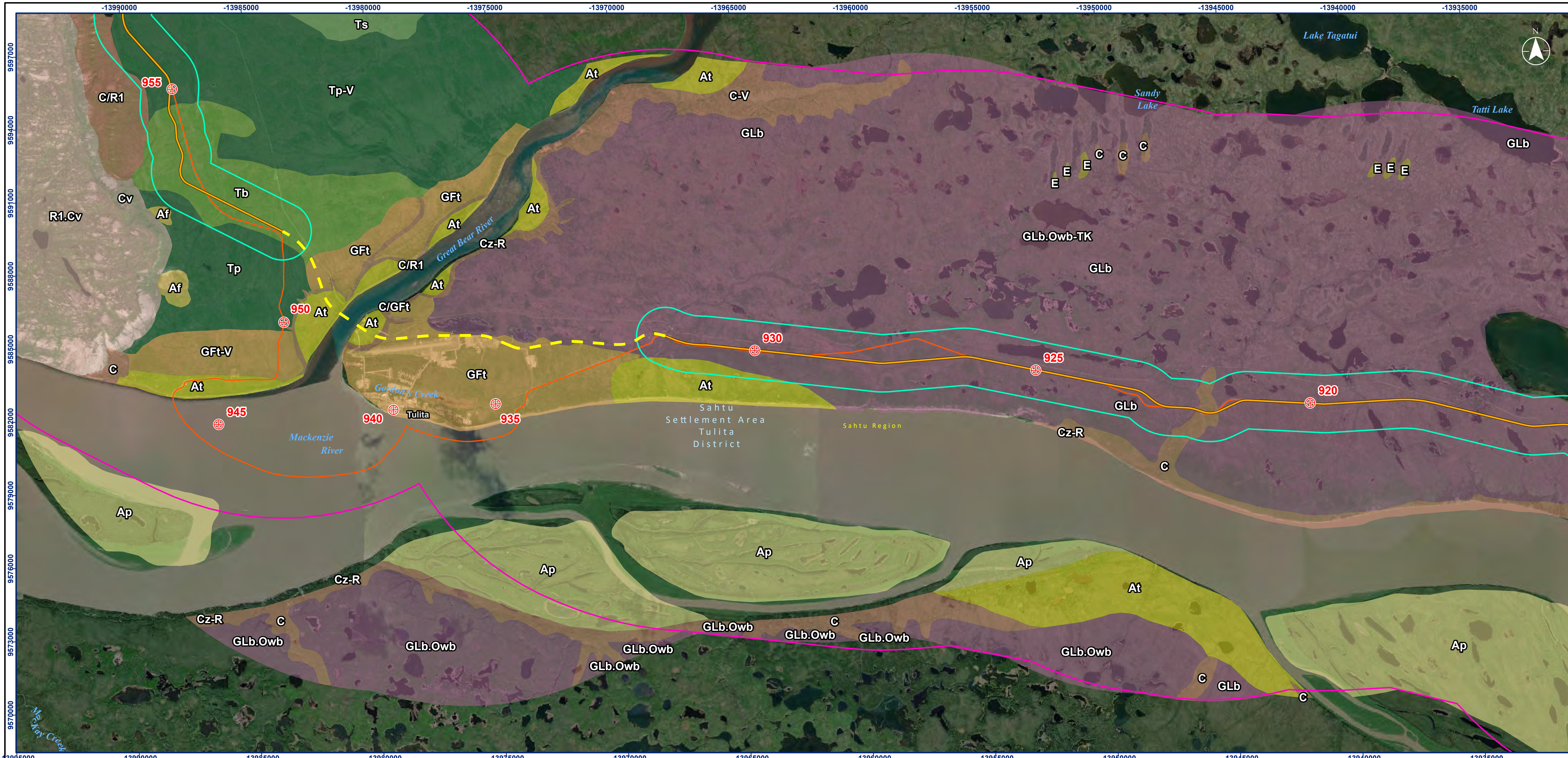
Client/Project
144903025-0020 REVB

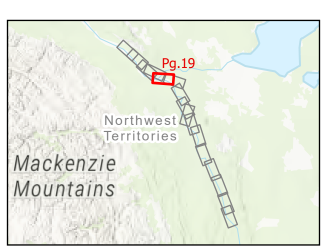
Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.18

Title
RSA Surficial Geology

Notes
1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada
3. Background: World Topographic Map: Northwest Territories, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Terrain mapping was compiled and modified based on a series of maps including OpenFile 7289 - middle east section from Côté et al. (2013), maps 371 and 375 from GSC (2019), and MGAR and Great bear prohibition mapping from G.V.M. Geological Consultant Ltd. (2016, 2019)





Surficial Geology

- Af: Alluvial fan
- Ap: Alluvial floodplain sediment
- At: Alluvial terraced sediment
- Av: Alluvial veneer
- C: Colluvial deposit, undfferentiated
- Cv: Colluvial veneer
- Cz: Landslide deposit
- E: Eolian deposit, undifferentiated
- GFf: Glaciofluvial outwash-fan sediment
- GFh: Glaciofluvial hummocky sediment
- GFp: Glaciofluvial outwash-plain sediment
- GFr: Glaciofluvial esker sediment
- GFt: Glaciofluvial terraced sediment
- GFv: Glaciofluvial veneer
- GLb: Glaciolacustrine blanket
- GLh: Glaciolacustrine hummocky sediment
- GLr: Glaciolacustrine beach sediment
- GLv: Glaciolacustrine veneer
- Owb: Bog deposit
- Owf: Fen deposit
- R1: Sedimentary bedrock
- Tb: Till blanket
- Th: Hummocky till
- Tp: Till plain (all)
- Ts: Streamlined till
- Tv: Till veneer
- Mackenzie Valley Highway Kilometre Post
- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Local Study Area
- Regional Study Area
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- Granular Borrow / Rock Quarry Site and Access
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

Geomorphological Process
R: Mass movement
TK: Thermokarst
V: Gullied

Example of terrain map unit symbol

Dominant surficial material and surface expression: Alluvial fan ⟹ AF/Tp - TK ⟸ Geomorphological process: Thermokarst (TK)

Dominant subsurface material and expression: till (M); plain (p)

Complex units
Two map-unit designators separated by a dot (.) are used where the surficial cover forms a complex area and the units are too small to be mapped individually (e.g. Ap.C designates an area of alluvial plain sediments with colluvial deposits).

Stratigraphic relationship
Two map-unit designators separated by a slash (/) are used where the stratigraphic relationship is observed or confidently inferred (e.g. GLv/T indicates glaciolacustrine veneer overlying till.)

0 1 2 Kilometres
1:70,000 (at original document size of 11x17)

Kálo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 2023-03-20
TR by AJ on 2023-03-20

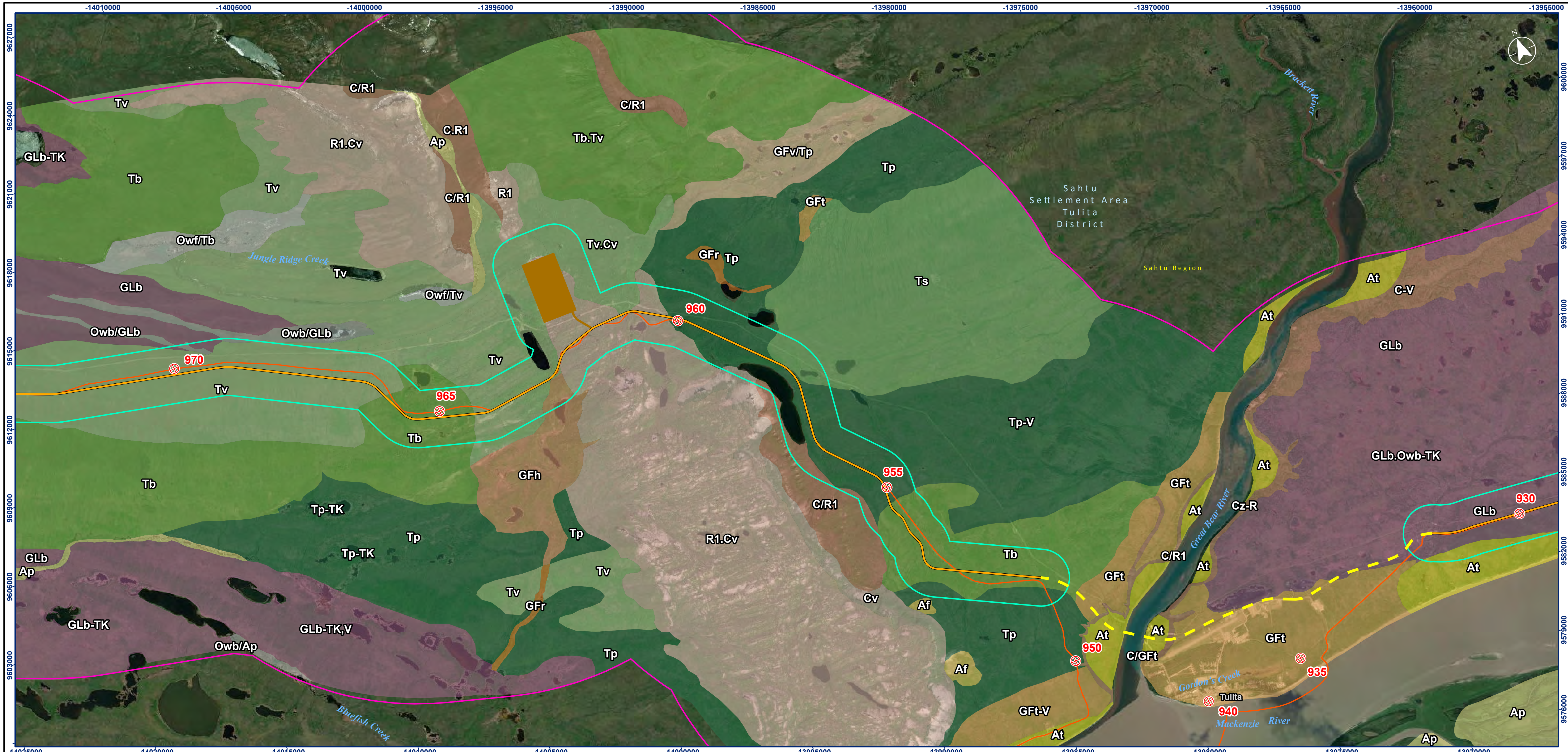
Client/Project
144903025-0020 REVB

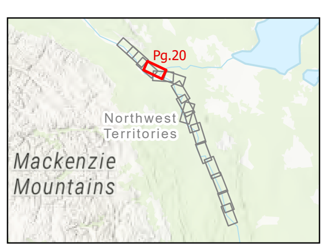
Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.19

Title
RSA Surficial Geology

Notes
1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada
3. Background: World Topographic Map: Northwest Territories, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Terrain mapping was compiled and modified based on a series of maps including OpenFile 7289 - middle east section from Côté et al. (2013), maps 371 and 375 from GSC (2019), and MGAR and Great bear prohibition mapping from G.V.M. Geological Consultant Ltd. (2016, 2019)





Surficial Geology

- Af: Alluvial fan
- Ap: Alluvial floodplain sediment
- At: Alluvial terraced sediment
- Av: Alluvial veneer
- C: Colluvial deposit, undfferentiated
- Cv: Colluvial veneer
- Cz: Landslide deposit
- E: Eolian deposit, undifferentiated
- GFf: Glaciofluvial outwash-fan sediment
- GFh: Glaciofluvial hummocky sediment
- GFp: Glaciofluvial outwash-plain sediment
- GFr: Glaciofluvial esker sediment
- GFt: Glaciofluvial terraced sediment
- GFv: Glaciofluvial veneer
- GLb: Glaciolacustrine blanket
- GLh: Glaciolacustrine hummocky sediment
- GLr: Glaciolacustrine beach sediment
- GLv: Glaciolacustrine veneer
- Owb: Bog deposit
- Owf: Fen deposit
- R1: Sedimentary bedrock
- Tb: Till blanket
- Th: Hummocky till
- Tp: Till plain (all)
- Ts: Streamlined till
- Tv: Till veneer
- Mackenzie Valley Highway Kilometre Post

- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Local Study Area
- Regional Study Area
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- Granular Borrow / Rock Quarry Site and Access
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

Geomorphological Process

R: Mass movement
TK: Thermokarst
V: Gullied

Example of terrain map unit symbol

Dominant surficial material and surface expression: Alluvial fan ⟹ AF/Tp - TK ⟸ Geomorphological process: Thermokarst (TK)

Dominant subsurface material and expression: till (M); plain (p)

Complex units
Two map-unit designators separated by a dot (.) are used where the surficial cover forms a complex area and the units are too small to be mapped individually (e.g. Ap.C designates an area of alluvial plain sediments with colluvial deposits).

Stratigraphic relationship
Two map-unit designators separated by a slash (/) are used where the stratigraphic relationship is observed or confidently inferred (e.g. GLv/T indicates glaciolacustrine veneer overlying till.)

0 1 2 Kilometres
1:70,000 (at original document size of 11x17)

Kålo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 2023-03-20
TR by AJ on 2023-03-20

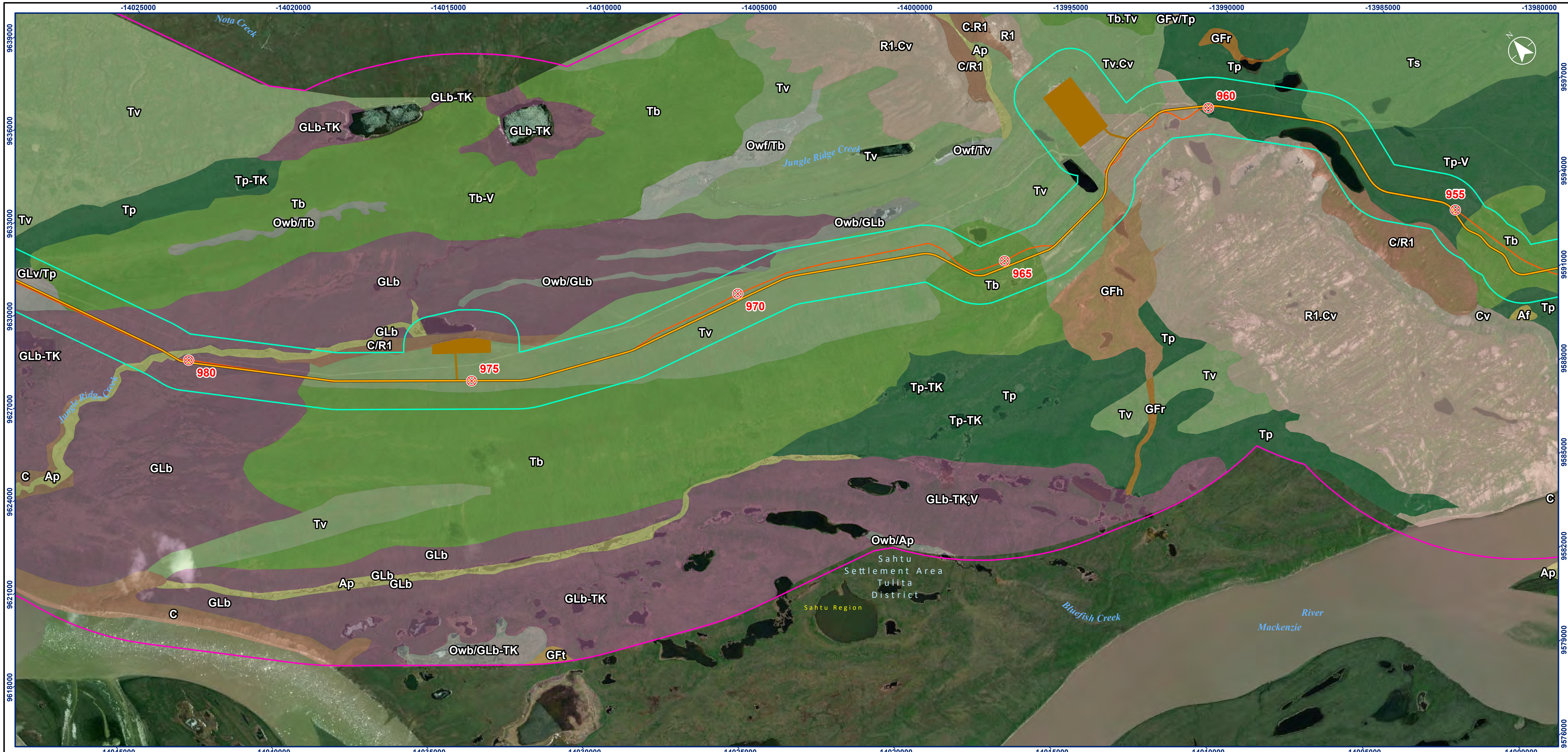
Client/Project
144903025-0020 REVB

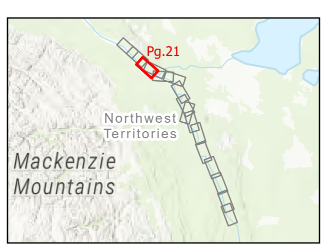
Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.20

Title
RSA Surficial Geology

Notes
1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada
3. Background: World Topographic Map: Northwest Territories, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Terrain mapping was compiled and modified based on a series of maps including OpenFile 7289 - middle east section from Côté et al. (2013), maps 371 and 375 from GSC (2019), and MGAR and Great bear prohibition mapping from G.V.M. Geological Consultant Ltd. (2016, 2019)





Surficial Geology

- Af: Alluvial fan
- Ap: Alluvial floodplain sediment
- At: Alluvial terraced sediment
- Av: Alluvial veneer
- C: Colluvial deposit, undfferentiated
- Cv: Colluvial veneer
- Cz: Landslide deposit
- E: Eolian deposit, undifferentiated
- GFf: Glaciofluvial outwash-fan sediment
- GFh: Glaciofluvial hummocky sediment
- GFp: Glaciofluvial outwash-plain sediment
- GFr: Glaciofluvial esker sediment
- GFt: Glaciofluvial terraced sediment
- GFv: Glaciofluvial veneer
- GLb: Glaciolacustrine blanket
- GLh: Glaciolacustrine hummocky sediment
- GLr: Glaciolacustrine beach sediment
- GLv: Glaciolacustrine veneer
- Owb: Bog deposit
- Owf: Fen deposit
- R1: Sedimentary bedrock
- Tb: Till blanket
- Th: Hummocky till
- Tp: Till plain (all)
- Ts: Streamlined till
- Tv: Till veneer
- Mackenzie Valley Highway Kilometre Post

- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Local Study Area
- Regional Study Area
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- Granular Borrow / Rock Quarry Site and Access
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

Geomorphological Process

R: Mass movement
TK: Thermokarst
V: Gullied

Example of terrain map unit symbol

Dominant surficial material and surface expression: Alluvial fan ⟹ AF/Tp - TK ⟸ Geomorphological process: Thermokarst (TK)

Dominant subsurface material and expression: till (M); plain (p)

Complex units
Two map-unit designators separated by a dot (.) are used where the surficial cover forms a complex area and the units are too small to be mapped individually (e.g. Ap.C designates an area of alluvial plain sediments with colluvial deposits).

Stratigraphic relationship
Two map-unit designators separated by a slash (/) are used where the stratigraphic relationship is observed or confidently inferred (e.g. GLv/T indicates glaciolacustrine veneer overlying till.)

0 1 2 Kilometres
1:70,000 (at original document size of 11x17)

Kálo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 2023-03-20
TR by AJ on 2023-03-20

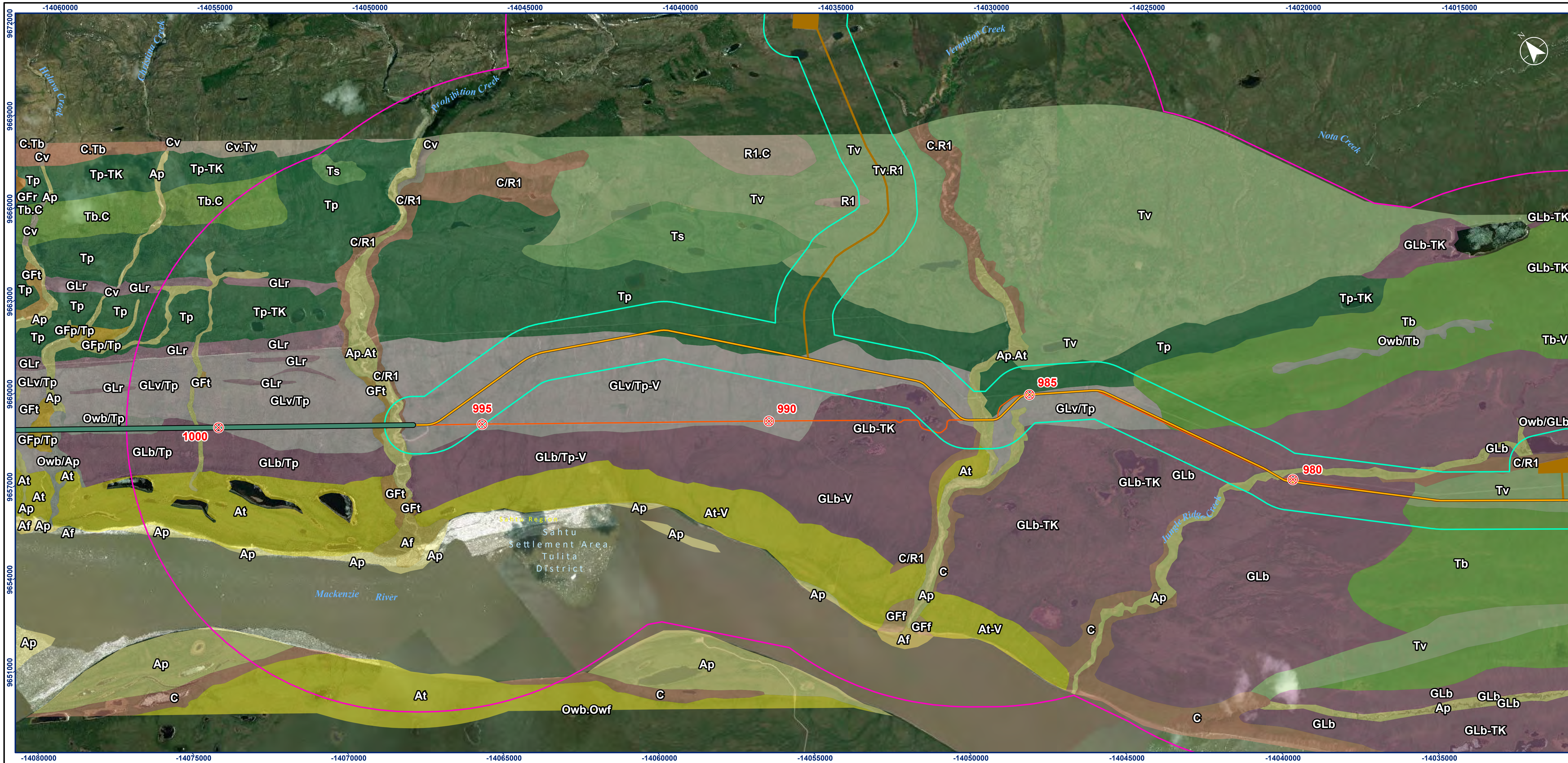
Client/Project
144903025-0020 REVB

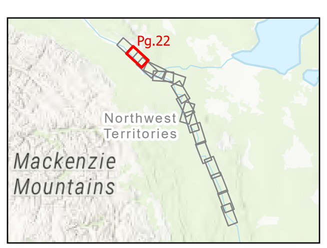
Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.21

Title
RSA Surficial Geology

Notes
1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada
3. Background: World Topographic Map: Northwest Territories, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Terrain mapping was compiled and modified based on a series of maps including OpenFile 7289 - middle east section from Côté et al. (2013), maps 371 and 375 from GSC (2019), and MGAR and Great bear prohibition mapping from G.V.M. Geological Consultant Ltd. (2016, 2019)





Surficial Geology

- Af: Alluvial fan
- Ap: Alluvial floodplain sediment
- At: Alluvial terraced sediment
- Av: Alluvial veneer
- C: Colluvial deposit, undfferentiated
- Cv: Colluvial veneer
- Cz: Landslide deposit
- E: Eolian deposit, undifferentiated
- GFf: Glaciofluvial outwash-fan sediment
- GFh: Glaciofluvial hummocky sediment
- GFp: Glaciofluvial outwash-plain sediment
- GFr: Glaciofluvial esker sediment
- GFt: Glaciofluvial terraced sediment
- GFv: Glaciofluvial veneer
- GLb: Glaciolacustrine blanket
- GLh: Glaciolacustrine hummocky sediment
- GLr: Glaciolacustrine beach sediment
- GLv: Glaciolacustrine veneer
- Owb: Bog deposit
- Owf: Fen deposit
- R1: Sedimentary bedrock
- Tb: Till blanket
- Th: Hummocky till
- Tp: Till plain (all)
- Ts: Streamlined till
- Tv: Till veneer
- Mackenzie Valley Highway Kilometre Post

- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Local Study Area
- Regional Study Area
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- Granular Borrow / Rock Quarry Site and Access
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

Geomorphological Process

R: Mass movement
TK: Thermokarst
V: Gullied

Example of terrain map unit symbol

Dominant surficial material and surface expression: Alluvial fan ⟹ AF/Tp - TK ⟸ Geomorphological process: Thermokarst (TK)

Dominant subsurface material and expression: till (M); plain (p)

Complex units
Two map-unit designators separated by a dot (.) are used where the surficial cover forms a complex area and the units are too small to be mapped individually (e.g. Ap.C designates an area of alluvial plain sediments with colluvial deposits).

Stratigraphic relationship
Two map-unit designators separated by a slash (/) are used where the stratigraphic relationship is observed or confidently inferred (e.g. GLv/T indicates glaciolacustrine veneer overlying till.)

0 1 2 Kilometres
1:70,000 (at original document size of 11x17)

Kálo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 2023-03-20
TR by AJ on 2023-03-20

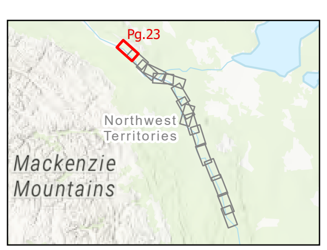
Client/Project
144903025-0020 REVB

Government of Northwest Territories
Mackenzie Valley Highway Project

Figure No.
A.22

Title
RSA Surficial Geology

Notes
1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada
3. Background: World Topographic Map: Northwest Territories, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Terrain mapping was compiled and modified based on a series of maps including OpenFile 7289 - middle east section from Côté et al. (2013), maps 371 and 375 from GSC (2019), and MGAR and Great bear prohibition mapping from G.V.M. Geological Consultant Ltd. (2016, 2019)



Surficial Geology

- Af: Alluvial fan
- Ap: Alluvial floodplain sediment
- At: Alluvial terraced sediment
- Av: Alluvial veneer
- C: Colluvial deposit, undfferentiated
- Cv: Colluvial veneer
- Cz: Landslide deposit
- E: Eolian deposit, undifferentiated
- GFf: Glaciofluvial outwash-fan sediment
- GFh: Glaciofluvial hummocky sediment
- GFp: Glaciofluvial outwash-plain sediment
- GFr: Glaciofluvial esker sediment
- GFt: Glaciofluvial terraced sediment
- GFv: Glaciofluvial veneer
- GLb: Glaciolacustrine blanket
- GLh: Glaciolacustrine hummocky sediment
- GLr: Glaciolacustrine beach sediment
- GLv: Glaciolacustrine veneer
- Owb: Bog deposit
- Owf: Fen deposit
- R1: Sedimentary bedrock
- Tb: Till blanket
- Th: Hummocky till
- Tp: Till plain (all)
- Ts: Streamlined till
- Tv: Till veneer
- Mackenzie Valley Highway Kilometre Post

- Proposed Mackenzie Valley Highway Alignment - Issued for EA 2022
- Local Study Area
- Regional Study Area
- Canyon Creek All Season Access Road
- Prohibition Creek Access Road
- Proposed Great Bear River Bridge Project
- Granular Borrow / Rock Quarry Site and Access
- All-Season Road
- Winter Road
- District Boundary
- Region Boundary
- Settlement Area Boundary

Geomorphological Process

R: Mass movement
TK: Thermokarst
V: Gullied

Example of terrain map unit symbol

Dominant surficial material and surface expression: Alluvial fan ⟹ AF/Tp - TK ⟸ Geomorphological process: Thermokarst (TK)

Dominant subsurface material and expression: till (M); plain (p)

Complex units
Two map-unit designators separated by a dot (.) are used where the surficial cover forms a complex area and the units are too small to be mapped individually (e.g. Ap.C designates an area of alluvial plain sediments with colluvial deposits).

Stratigraphic relationship
Two map-unit designators separated by a slash (/) are used where the stratigraphic relationship is observed or confidently inferred (e.g. GLv/T indicates glaciolacustrine veneer overlying till.)

0 1 2 Kilometres
1:70,000 (at original document size of 11x17)

Kálo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by AT on 2023-03-20
TR by AJ on 2023-03-20

Client/Project
144903025-0020 REVB

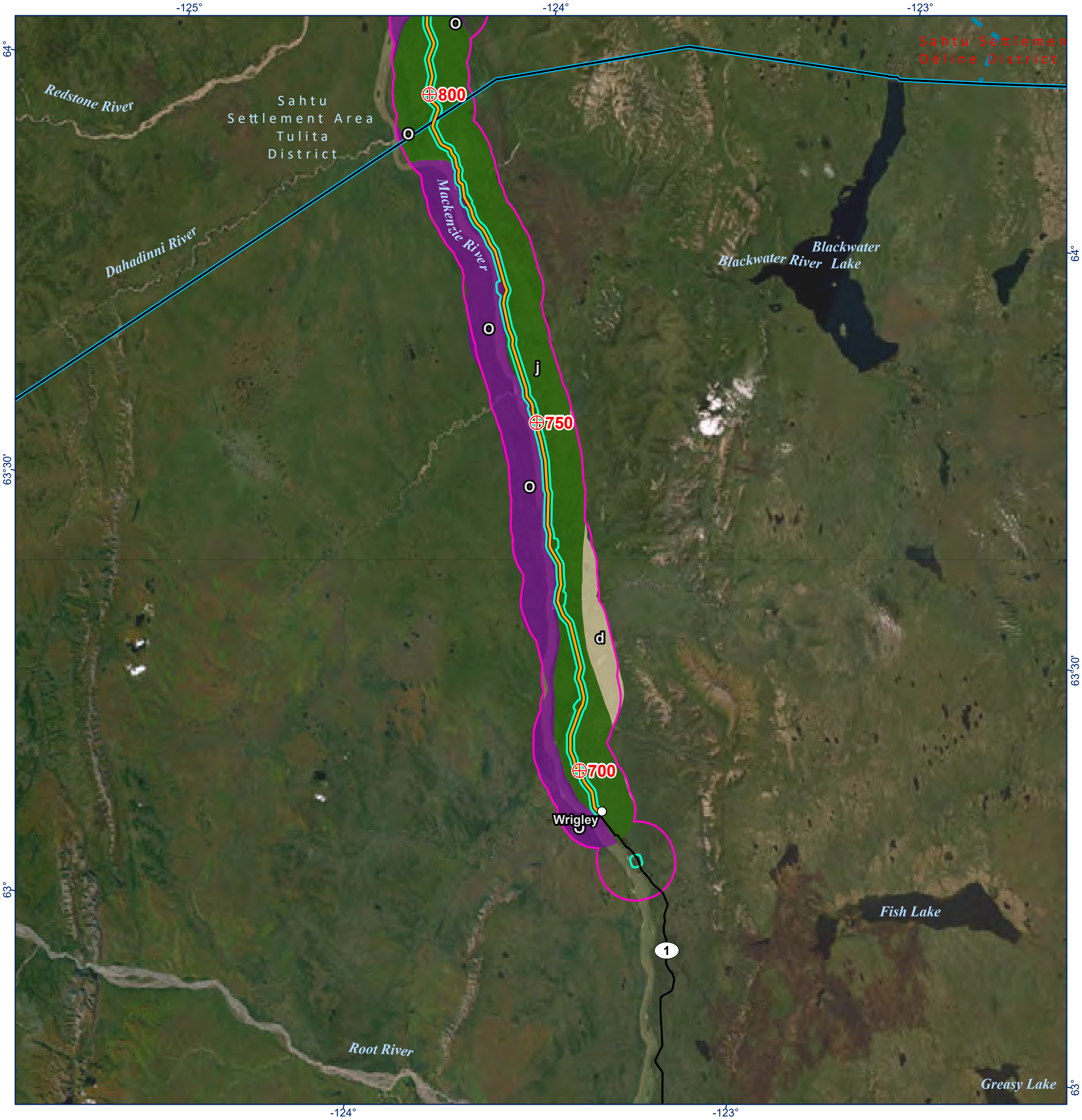
Government of Northwest Territories
Mackenzie Valley Highway Project

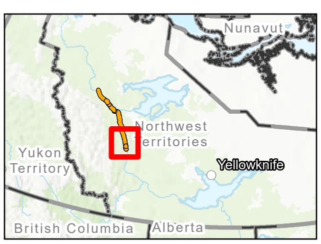
Figure No.
A.23

Title
RSA Surficial Geology

Notes

1. Coordinate System: NAD 1983 UTM Zone 10N
2. Data Sources: Government of Canada
3. Background: World Topographic Map: Northwest Territories, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NRCan, Parks Canada
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Terrain mapping was compiled and modified based on a series of maps including OpenFile 7289 - middle east section from Côté et al. (2013), maps 371 and 375 from GSC (2019), and MGAR and Great bear prohibition mapping from G.V.M. Geological Consultant Ltd. (2016, 2019)





Soil Classification

- d: Brunisolic Turbic Cryosol
- j: Gleysolic Static Cryosol
- O: Organic Cryosol
- Mackenzie Valley Highway Kilometre Post
- Mackenzie Valley Highway Extension Project
- Local Study Area
- Regional Study Area
- Community
- All-Season Road
- District Boundary
- Settlement Area Boundary

0 10 20 Kilometres

(At original document size of 8.5x11)
1:800,000

N

Kalo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by ZN on 2020-10-25
TR by CS on 2020-12-01

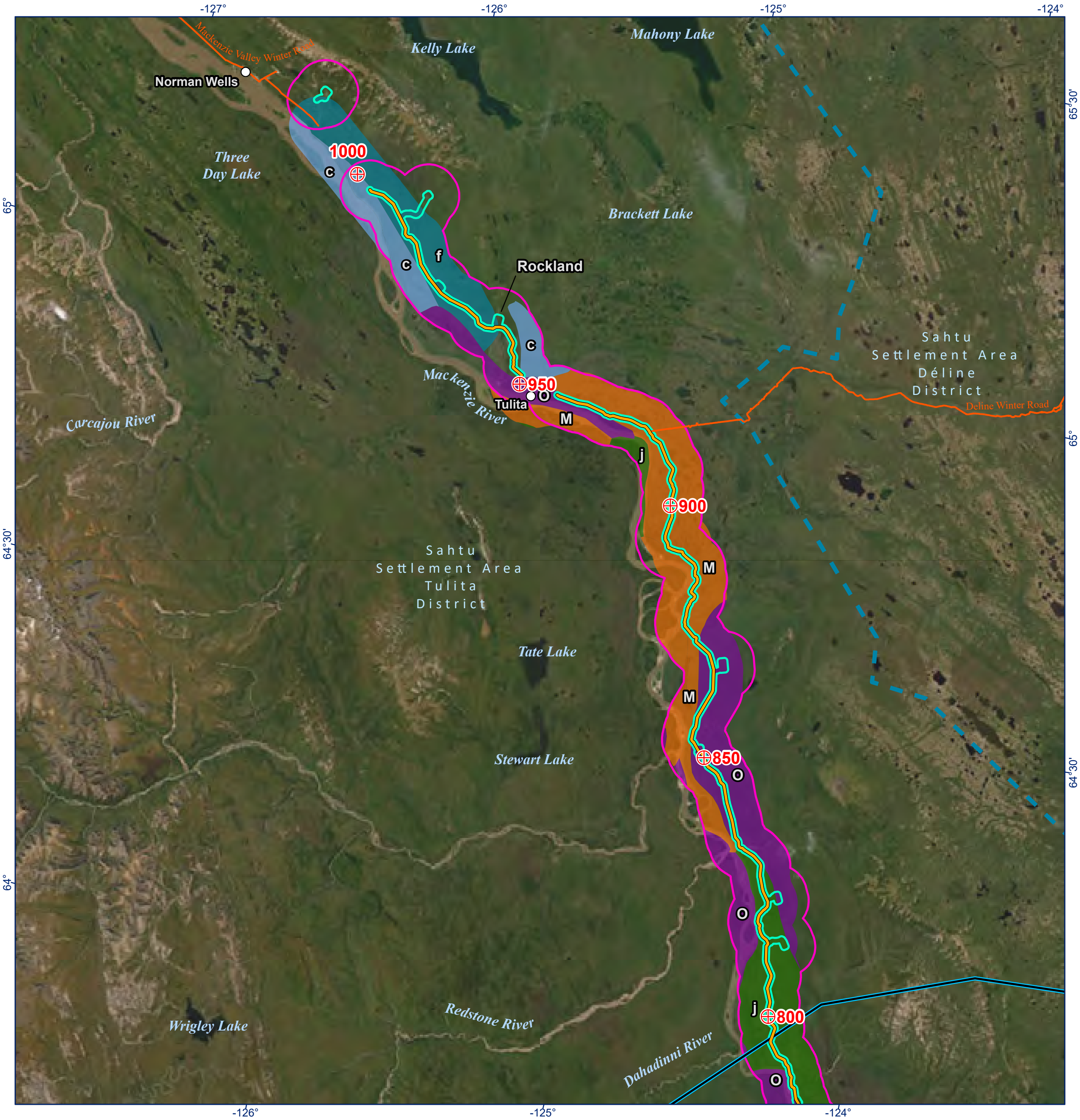
Client/Project
144903025-0028 REVA

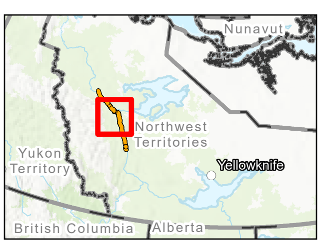
Government of Northwest Territories
Mackenzie Valley Highway

Figure No.
A.24

Title
RSA Soils

Notes
1. Coordinate System: NAD 1983 Northwest Territories Lambert
2. Data Sources: Centre of Geomatics of Government of NWT, Government of Canada, Stantec
3. Background: World Topographic Map: Esri, FAO, NOAA, USGS, NRCan
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Soil Mapping: National Soil DataBase, Agriculture and Agri-Food Canada (1996)





Soil Classification

- M: Eutric Brunisol
- j: Gleysolic Static Cryosol
- f: Gleysolic Turbic Cryosol
- O: Organic Cryosol
- c: Orthic Turbic Cryosol
- Mackenzie Valley Highway Kilometre Post

- Mackenzie Valley Highway Extension Project
- Local Study Area
- Regional Study Area
- Community
- Winter Road
- District Boundary
- Settlement Area Boundary

0 10 20 Kilometres

(At original document size of 8.5x11)
1:1,000,000

N

Kálo-Stantec

Project Location
Wrigley to Norman Wells, NWT

Prepared by ZN on 2020-10-25
TR by CS on 2021-03-31

Client/Project
144903025-0027 REVA

Government of Northwest Territories
Mackenzie Valley Highway

Figure No.
A.25

Title
RSA Soils

Notes

1. Coordinate System: NAD 1983 Northwest Territories Lambert
2. Data Sources: Centre of Geomatics of Government of NWT, Government of Canada, Stantec
3. Background: World Topographic Map: Esri, FAO, NOAA, USGS, NRCan
World Imagery: Earthstar Geographics
World Hillshade: Esri, USGS
4. Soil Mapping: National Soil DataBase, Agriculture and Agri-Food Canada (1996)