AER/AGS Open File Report 2023-05

Revised Bedrock Topography and Stratigraphy Above Bedrock in the South Athabasca Oil Sands (SAOS) Region, Northeastern Alberta

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Contents

Tables

Figures

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Abstract

This report summarizes studies related to updating the bedrock topography and the stratigraphy of the sediment units above bedrock in the South Athabasca Oil Sands region. Beneath the uplands in the study area, deep preglacial valleys are buried by hundreds of metres of a succession of multiple till, lacustrine, and fluvial deposits. The deposits at the base of the buried valleys are from the Ipiatik Formation of the Empress Group. These include the preglacial basal gravels of the House Member, which are capped by glaciolacustrine deposits of the Wappau Member followed by the glaciofluvial deposits of the Calder Member. On a higher level are the glaciofluvial deposits of the Winefred Formation. The Ipiatik and Winefred formations are buried by the reversely magnetized Bronson Lake Formation till. Above this is the fluvial Muriel Lake Formation, which is then overlain by Bonnyville Formation units 1 and 2, which are tills that in places have an intervening sand deposit. The Ethel Lake Formation, a glaciolacustrine and glaciofluvial package, rests on the Bonnyville Formation, likely where there were low spots in the preglacial topography. The Marie Creek, Sand River, and Grand Centre formations cap the succession, but these were not differentiated in this study due to limited data. The lowland areas are covered by relatively thin till deposits, with at least one subglacial channel, the Gregoire, incised deeply into the bedrock in the northeast of the study area, as well as the north and south Hangingstone channels north of the Stony Mountain Upland. This report includes a description of the cores and borehole data used to make picks on geophysical logs from oil and gas wells over the area.

1 Introduction

This report provides a summary of the investigations into updating the bedrock topography and stratigraphy above bedrock in the South Athabasca Oil Sands (SAOS) region. Since the previous Alberta Geological Survey (AGS) studies in the region (Parks and Andriashek, 2002; Andriashek, 2003), industry has undertaken extensive seismic surveys and drilling, along with the collection of geophysical log data and cores. This increase in available data and industry activity in the region warranted an update to the stratigraphic framework.

This report outlines the changes and modifications to the bedrock topography (Utting and Pawley, 2021) and stratigraphy above bedrock (Utting, 2021a), and provides a description of the data sources used to make these updates. In this report, there is also an outline of how these units relate to the Quaternary stratigraphic domains of Utting (2021b). Although the original work was found to be generally consistent with the new data, there were some updates and refinements, which are outlined in this report.

2 Study Area

2.1 Physiography

The South Athabasca Oil Sands (SAOS) region is a 34 000 km^2 area south of the Clearwater River and north of the Cold Lake Oil Sands Area (Figure 1). The eastern and western boundaries are the Saskatchewan border and along the Athabasca River, respectively. The area includes the Mostoos Upland, Crow Lake Upland, and May Hills, the last two of which combine to make up the Stony Mountain Upland (Figure 1; Pettapiece, 1986). Surrounding these uplands are lowlands, including the Algar, Brulé, Christina Lake, Dover, Garson, Owl River, Steepbank, Wabasca, and Wandering River plains.

2.2 Bedrock Geology

The types of bedrock units that outcrop and subcrop in the study area (Figure 2) are dependent on the amount of incision and erosion that occurred during the formation of buried valleys and are thus particularly relevant to this study. At the base of the succession in the study area are metamorphic and igneous rocks of Precambrian age (Figure 2). Overlying the Precambrian basement are Devonian strata, which dip to the southwest; neither of these rock units subcrop in the study area.

Resting on the Devonian units are the Cretaceous Mannville and Colorado groups. The lowest unit in Mannville Group is the McMurray Formation, which is overlain by the Wabiskaw Member of the Clearwater Formation (Figure 2). Combined, the sandstone-dominated Wabiskaw-McMurray deposit is a significant regional aquifer. This aquifer is overlain by the upper portion of the Clearwater Formation, which is shale dominated and acts as an aquitard. The Clearwater Formation is, in turn, overlain by the Grand Rapids Formation (interbedded siltstone and shale), which outcrops in the Athabasca and Clearwater river valleys.

The Grand Rapids Formation is overlain by the Colorado Group, of which the lowest unit is the Joli Fou Formation (Figure 2). This formation subcrops along the northern end of the Stony Mountain Upland and is overlain by the Pelican (Viking) Formation, which subcrops near the Christina River, as well as within some of the major buried valleys. The Pelican (Viking) Formation acts as an aquifer, and potentially contains natural gas. This formation is overlain by a shale dominated succession comprising the Westgate, Fish Scales, Belle Fourche, Second White Specks, Carlile, Niobrara, Lea Park, and Wapiti formations, which act as aquitards. The Westgate, Fish Scales, Belle Fourche, Second White Specks, Carlile, Niobrara, and Lea Park formations were previously referred to as the Labiche Formation (Glass, 1990; Hay et al., 2012).

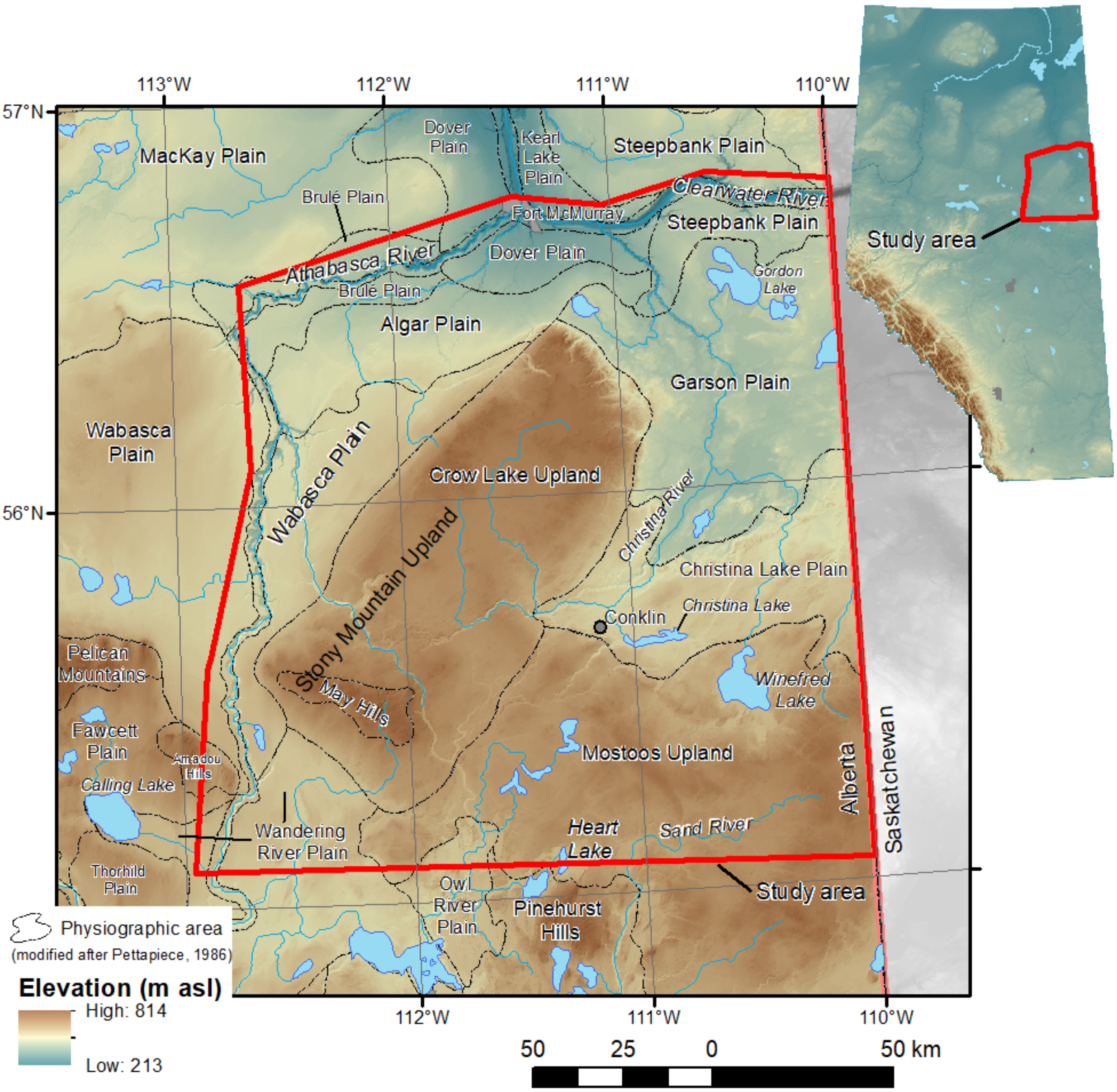

Figure 1. Location and physiography of the South Athabasca Oil Sands region shown on a bare-earth LiDAR (light detection and ranging) digital elevation model image.

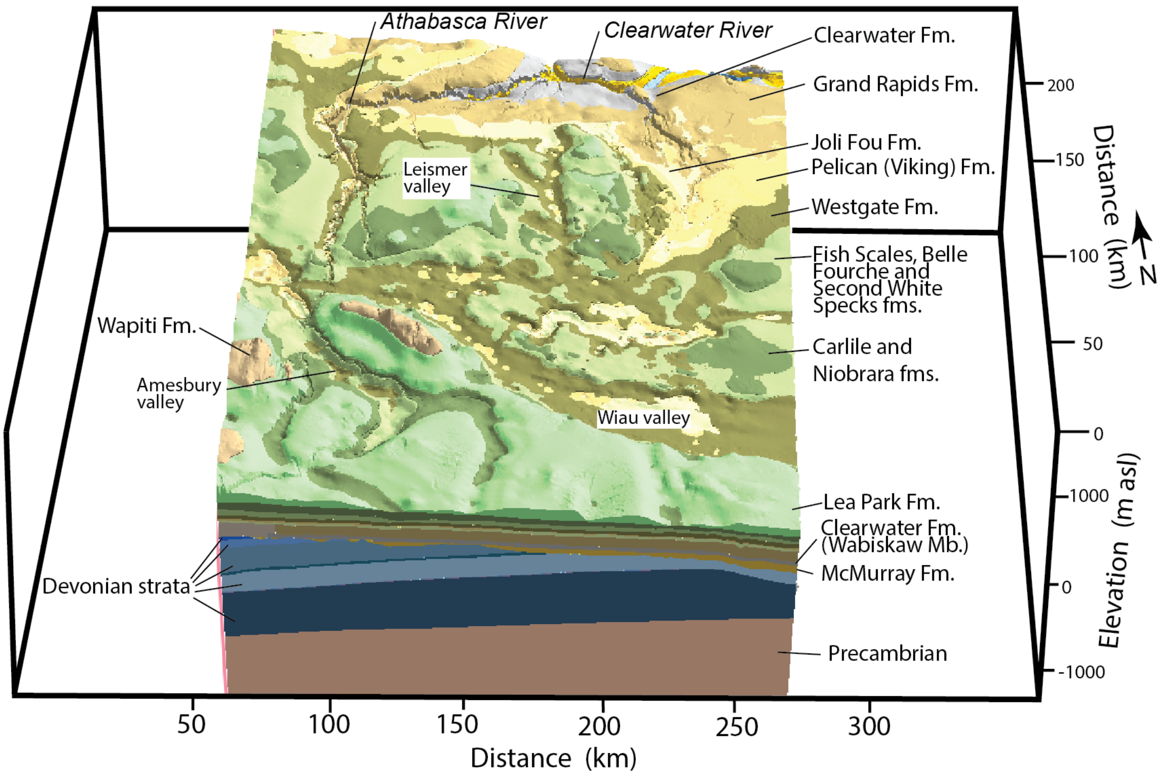

Figure 2. Three-dimensional rendering of the bedrock geology in the South Athabasca Oil Sands region (modified after Alberta Geological Survey, 2019). Sediment units above bedrock are not shown. Vertical exaggeration is 50 times.

3 Bedrock Topography and Sediment Thickness

The bedrock topography and sediment thickness models produced for the study area (Figure 3a and b) were based on a compilation of bedrock depth values (Utting, 2021a). These were picked primarily from oil and gas well logs (n = 7970), but also water well logs (n = 68), geological test hole logs (n = 16), and bedrock outcrops identified during fieldwork (n = 259) or on satellite imagery (n = 175). The picks were complemented by artificial control points (n = 136) inserted to improve the position of buried valleys, as well as control points (n = 222) based on industry seismic data (Devon ARL Corporation, 2006).

The bedrock depth data were used to model the sediment thickness using a machine learning method (summarized in the metadata of Utting and Pawley, 2021). The sediment thickness values in this model, which range from 0 to 340 m, were then subtracted from the elevation values in the present-day surface topography model to derive the bedrock topography model. In general, the bedrock topography of the study area is an inversion of the present-day surface topography. For example, the Wiau valley, a deep and broad buried paleovalley, underlies the Stony Mountain Upland, which is the highest topographic feature on the modern landscape.

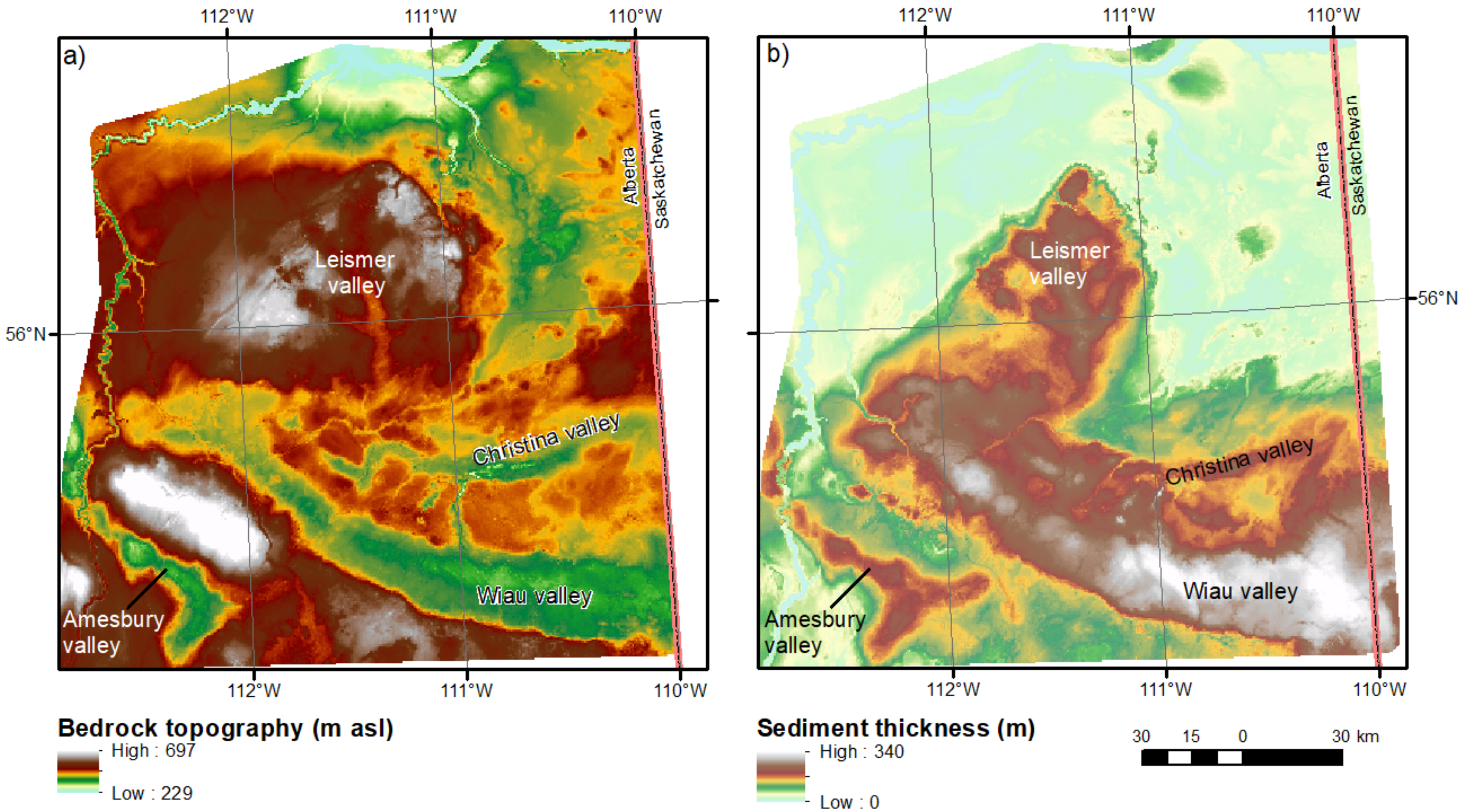

Figure 3. (a) Bedrock topography and (b) sediment thickness of the study area (modified from Utting and Pawley, 2021).

3.1 Buried Valleys and Channels

There are numerous buried valleys and channels, which were incised into the bedrock, in the study area (Figure 4). These are important because they host basal aquifers and influenced deposition of overlying Quaternary units, furthermore, the additional erosion in those areas may have eliminated or reduced caprocks overlying hydrocarbon resources. Buried valleys with broad bases and low gradients (width to depth ratio of up to 250:1) are thought to have a preglacial fluvial origin but may have subsequently been modified by glaciation (Andriashek, 2003). Buried channels with low width to depth ratios may have formed by subglacial meltwater flow (Atkinson et al., 2013). In the study area, the valleys are more numerous and are typically larger than the channels. All or portions of the Wiau, Leismer, Amesbury, Christina, and Imperial Mills valleys and the Kirby, Sunday Creek, and Gregoire channels are located in the study area (Andriashek, 2019), as well as the north and south Hangingstone channels (Athabasca Oil Corporation, 2013).

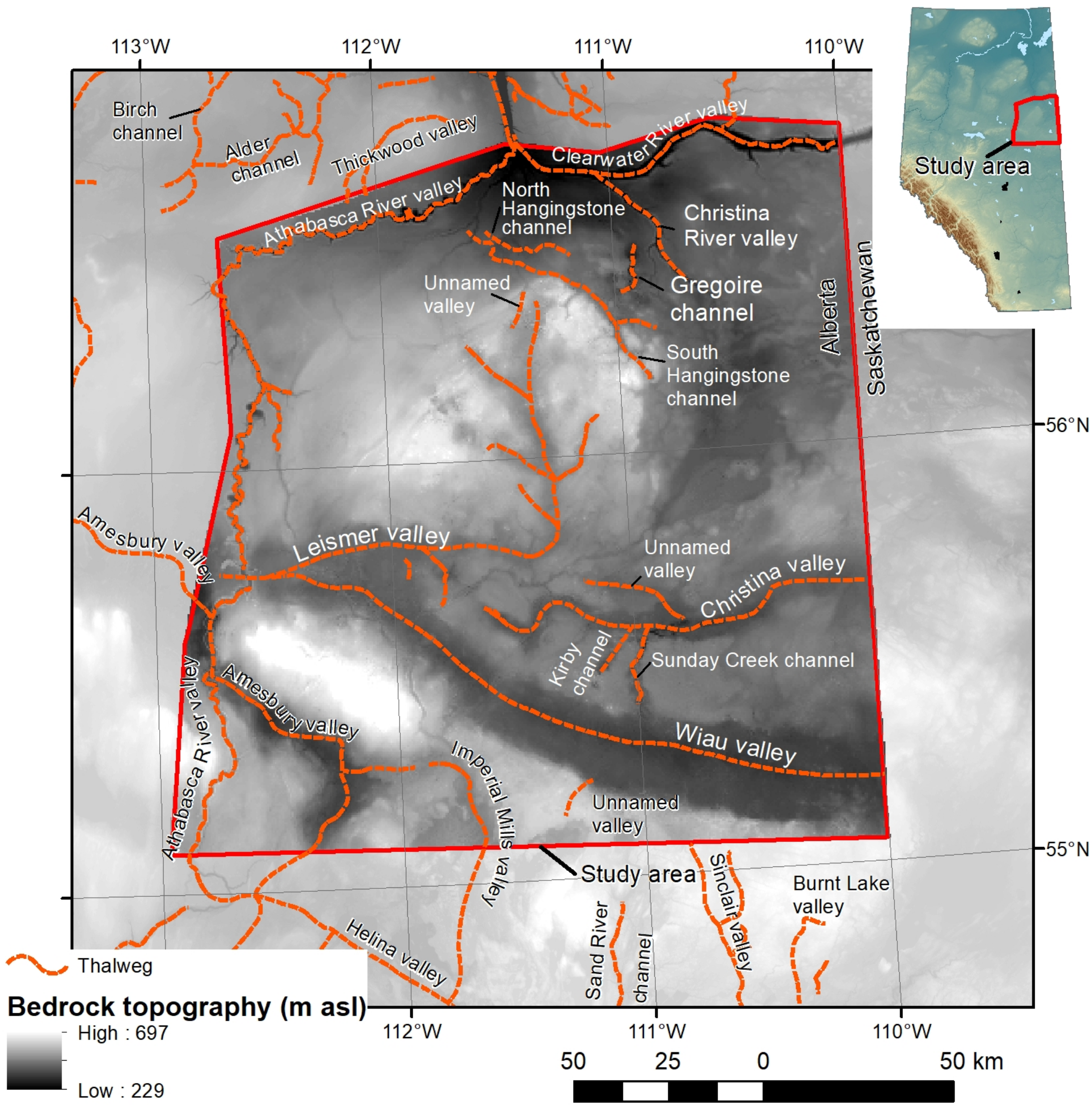

Figure 4. Thalwegs of buried bedrock valleys and channels within the study area (modified from Andriashek, 2019), shown on the bedrock topography. Bedrock valleys are considered preglacial in origin, whereas channels were formed subglacially. The thalweg is the lowest point of these fluvially incised features.

The Wiau valley is the largest buried valley in the province, cutting across the study area from west to east (Figures 3 and 4). It is 180 km long in Alberta and continues into Saskatchewan. It is generally straight and ranges in width from 11 to 36 km, widening towards the east. The base of the valley grades from 440 m asl in the western part of the study area to 400 m asl in the east. The valley was incised approximately 130 m into bedrock and lies more than 300 m beneath the ground surface. The broad and flat base of this buried valley suggests it developed over a long period of time, consistent with a preglacial origin. The preglacial river incised through the Westgate Formation and into the Pelican and Joli Fou formations (Figure 2).

Like the Wiau valley, the Christina valley is also generally oriented west to east but it is more curved (Figures 3 and 4). It starts in the middle of the study area and extends 110 km in Alberta, widening from 4.5 km in the west to 14 km in the east. The elevation of the base of the valley varies from 420 to 440 m asl, although it is not clearly inclined in either a west or east direction. Eastward paleoflow is presumed based upon eastward valley widening. The valley was incised 50–75 m into bedrock and is buried by 140–240 m of sediments. Previously, the western end of this valley was thought to connect to the Wiau valley (Figure 4) but there are no wells, boreholes, or other data near the presumed confluence with which to confirm a connection.

The Kirby channel, which extends for 12–14 km and is 2–3 km wide (Figure 4), was shown by Andriashek (2003) to connect the Christina and Wiau valleys. However, after review of all the data in the presumed confluence area, including seismic data from industry surveys (Devon ARL Corporation, 2006), it is most likely that this channel does not connect to the Wiau valley.

The Sunday Creek channel creates a 20 km long connection between the Wiau and Christina valleys (Figures 3 and 4). It was identified based on three-dimensional (3D) and two-dimensional (2D) seismic survey data and confirmed by well data analysis (Devon ARL Corporation, 2006; Rayner and Rosenthal, 2008). Although the seismic survey data were not available to the author, the channel was added to the bedrock topography model via control points. Consequently, the width, depth, and orientation of the channel, as depicted in the model, are approximate. The Sunday Creek channel may range from 1.5 to 2 km in width, with basal elevations between 440 m asl in the south and 340 m asl in the north.

The Leismer valley is oriented north to south and curves westward near its confluence with the Wiau valley (Figures 3 and 4). This valley has unique morphology for buried valleys in Alberta; a series of five feeder valleys, 10–20 km long, merge with the main 120 km long valley, giving the appearance of a subaerial drainage network. This system underlies approximately 200 m of sediments and was incised 70 m into the bedrock. The valley widens from 2 km at the north end to 5 km where it joins the Wiau valley. The elevation of the base of the valley is approximately 500 m asl at its north end and 440 m asl at its south end, where it is equivalent to the elevation of the base of the Wiau valley.

The Amesbury valley crosses the southwestern part of the study area and extends beyond to the northwest (Figures 3 and 4). The valley is 65 km long and 6–10 km wide in the study area. It was incised 120 m into bedrock and has a base elevation of approximately 400 m asl. Although the Amesbury valley crosses the western end of the Wiau valley, there appears to be no connection between these two valleys based on the 40 m difference in the elevation of the base of these channels. The Imperial Mills valley, however, appears to connect to the Amesbury valley in the southwestern part of the study area (Figure 4). The valley is 30 km long in the study area, 5 km wide (although its boundaries are poorly defined), and was incised 20 m into bedrock.

The Gregoire channel, located on the Garson Plain to the northeast of the Stony Mountain Upland, is oriented generally south to north (Figure 4). Geophysical data (Nexen Inc., 2012) reveal the configuration of the channel, which has incised into the McMurray Formation. The channel was incised 45 m into bedrock and is 13 km long, 0.8–1.3 km wide, and buried beneath 75 m of sediments. Due to its low width to depth ratio, Andriashek (2003) interpreted the channel as being subglacial in origin. This channel is similar to landforms interpreted as subglacial in origin in the area to the north (Atkinson et al., 2013; Utting and Andriashek, 2020).

The north and south Hangingstone channels are, like the Gregoire channel, located on the Garson Plain, but are oriented generally east-west (Figure 4). These channels were outlined using airborne geophysical surveys (Athabasca Oil Corporation, 2013). Although the survey data are not available to the author, the channel thalwegs (Figure 4) were inferred from channel extents reported by Athabasca Oil Corporation (2013) as well as borehole data.

4 Core and Borehole Data

Cores provide valuable information on the subsurface geology and are used as guides for interpreting geology from geophysical logs in adjacent oil and gas wells. Cores examined included seven collected by the AGS in 1999–2000 (previously reported in Andriashek, 2003) as well as three cores more recently collected by industry (Figure 5). In addition, drill cuttings from a borehole drilled through the Gregoire channel were also examined. The key relevant findings from the examination of these cores are summarized herein. Relevant additional work on the AGS cores described by Andriashek and Barendregt (2016, 2017) is also included.

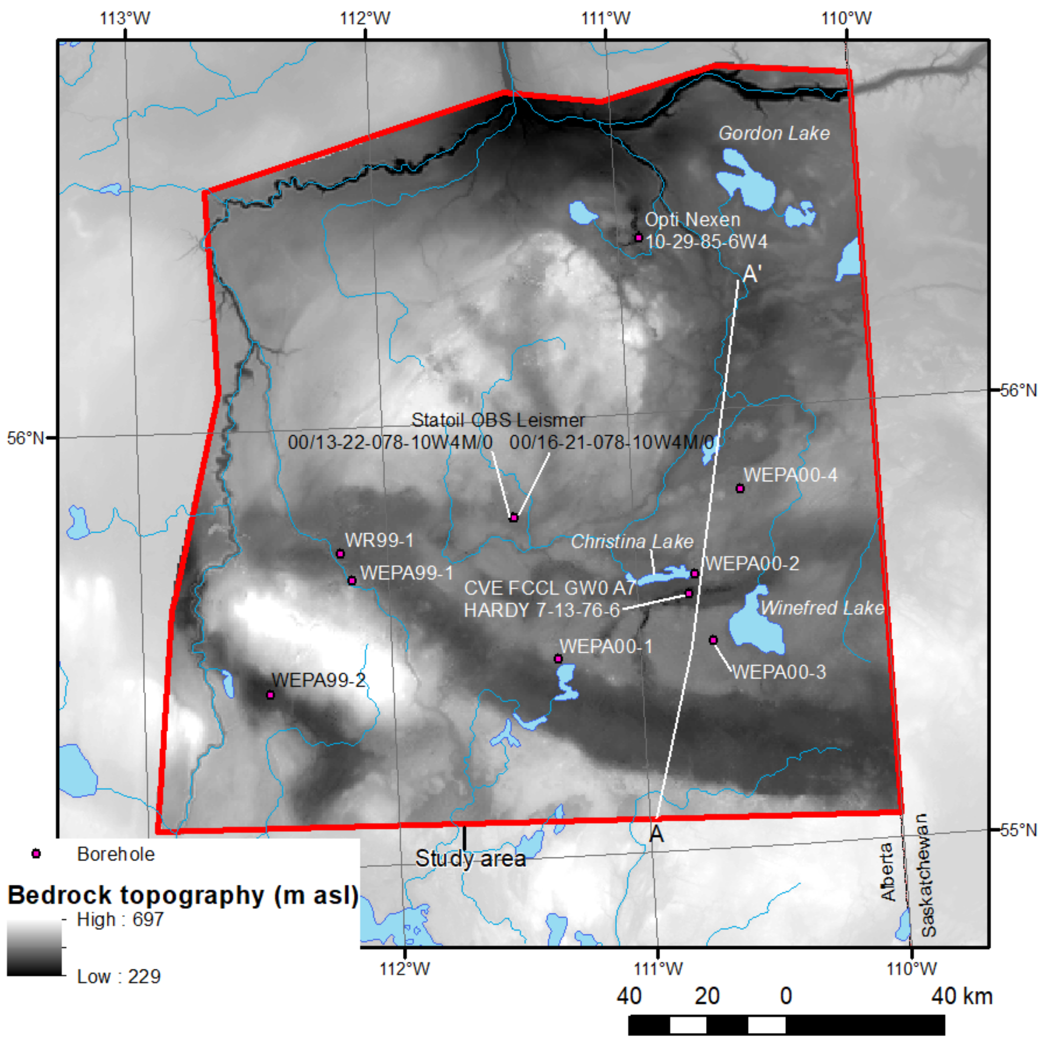

Figure 5. Locations of boreholes described in this study, and the location of the cross-section (A–A′) shown in Figure 6.

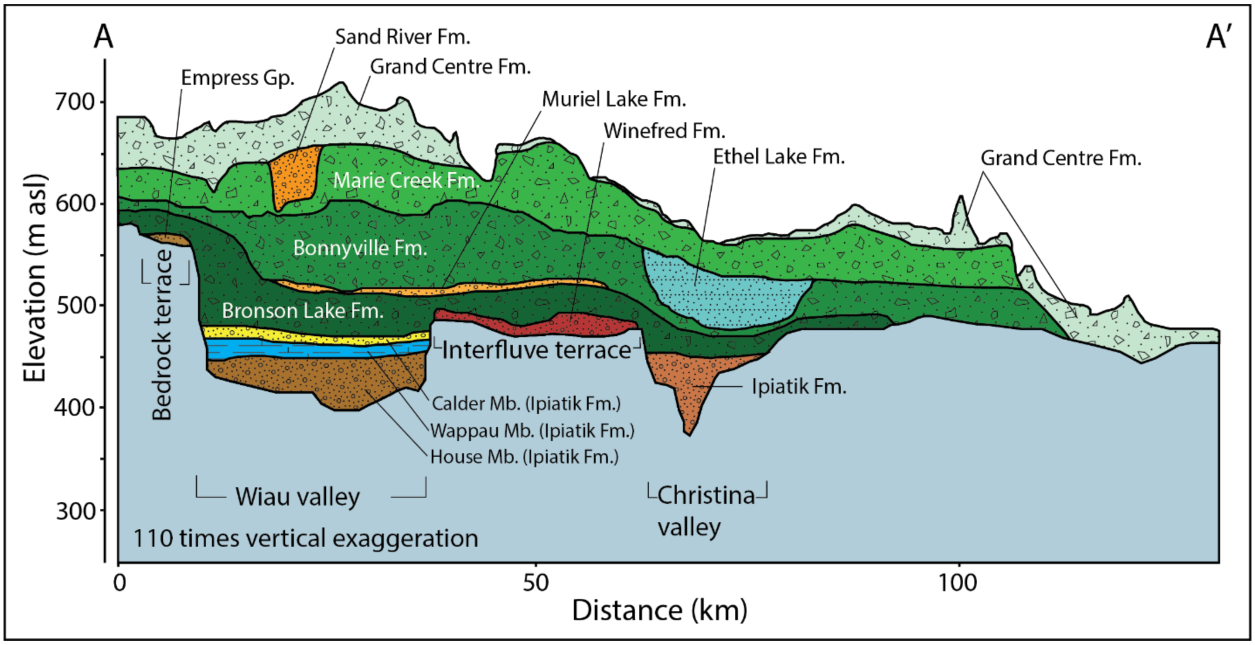

Figure 6. South-north (A–A′) cross-section of units in the South Alberta Oil Sands region (modified from Hartman et al., 2023, © Canadian Science Publishing or its licensors; location shown on Figure 5). Note the Bronson Lake Formation extends over the southern bedrock strath based on the occurrence of reversely magnetized till in that area (Andriashek and Barendregt, 2017).

Recently there have been some updates to the stratigraphic nomenclature of Quaternary and Neogene units in the province that relate to work in this study. Hartman et al. (2023) re-examined the basal gravel deposits in the SAOS region, which were previously included in the Empress Formation (Andriashek, 2003). Their update raised the rank of the formation to group status (i.e., Empress Group) and described two formations in the SAOS region: the Ipiatik and Winefred formations. The Ipiatik Formation includes those deposits at the base of preglacial paleovalleys, such as the Wiau, Leismer, Amesbury, and Christina valleys, and comprises three members including the House, Wappau, and Calder, which correspond with units 1, 2, and 3 of the former Empress Formation, respectively. The Winefred Formation includes deposits present on the interfluve between the Wiau and Christina valleys (Figures 3 and 4). Deposits within glacial channels, such as the Gregoire channel (Figure 4), are not included in the Empress Group. A south-north cross-section modified from Hartman et al. (2023) reveals the general relationship between the stratigraphic units in the study area (Figure 6).

4.1 Borehole WEPA99-1

Borehole WEPA99-1 (Figure 7) was drilled along the southern flank of the western end of the Wiau valley (Figure 5; Andriashek, 2003). It was drilled through 154.5 m of sediments before encountering bedrock. Although fluvial Empress Group (formerly Empress Formation; Hartman et al., 2023) deposits have been encountered at the base of the Wiau valley, this unit was not encountered in this borehole, likely because the borehole was located over the valley wall. A weathered till horizon observed at 62 m depth was interpreted as the top of the Marie Creek Formation. This till overlies the Ethel Lake Formation silt, and a lower till that has been reinterpreted as the Bronson Lake Formation by Andriashek and Barendregt (2016) based on its reversed paleomagnetic signature.

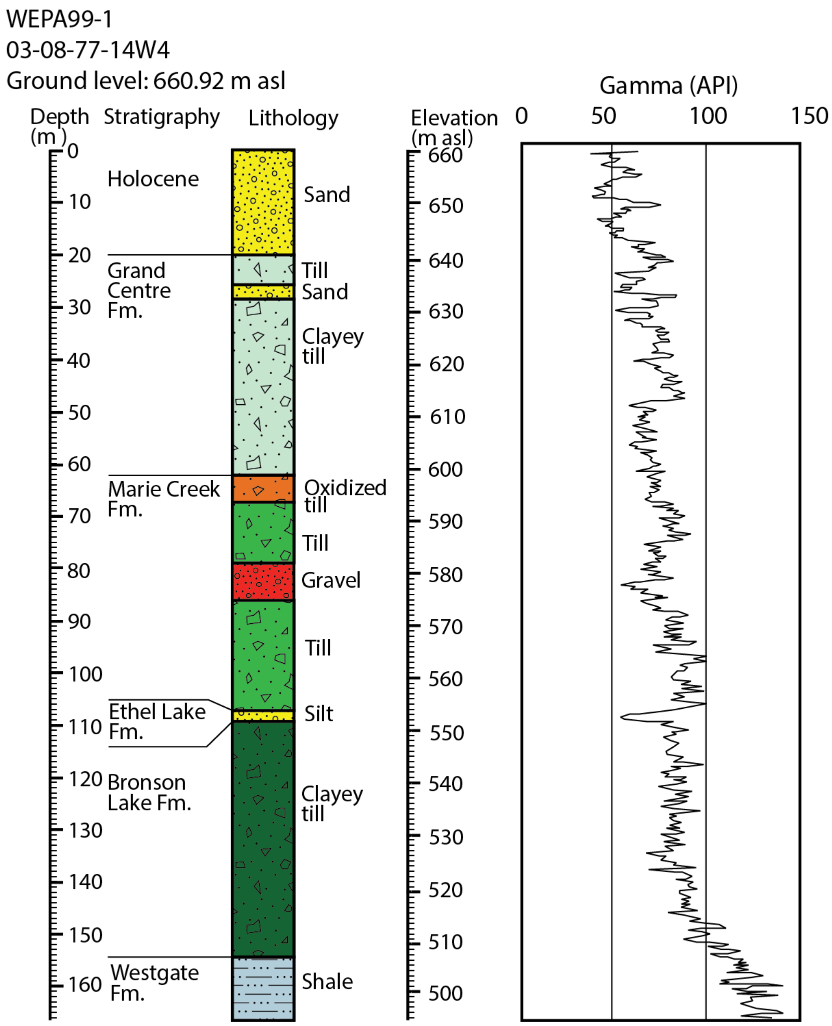

Figure 7. Stratigraphic, lithological, and gamma-ray logs for borehole WEPA99-1 (adapted from Andriashek, 2003, and Andriashek and Barendregt, 2016). Andriashek (2003) interpreted the lowest till to be the Bonnyville Formation but it was reinterpreted by Andriashek and Barendregt (2016) as Bronson Lake Formation because it was found to be reversely magnetized.

4.2 Borehole WEPA99-2

Borehole WEPA99-2 (Figure 8) was drilled over the thalweg of the Amesbury valley (Figure 5). Using a water well drill, the borehole was drilled through Quaternary sediments until shale was encountered at 158 m (Andriashek, 2003). Andriashek (2003) expected bedrock to be encountered at a greater depth and suggested that the shale may have been a bedrock raft with Quaternary sediments below it. Marie Creek Formation till was tentatively identified based on a higher carbonate content compared to the tills above and below (Andriashek, 2003). Additionally, there is a shift to slightly higher gamma-ray values at the base of the Grand Centre Formation. Andriashek and Barendregt (2016) subdivided the Bonnyville Formation into two units (1 and 2) based on an observed change in log response (unit 2 has a lower gamma-ray response than unit 1). This is consistent with Andriashek (2003) reporting that unit 1 is finer grained than unit 2, although they did not differentiate these units on the borehole log.

The 2 m of till underlying 17 m of Bonnyville Formation silt at the base of this borehole was interpreted as Bonnyville Formation based on its normal magnetization (i.e., not Bronson Lake Formation, which is reversely magnetized) and geochemical signature (Andriashek and Barendregt, 2016).

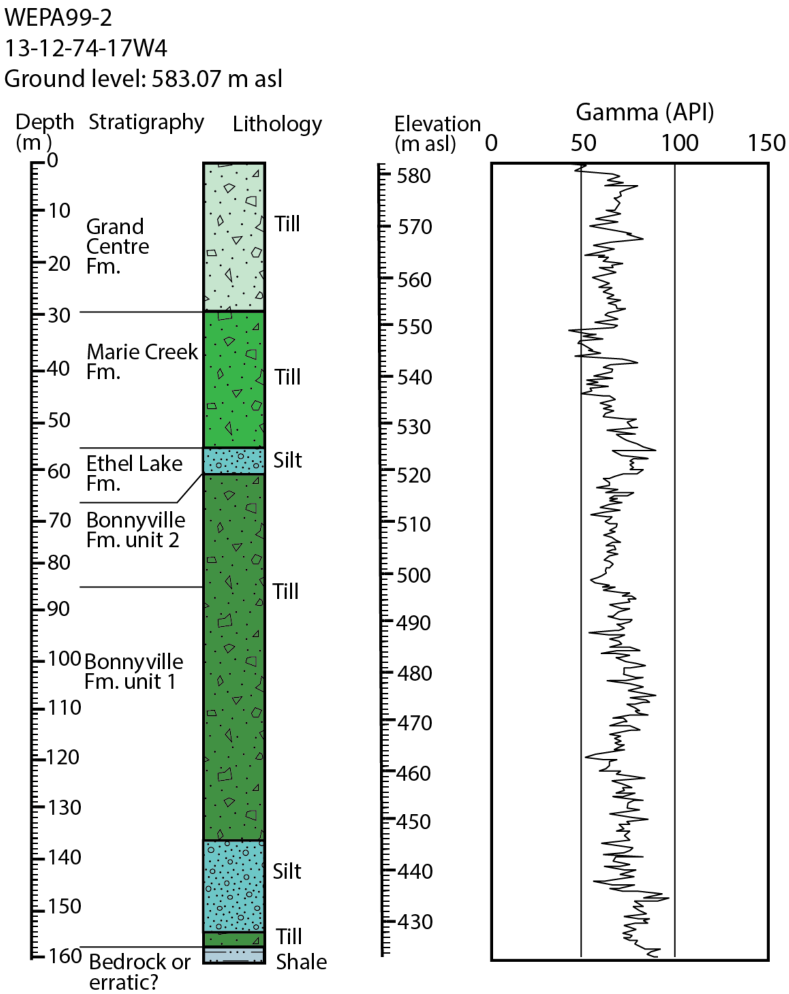

Figure 8. Stratigraphic, lithological, and gamma-ray logs for borehole WEPA99-2 (adapted from Andriashek, 2003, and Andriashek and Barendregt, 2016).

4.3 Borehole WR99-1

Borehole WR99-1 (Figure 9) was drilled over the western end of the Wiau valley (Figure 5) using an oil and gas rig with a blowout preventer (upper 20 m of the borehole cased). The borehole was drilled through 235.3 m of Quaternary and Neogene (Pliocene) sediments, about 1 m of Pelican Formation sandstone, and 14 m of Joli Fou Formation shale.

Grand Centre Formation till comprises the upper 74 m of this core. Beneath this is a sand unit interpreted by Andriashek (2003) as Ethel Lake Formation, which is in turn underlain by a thin till layer of the Bonnyville Formation. Beneath the till are two cycles of fining-upwards sequences. The first (lowest) sequence includes the House and Wappau members of the Ipiatik Formation (formerly units 1 and 2 of the Empress Formation, respectively; Hartman et al., 2023). Samples recovered from the House Member were examined by Andriashek (2003) and revealed a clast petrology of metaquartzite and chert, suggesting local and Cordilleran (mountain) sources of the material. The fine-grained material of the Wappau Member, between 161 and 191 m depth, contains some granitic rock fragments, indicating a glacial origin of these sediments, or at least glacial influence within the catchment. The overlying second fining-upwards sequence is the Calder Member of the Ipiatik Formation (formerly unit 3 of the Empress Formation; Hartman et al., 2023), which consists of gravel, sand, and clay units with abundant Canadian Shield–derived material.

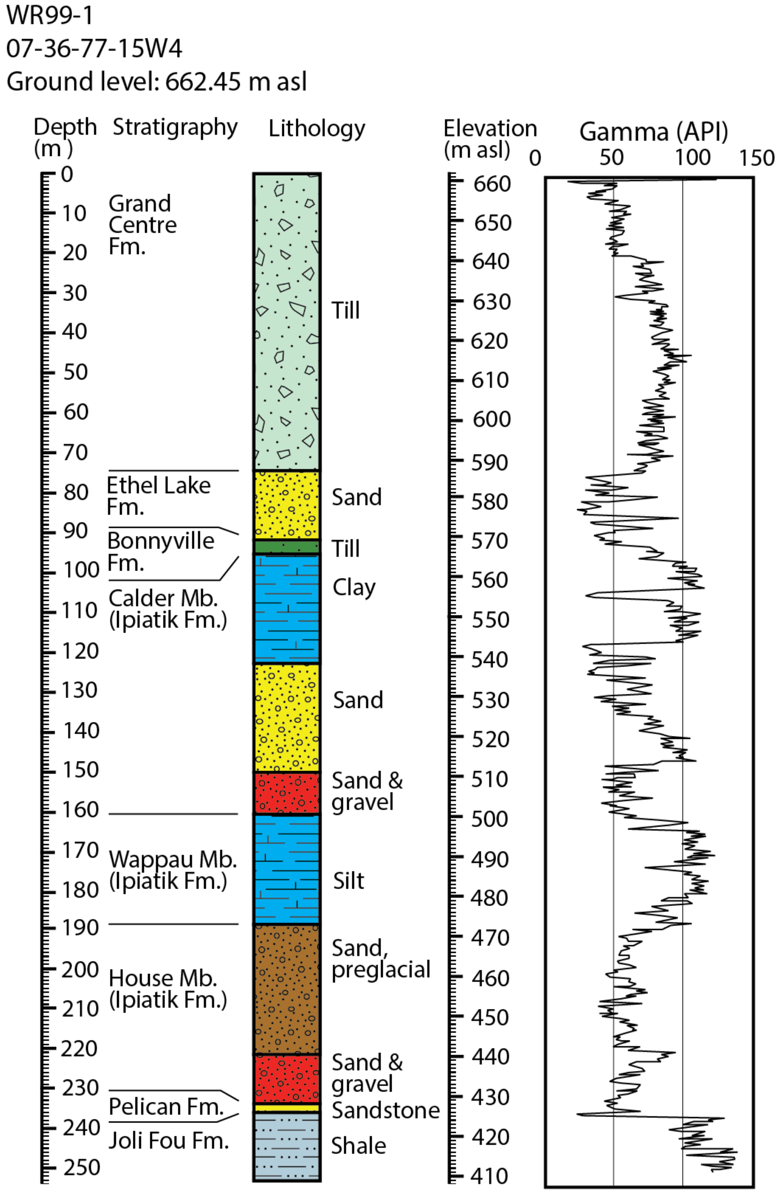

Figure 9. Stratigraphic, lithological, and gamma-ray logs for borehole WR99-1 (adapted from Andriashek, 2003). Note, the shift in gamma-ray response in the upper 20 m corresponds with the presence of a surface casing.

4.4 Borehole WEPA00-1

Borehole WEPA00-1 (Figure 10) was drilled above the interfluve between the Wiau and Christina valleys (Figure 5). The borehole was intentionally terminated above bedrock due to the risk of encountering natural gas. Therefore, basal gravel was not intercepted.

Bronson Lake Formation till was encountered at 150 m depth, which corresponds with a noticeable change in gamma-ray (Figure 10) and resistivity response. Andriashek and Barendregt (2016) also determined that the till was reversely magnetized. The tills of the Bonnyville Formation units 1 and 2 are noncalcareous, which differentiate them from the upper Marie Creek Formation till, which is highly calcareous. In this borehole, the Bonnyville Formation sand is about 30 m thick and is composed of an upper 10 m of sand and lower 20 m of gravel.

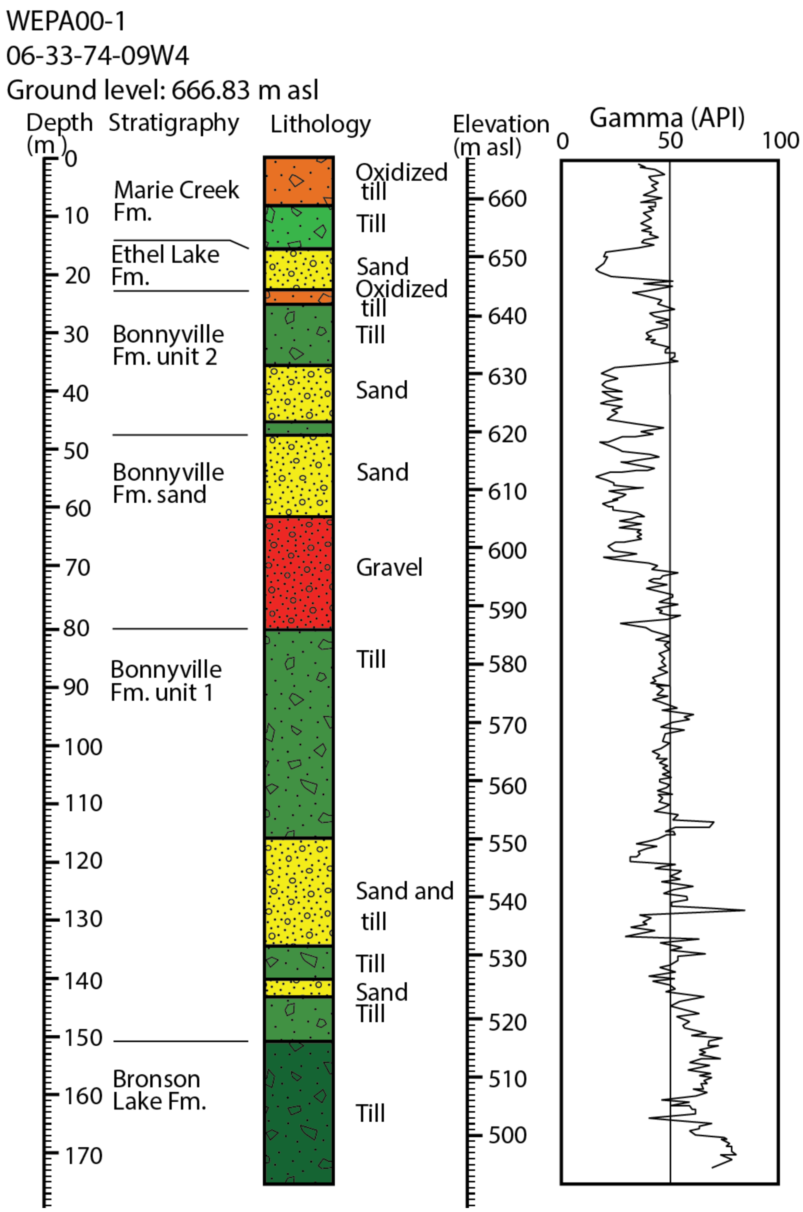

Figure 10. Stratigraphic, lithological, and gamma-ray logs for borehole WEPA00-1 (adapted from Andriashek, 2003, and Andriashek and Barendregt, 2016).

4.5 Borehole WEPA00-2

Borehole WEPA00-2 (Figure 11) was drilled in the Christina valley, northeast of Christina Lake (Figure 5). The borehole intercepted 115 m of sediments before tagging bedrock. The upper 34 m consist of carbonate-bearing till interpreted by Andriashek (2003) as Marie Creek Formation. Beneath this till, from 34 to 88 m depth, is stratified silt, clay, and sand of the Ethel Lake Formation. These deposits include some rhythmically bedded units suggesting deposition in a proglacial lacustrine environment.

Bonnyville Formation till occurs above an oxidized zone of Bronson Lake Formation till followed by Empress Group (formerly Empress Formation; Hartman et al., 2023) sediments in the remainder of the borehole. Initially Andriashek (2003) interpreted the top of the Bronson Lake Formation to be at 95 m depth, but Andriashek and Barendregt (2016) reinterpreted the top to coincide with the top of the oxidized till, although the underlying succession is normally magnetized.

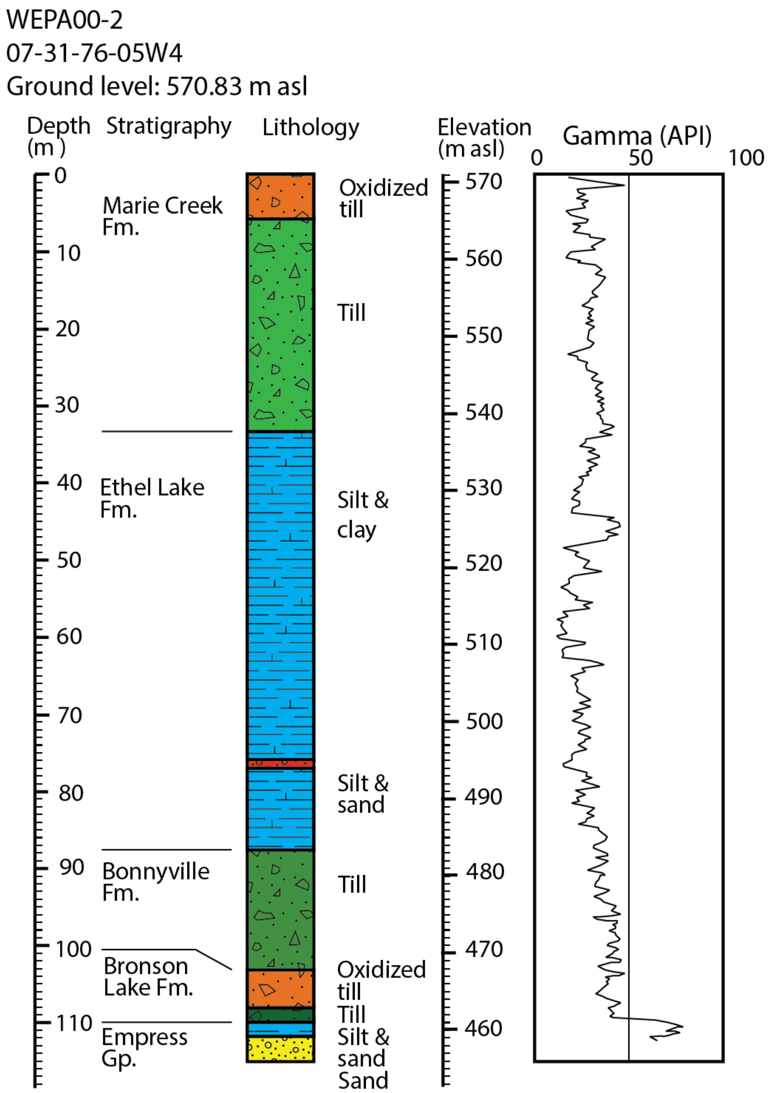

Figure 11. Stratigraphic, lithological, and gamma-ray logs for borehole WEPA00-2 (adapted from Andriashek, 2003, and Andriashek and Barendregt, 2016).

4.6 Borehole WEPA00-3

Borehole WEPA00-3 (Figure 12) was drilled near Winefred Lake (Figure 5). The location was specifically chosen to sample sediments overlying the bedrock interfluve between the Wiau and Christina valleys (Figures 3 and 4) and thus determine the petrology of the basal gravel unit. The borehole intercepted 156 m of Quaternary sediments. The hole was extended without coring to tag bedrock at 177.5 m depth. The geology below the cored interval was determined from drill cuttings.

The upper 78 m of core, which is highly calcareous, was interpreted as Marie Creek Formation till. Beneath that till, Andriashek (2003) interpreted the Bonnyville Formation units 1 and 2 (oxidized, low carbonate tills) overlying the Muriel Lake Formation (sand and gravel unit), and beneath that was the Bronson Lake Formation (till). However, the top of the Bronson Lake Formation till was lowered from 125 to 145 m depth by Andriashek and Barendregt (2016) based on the magnetic signature of the till, which is reversed below 145 m. The reassessment of the top of the Bronson Lake Formation necessitated reinterpretation of the Muriel Lake Formation (sand and gravel between 122 and 124 m depth) as an unnamed intratill unit (Andriashek and Barendregt, 2016).

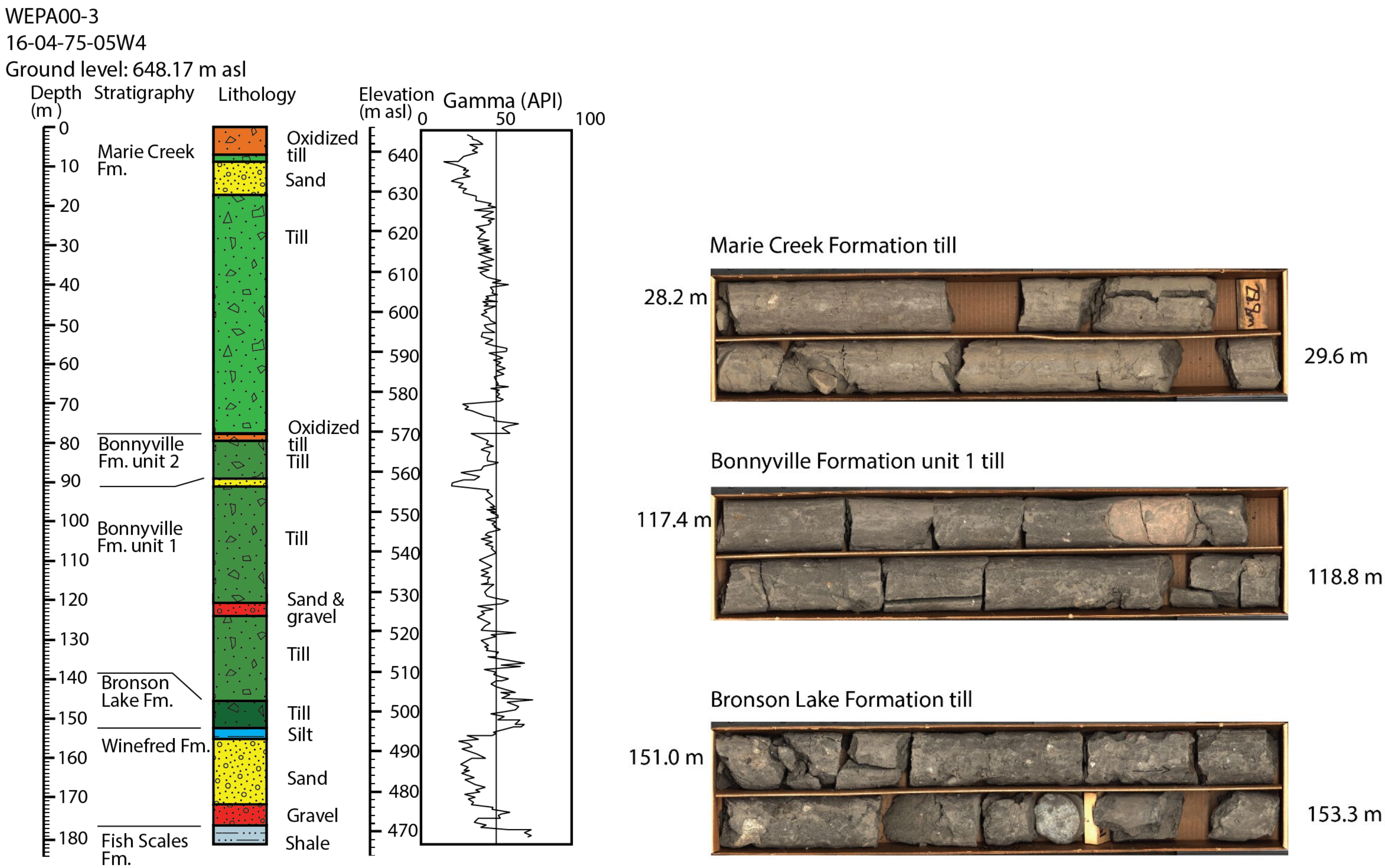

Figure 12. Stratigraphic, lithological, and gamma-ray logs and core photographs for borehole WEPA00-3 (logs adapted from Andriashek, 2003, and Andriashek and Barendregt, 2016).

The sand unit at the base of the borehole from 162 to 172.5 m depth was interpreted as glacial in origin by Andriashek (2003) based on clast lithologies from hand samples. The underlying 5 m of sand and gravel were similarly interpreted as glacial in origin based on the clast lithology (Andriashek, 2003). These two units were termed the Empress Formation interfluve terrace sand and gravel by Andriashek (2003). These deposits were renamed the Winefred Formation of the Empress Group by Hartman et al. (2023).

4.7 Borehole WEPA00-4

The 90 m deep borehole WEPA00-4 (Figure 13) was drilled north of the Christina valley (Figure 5), in a location selected to confirm the presence of thick drift north of that paleovalley (Andriashek, 2003). Bedrock was not encountered, indicating at least moderately thick drift at this location. Correlation of the upper till units to the Grand Centre and Marie Creek formations was tentative due to ambiguous values of carbonate in the matrix (Andriashek, 2003).

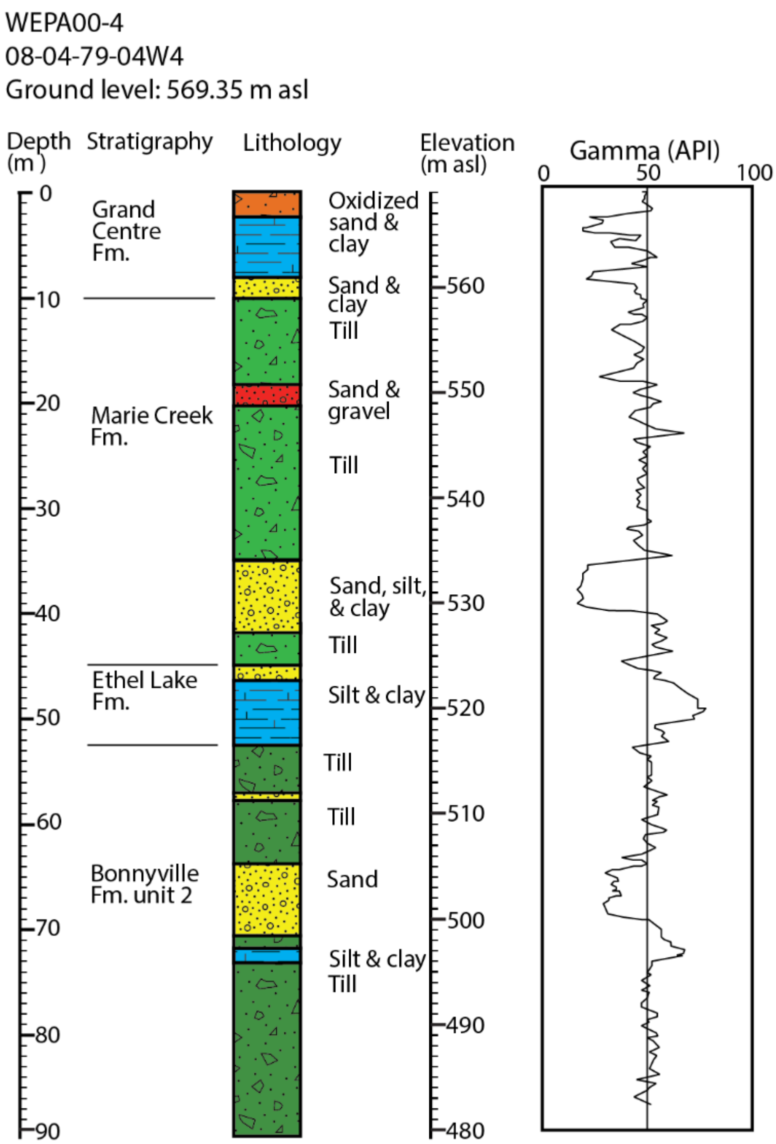

Figure 13. Stratigraphic, lithological, and gamma-ray logs for borehole WEPA00-4 (adapted from Andriashek, 2003).

4.8 Borehole Statoil OBS Leismer 00/16-21-078-10W4M/0

Borehole Statoil OBS Leismer 00/16-21-078-10W4M/0 (Figure 14) was drilled in the Leismer valley (Figure 5) by Statoil Canada Ltd. and logged by Matrix Solutions Inc. (2011). The borehole was cored from 154.9 to 180.1 m and completed in bedrock. This core is significant because it includes the lowest sand and gravel unit, interpreted as the House Member of the Ipiatik Formation (formerly Empress Formation unit 1; Hartman et al., 2023), which is considered preglacial (Andriashek, 2003; Hartman et al., 2023). The core contains a gneiss clast within the succession that Hartman et al. (2023) interpreted as indicative of a transition from preglacial to glacial conditions upon the first arrival of continental ice within the catchment.

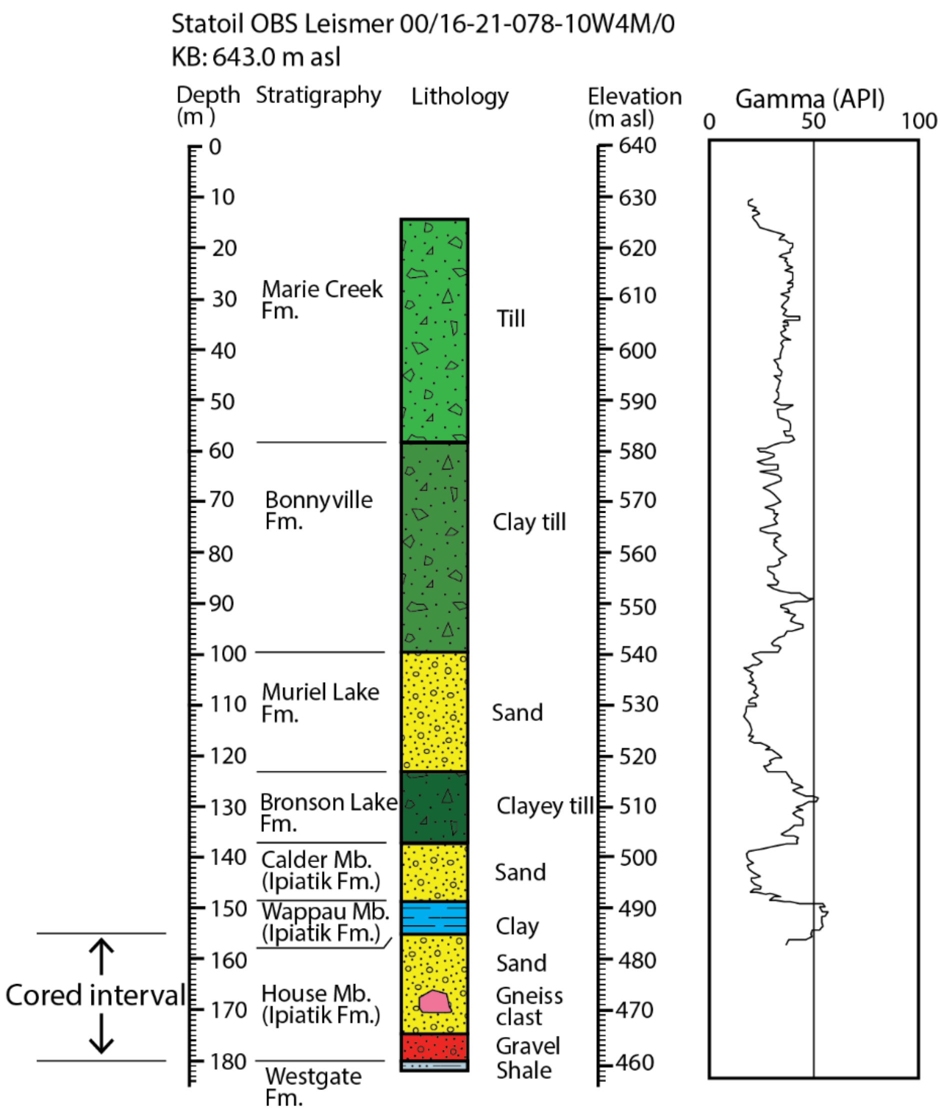

Figure 14. Stratigraphic, lithological, and gamma-ray logs for borehole Statoil OBS Leismer 00/16-21-078-10W4M/0 (adapted from Matrix Solutions Inc., 2011). Abbreviation: KB, kelly bushing.

4.9 Borehole Statoil OBS Leismer 00/13-22-078-10W4M/0

Borehole Statoil OBS Leismer 00/13-22-078-10W4M/0 (Figure 15) was drilled near borehole Statoil OBS Leismer 00/16-21-078-10W4M/0 (Figure 5) and was cored from 153.6 to 180.0 m depth and completed in bedrock. This hole was also drilled by Statoil Canada Ltd. and logged by Matrix Solutions Inc. (2011). Of note is the bedded fine-grained material of the Wappau Member of the Ipiatik Formation (formerly Empress Formation unit 2; Hartman et al., 2023), which suggests deposition in a proglacial lacustrine environment. The underlying House Member (formerly Empress Formation unit 1; Hartman et al., 2023) is predominantly sand with a salt and pepper appearance and does not contain granite or granite gneiss clasts.

4.10 Borehole CVE FCCL GW0 A7 HARDY 7-13-76-6

Borehole CVE FCCL GW0 A7 HARDY 7-13-76-6 (Figure 16) was drilled over the Christina valley by Cenovus Energy Inc. (Figure 5). The borehole was cored from 12.4 to a depth of 131.2 m and the author examined photographs of the core. The core includes thick till units correlated to the Grand Centre and Bonnyville formations based on geophysical log signature (geochemical analysis was not available). Coring recovered fine-grained material interpreted as Ethel Lake Formation, although a portion (inferred as loose sand) was not recovered.

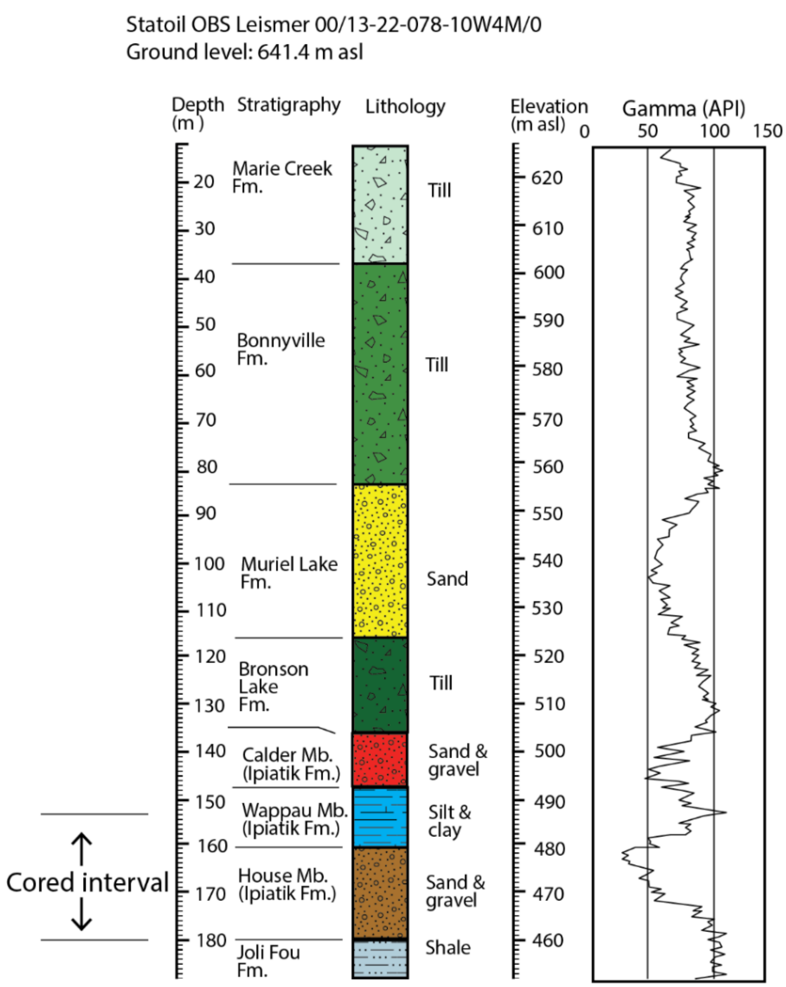

Figure 15. Stratigraphic, lithological, and gamma-ray logs for borehole Statoil OBS Leismer 00/13-22-078-10W4M/0 (Matrix Solutions Inc., 2011).

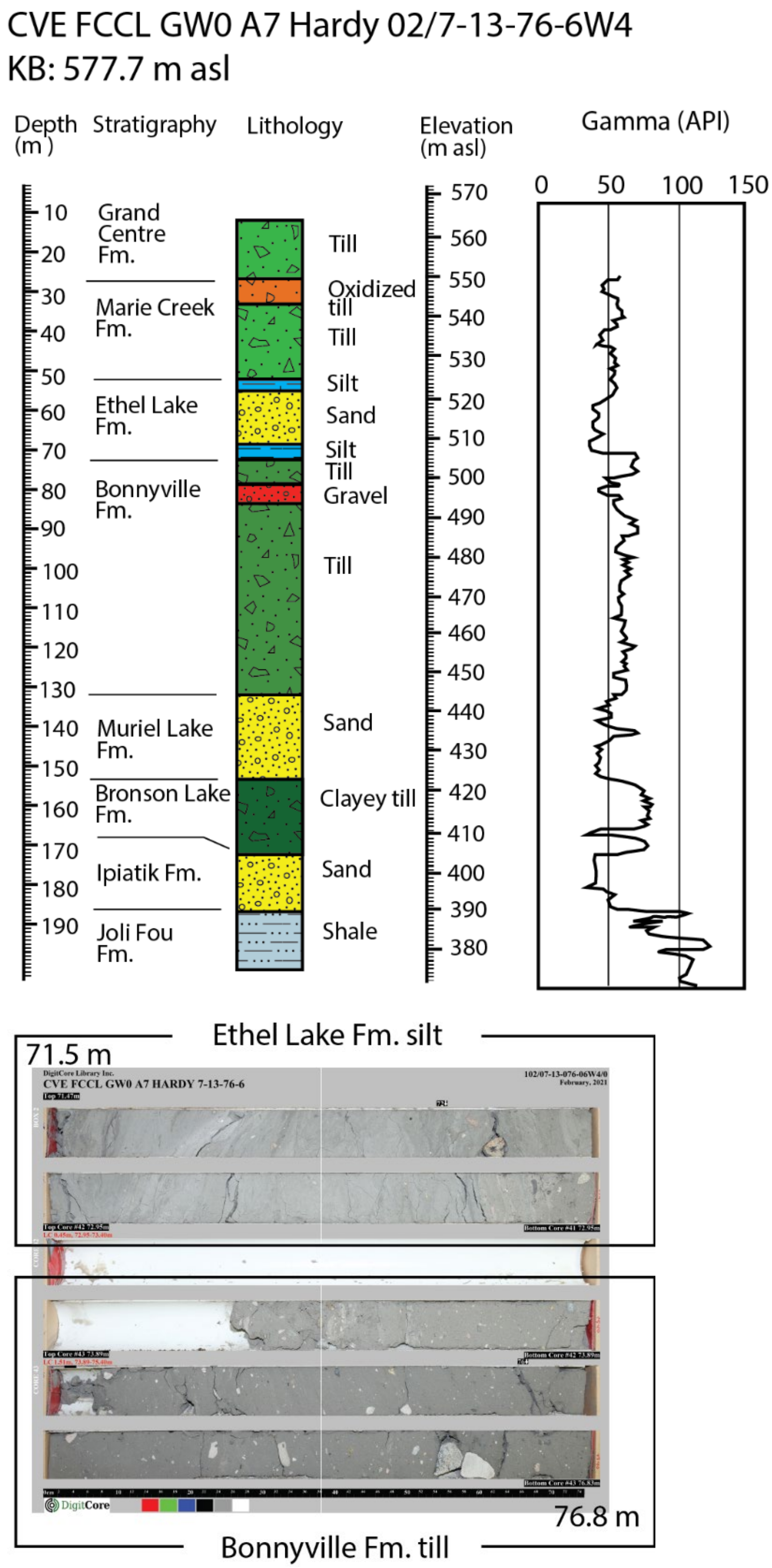

Figure 16. Stratigraphic, lithological, and gamma-ray logs for borehole CVE FCCL GW0 A7 HARDY 7-13-76-6W4. Photographs of core from Alberta Geological Survey (unpublished, 2021). Abbreviation: KB, kelly bushing.

4.11 Opti Nexen 10-29-85-6W4

Borehole Opti Nexen 10-29-85-6W4 (Figure 17) was drilled by Nexen Inc. on the Garson Plain to the northeast of the Stony Mountain Upland (Figure 5). The borehole was drilled over the Gregoire channel and encountered bedrock at a depth of 124 m. Drill cuttings from the borehole confirmed the presence of a thick glaciogenic sand unit beneath the Grand Centre Formation till. Note that the sand deposit is not included in the Empress Group because it was not deposited in a preglacial valley (after Hartman et al., 2023).

5 Stratigraphic Picking and Modelling of Sediment Units Above Bedrock

Stratigraphic units (Table 1) were picked on geophysical logs based on borehole descriptions in Section 4 and descriptions in Andriashek (2003). These picks were informed by previous work from industry, especially those based on geophysical surveys (Devon ARL Corporation, 2006; Canadian Natural Resources Limited, 2020), and picks in Andriashek (2003). The results from this picking are presented in Utting (2021a). Further subdivision of the Bonnyville Formation into units 1 and 2, and identification of the intervening Bonnyville Formation sand are from Utting (2023).

Stratigraphic picks were made across the regional subsurface dataset following the stratigraphic framework outlined herein, using the cross-section module in S&P Global Inc.'s Petra® to create cross-sections at progressively increasing distances from the reference core locations. The pick sets were imported into Esri's ArcMap GIS software to generate kriged stratigraphic top surfaces (Utting, 2021b; Figures 18a–e and 19a–f), which were cropped at their intersection with the bedrock digital elevation model (DEM), the surface DEM, or zero-thickness boundaries (constrained by logs in which units are absent).

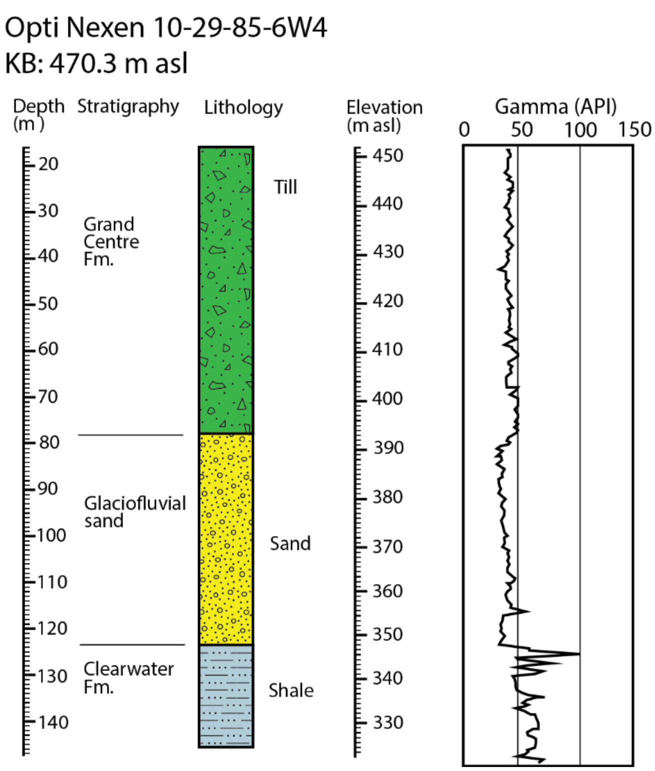

Figure 17. Stratigraphic, lithological, and gamma-ray logs for borehole Opti Nexen 10-29-85-6W4. Abbreviation: KB, kelly bushing.

Table 1. Stratigraphic units in the South Athabasca Oil Sands (SAOS) region.

Stratigraphic Unit	Material	Hydrostratigraphy	Notes, Description	Distribution	Reference(s)
Grand Centre Fm.	Till	Aquitard	Surface till, low carbonate matrix	Thin or discontinuous distribution. If present, it would be above most logged intervals; not modelled in this study	Andriashek, 2003
Sand River Fm.	Stratified sediments	Aquifer	Sand and silt with lesser amounts of clay and gravel	Only locally deposited in channels. If present, it would be above most logged intervals; not modelled in this study	Andriashek, 2003
Marie Creek Fm.	Till	Aquitard	High carbonate matrix, surface till or may be buried by Sand River and Grand Centre fms. May have oxidized upper surface	Regional? If present, it would be above most logged intervals; not modelled in this study	Andriashek, 2003
Ethel Lake Fm.	Stratified sediments	Aquifer	Clay, silt, sand, and gravel	Patchy deposits, presumably related to predeposition topography	Andriashek, 2003; Utting, 2021b
Bonnyville Fm. unit 2	Till	Aquitard	Sandy diamicton, low carbonate content. May have oxidized upper surface	Similar distribution to Bonnyville Fm. unit 1	Andriashek, 2003; Utting, 2023
Bonnyville Fm. sand	Stratified sediments	Aquifer	Sand and gravel, locally fine-grained deposits	Patchy distribution, less extensive than Bonnyville Fm. units 1 and 2	Andriashek, 2003; Utting, 2023
Bonnyville Fm. unit 1	Till	Aquitard	Clayey diamicton	Present in most of the upland areas, absent from plains area	Andriashek, 2003; Utting, 2023
Pre-Bonnyville sand	Stratified sediments	Aquifer	Sand	Kirby channel region; not modelled in this study	Canadian Natural Resources Limited, 2020
Pre-Bonnyville till	Till	Aquitard	Diamict	Kirby channel region; not modelled in this study	Canadian Natural Resources Limited, 2020
Muriel Lake Fm.	Stratified sediments	Aquifer	Sand and gravel, lesser amounts of silt and clay	Mostly where Bronson Lake Fm. occurs, but there are some gaps	Andriashek, 2003; Utting, 2021b
Bronson Lake Fm.	Till	Aquitard	Clayey diamicton, low carbonate matrix, reversely magnetized	Covers much of the Wiau, Christina, and Leismer valleys, more extensive than shown in Andriashek (2003)	Andriashek, 2003; Andriashek and Barendregt, 2017; Utting, 2021b
Winefred Fm. (formerly Empress Fm. terrace deposits)	Sand and gravel	Aquifer	Contains Canadian Shield–derived material	Terrace glaciofluvial deposits	Andriashek, 2003; Utting, 2021b; Hartman et al., 2023
Ipiatik Fm. Calder Mb. (formerly Empress Fm. unit 3)	Sand and gravel	Aquifer	Quaternary in age, based on overlying reversely magnetized till and glaciofluvial origin inferred from occurrence of Canadian Shield material	Wiau and Leismer valleys	Andriashek, 2003; Utting, 2021b; Hartman et al., 2023
Ipiatik Fm. Wappau Mb. (formerly Empress Fm. unit 2)	Clay and silt	Aquitard	Quaternary in age, based on overlying reversely magnetized till and inferred glaciolacustrine genesis	Wiau and Leismer valleys	Andriashek, 2003; Utting, 2021b; Hartman et al., 2023
Ipiatik Fm. House Mb. (formerly Empress Fm. unit 1)	Stratified sediments	Aquifer	Quaternary to Pliocene in age, based on overlying reversely magnetized till. Preglacial based on pebble lithology	Wiau and Leismer valleys	Andriashek, 2003; Utting, 2021b; Hartman et al., 2023

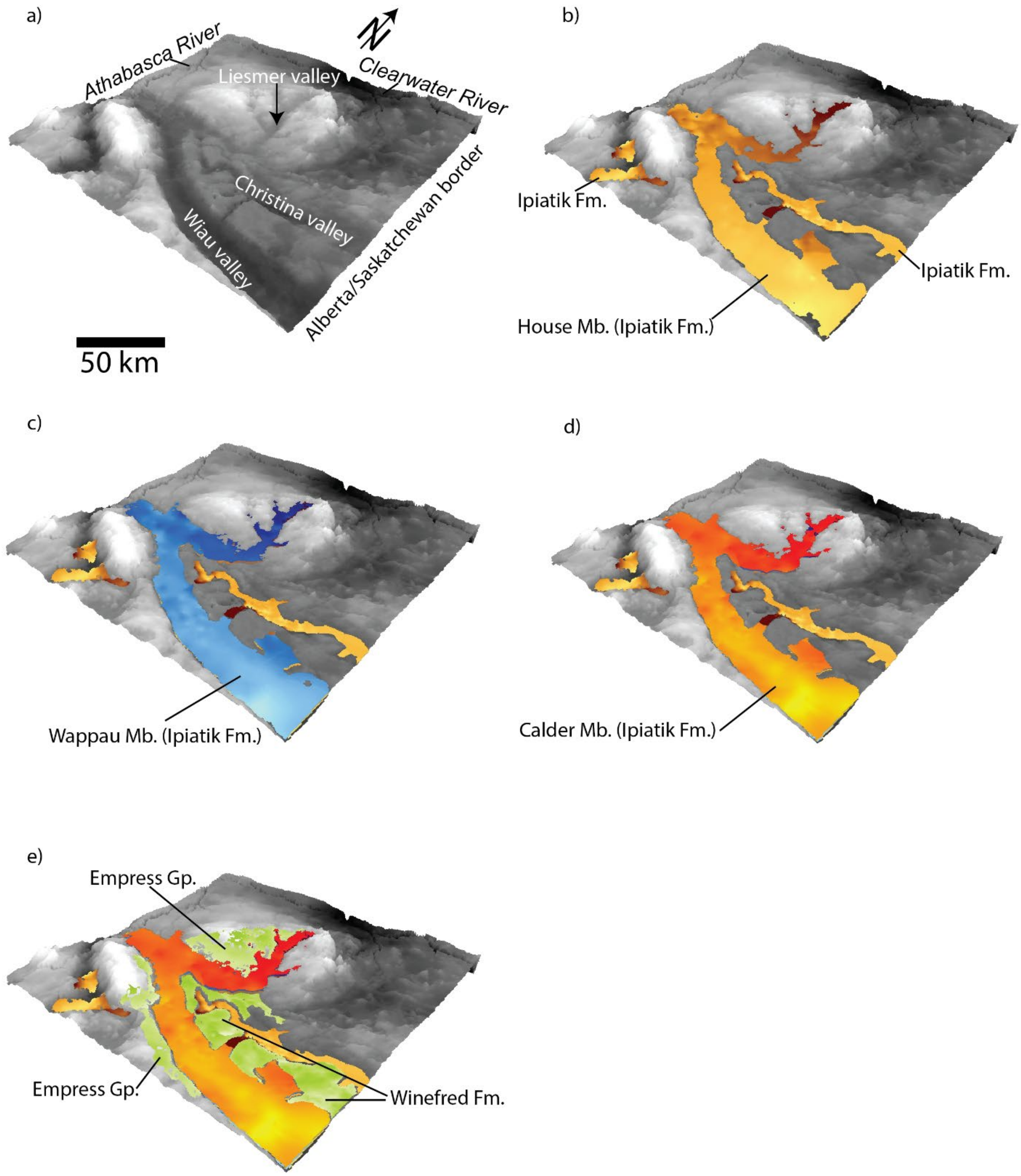

Figure 18. (a) Bedrock topography of the South Athabasca Oil Sands region. (b) The extent of the basal sand and gravel of the Ipiatik Formation, as well as the extent of just the House Member (Ipiatik Formation) preglacial deposits in the Wiau and Leismer valleys. (c) The extent of the Wappau Member (Ipiatik Formation) glaciolacustrine deposits in the Wiau and Leismer valleys. (d) The extent of the Calder Member (Ipiatik Formation) glaciofluvial sand and gravel deposits. (e) The extent of the Winefred Formation glaciofluvial deposits as well as the undivided Empress Group deposits flanking the Wiau and Leismer valleys. Modified from Utting (2021b).

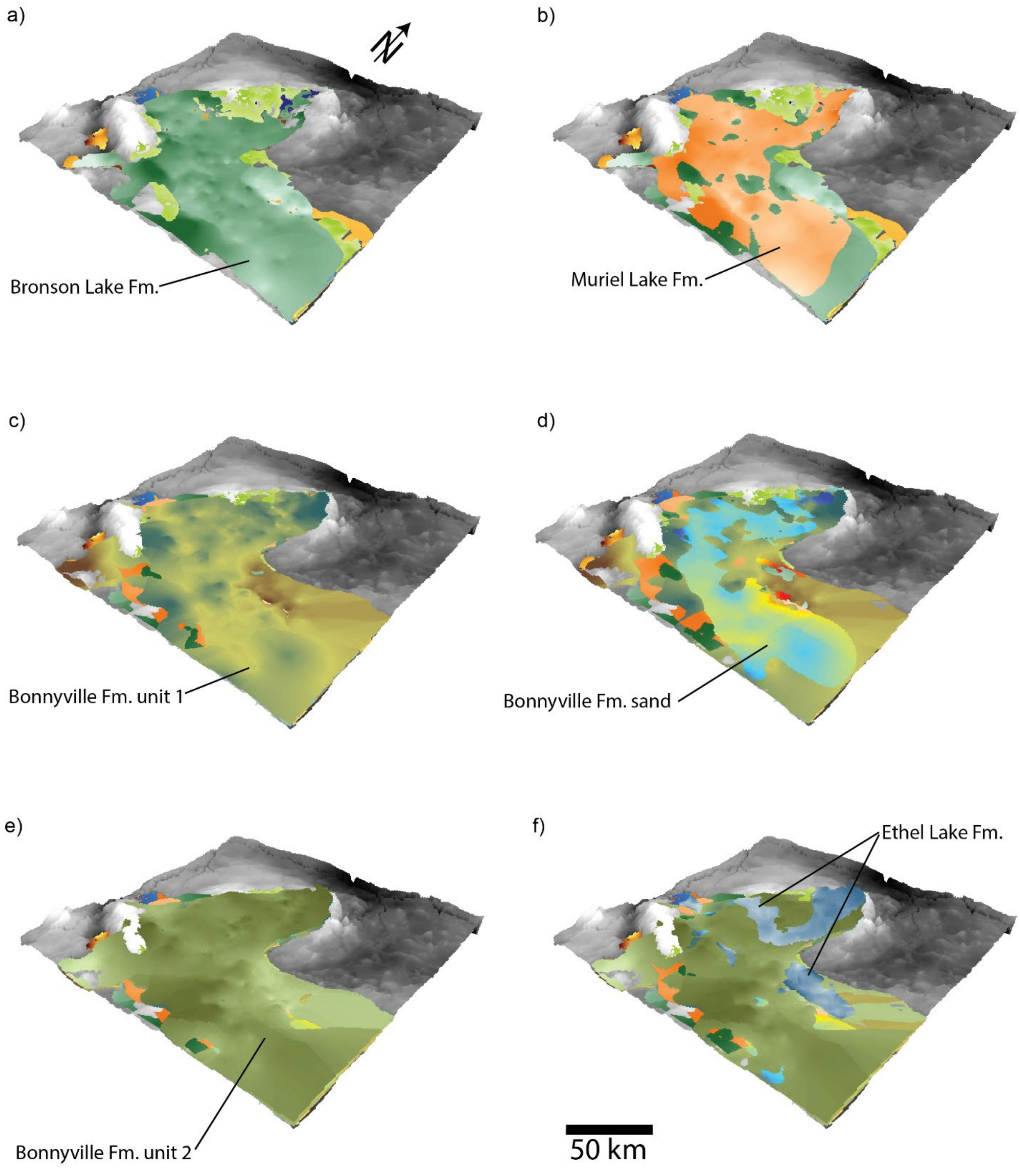

Figure 19. Bedrock topography with stratigraphic units of the Empress Group and the overlying (a) reversely magnetized Bronson Lake Formation (primarily till); (b) the Muriel Lake Formation (fluvial sediments); (c) Bonnyville Formation unit 1 (till); (d) the intratill Bonnyville Formation sand; (e) the overlying Bonnyville Formation unit 2 (till); and (f) the Ethel Lake Formation (glaciolacustrine and glaciofluvial deposits). Overlying the Ethel Lake Formation are the Marie Creek and Grand Centre formation tills and Sand River Formation sand (not shown or modelled in this study). Modified from Utting (2021b) and Utting (2023).

In picking the tops, especially as distance from the cored boreholes increased, there is a tendency to group similar log responses into units in stratigraphic order and position. This method of picking may contribute to the modelled surfaces having a 'layer cake' pattern, even though it is known the region has experienced significant glaciotectonic disturbance (e.g., Andriashek et al., 1999). Complexity and irregularities in the tops due to depositional processes and glaciotectonic activity in the region was shown in a cross-section by Devon ARL Corporation (2006, Appendix 3, Figure 7). However, in the absence of seismic data, these types of irregularities cannot be accurately mapped between boreholes.

6 Quaternary Stratigraphic Domains

Geographic areas with similar sediment thicknesses and stratigraphic sequences (above bedrock) were grouped into 'Quaternary stratigraphic domains' by Utting and Andriashek (2020) in the area to the north. Similarly, in the SAOS region, domains (Figure 20) were delineated based on comparable characteristics (summarized in Table 2). The House Member is thought to be older than the Quaternary because it does not contain material related to glaciation.

Table 2. Stratigraphic domains in the South Alberta Oil Sands (SAOS) region.

Stratigraphic Domain	Characteristics
Wiau valley domain	Upland area, deep bedrock paleovalley, very thick sediments (~130–325 m), major basal aquifer (House and Calder mbs. of the Ipiatik Fm. [formerly Empress Formation units 1 and 3, respectively]) and intertill aquifers (Ethel Lake and Muriel Lake fms.)
Leismer valley domain	Upland area, deep bedrock paleovalley, thick sediments (~120–230 m). Channel and surrounds have Ipiatik Fm. (House, Wappau, and Calder mbs. [formerly Empress Formation units 1, 2, and 3, respectively]) at base, overlain by Bronson Lake Fm. till, and Muriel Lake and Ethel Lake fms. aquifers
Northeast and West Stony Mountain upland domains	Upland areas, moderately thick sediments (~7–220 m), no known major aquifer units above bedrock
North SAOS, Wabasca, and Lac La Biche plain domains	Lowland areas, generally thin sediments (~0–65 m); exceptions are the Gregoire channel with 75 m of sediments, the north and south Hangingstone channels, and potentially other channels. No known major aquifer units above bedrock
Christina Lake Plain domain	Lowland area, moderately thick sediments (~25–130 m), no known major aquifer units above bedrock
Christina valley domain	Lowland area, deep bedrock paleovalley, thick sediments (~120–250 m). Ipiatik Fm. is at the base and is overlain by Ethel Lake Fm. (glaciolacustrine and glaciofluvial deposit)
Central and East Mostoos upland domains	Bedrock interfluve, moderately thick sediments (~125–260 m). Glaciofluvial Winefred Fm. on bedrock surface, overlain by Bronson Lake Fm. till and Muriel Lake Fm. aquifer
May Hills domain	Upland area, moderately thick sediments (~50–140 m), no known major aquifer units above bedrock
Pinehurst Hills domain	Bedrock interfluve, moderately thick sediments (~80–160 m). Patchy glaciofluvial Winefred Fm. on bedrock surface, overlain by Bronson Lake Fm. till and Muriel Lake Fm. aquifer
Amesbury valley domain	Lowland area, deep bedrock paleovalley, thick sediments (~150–250 m), Ipiatik Fm. at base appears discontinuous
Owl River Plain domain	Lowland area, moderately thick sediments (~80–140 m), no known major aquifer units above bedrock

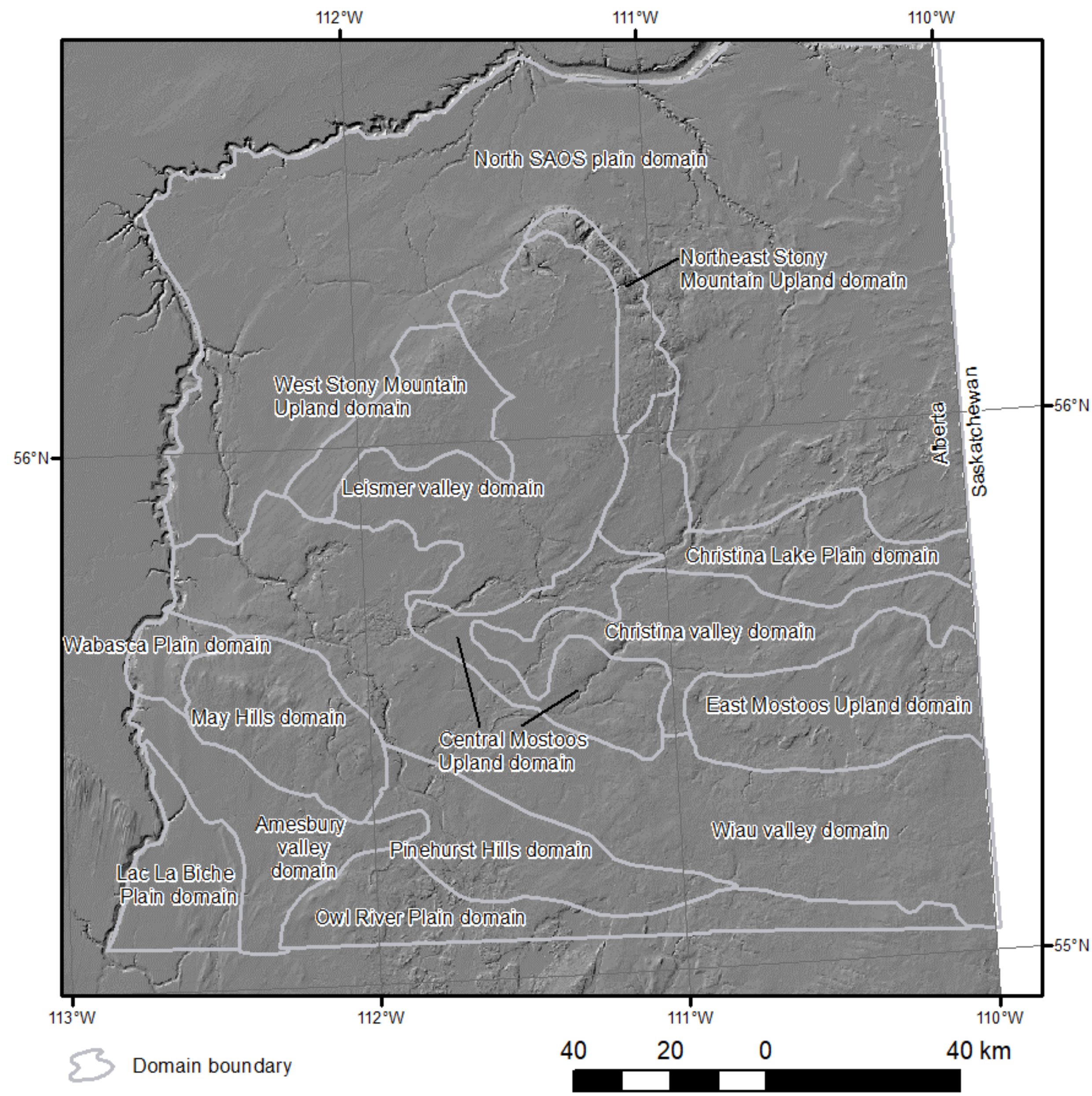

Figure 20. Quaternary stratigraphic domains within the South Athabasca Oil Sands (SAOS) region (Utting, 2021c). Background is a hill-shaded surface topography image.

7 Extension of Wiau Valley into Saskatchewan

There is limited information on the subsurface in the eastern portion of the study area, and even less across the border in Saskatchewan. However, information exists from testholes drilled in the early 1980s through a collaboration between the governments of Alberta and Saskatchewan in the Canoe Lake area (Maathuis, 1984; Appendix 1). The bedrock top depths reveal a potential extension of the Wiau valley to the east, with an elevation of about 400 m asl (Figure 21). This projection of the Wiau valley may connect to the Hatfield valley, a major buried valley in Saskatchewan (Whitaker and Christiansen, 1972). Figure 21 also includes data recently compiled by Bédard et al. (2023), which do not indicate the presence of the Wiau valley in Saskatchewan.

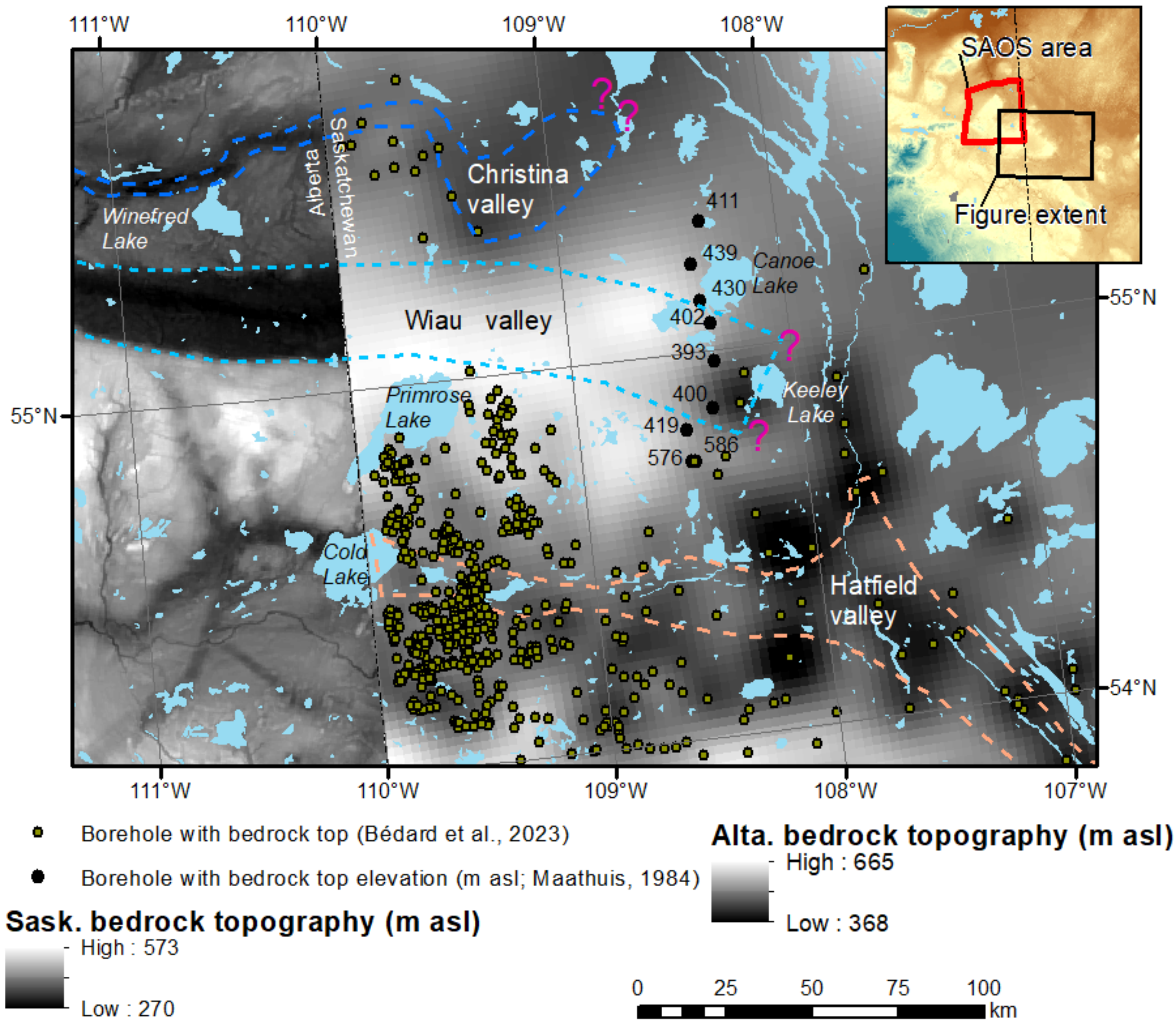

Figure 21. Bedrock topography of the area east and south of the study area (South Athabasca Oil Sands [SAOS] region), showing potential extension of the Wiau valley into Saskatchewan. The extent of the Wiau and Christina valleys shown in Alberta are based on this study, and in Saskatchewan the extent of the Wiau valley is inferred from bedrock top elevations west of Keeley Lake, reported in Maathuis (1984; Appendix 1) and the Christina valley is inferred from the bedrock topography (Bédard et al., 2023). Extent of Hatfield valley based on Whitaker and Christiansen (1972). Bedrock topography for Alberta from Alberta Geological Survey (2020) and for Saskatchewan from Bédard et al. (2023).

8 Conclusions

This report summarizes recent work on the Quaternary and Neogene (Pliocene) deposits in the South Athabasca Oil Sands (SAOS) region. The work included the generation of new bedrock topography and sediment thickness models, stratigraphic picks, and top surface models of stratigraphic units. This report summarizes the data, particularly from boreholes, upon which the models are based.

Key updates include

- refining the bedrock topography and sediment thickness models,
- incorporating the Sunday Creek channel into the bedrock topography model,
- updating the stratigraphic nomenclature of the Empress Group, and
- modelling the Empress Group, and the Bronson Lake, Muriel Lake, Bonnyville (units 1 and 2), and Ethel Lake formations.

Overall, these results provide a foundation for future studies in the SAOS region.

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Appendix 1 – Saskatchewan Borehole Data

Table 3. Saskatchewan borehole data reported in Maathuis (1984).

Borehole Name	UWI	Easting (NAD83 UTM Zone 12)	Northing (UTM Zone 12)	Ground Elevation (m asl)	Ground Elevation Source	Bedrock Top Elevation (m asl)
SRC Barnett Ridge	NW 2-21-66-17 W3	274004.2	6069372.7	645.0	SRTM DEM[a]	576
Clark Flotten Lake	4-22-66-17 W3	275125.8	6069206.1	635.0	SRTM DEM[a]	586
AE/SRC Low Creek	SE 13-15-67-17 W3	274152.2	6078508.0	615.7	Borehole log header	419[b]
AE/SRC Keeley Lake	NW 3-4-68-16 W3	282747.8	6083441.9	733.0	Borehole log header	400
AE/SRC Perch Lake	NW 7-15-69-16 W3	285419.5	6096798.8	518.1	Borehole log header	393
SRC Canoe Lake	NE 2-22-70-16 W3	286114.9	6107625.6	457.0	SRTM DEM[a]	402
AE/SRC Canoe Lake 001	SW 6-10-71-16 W3	284402.2	6114430.6	466.3	Borehole log header	430
AE/SRC Canoe Lake 002	NE 3-2-72-16 W3	283454.5	6125556.8	435.8	Borehole log header	439
AE/SRC Parker Lake	NE 10-23-73-16 W3	287749.9	6137554.8	449.6	Borehole log header	411

[a] From U.S. Geological Survey and National Geospatial-Intelligence Agency (2010)

[b] Bedrock not encountered, depth to bottom of hole

Abbreviations: DEM, digital elevation model; SRTM, Shuttle Radar Topography Mission