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Buried Channels and Glacial-Drift Aquifers in the Fort McMurray Region, Northeast Alberta

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L.D. Andriashek and N. Atkinson

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Abstract

The understanding of the bedrock topography, buried bedrock valleys and channels, drift thickness and glacial aquifers in the surface-mineable and in situ–recoverable oil sands north of Fort McMurray has been updated by the acquisition and interpretation of more than 35 000 new borehole logs from the oil sands industry. Interpretations of these new data enable the construction of a three-dimensional model of the bedrock topography and subcrop, as well as the major buried aquifers contained within buried valleys and channels. From this model, a series of maps and cross-sections has been generated depicting the subsurface distribution of previously known and newly discovered buried aquifers that underlie the oil sands operations in the region.

Numerous buried fluvial erosional features have been mapped on the bedrock surface, either as bedrock valleys formed prior to the last glaciation, or as bedrock channels formed by glacial meltwater. Names have been assigned to the major valleys and channels to facilitate common understanding and discussion between industry, government and research institutions. Many of the buried channels exhibit features indicative of erosion by subglacial meltwater under a significant hydraulic head. These channels, referred to as tunnel channels, are commonly narrow, deeply entrenched, discontinuous to anastomosing and unconstrained by the topography of the pre-glacial landscape. Subsequent deposition of glacial sediment has effectively masked any surface expression of the buried valleys and channels on the modern landscape. As a consequence, and given their narrow form and discontinuous nature, many channels fall between regional oil sand resource-evaluation boreholes and remain undetected following initial exploration drilling. Mapping of the bedrock topography and buried drift aquifers also has been complicated by glaciotectonism, which has disrupted the normal stratigraphic setting in some areas by the processes of glacial thrusting, displacement and superposition of pre-existing strata on younger units.

Most of the buried bedrock valleys and channels contain a thick infill, as much as 90 m thick, of water-saturated coarse fluvial sediment ranging from fine sand to metre-sized boulders. These constitute buried aquifers that may be targets for the supply of potable water for municipal and industrial use. In places, the tops of the aquifers lie within 5 m of the surface. Unlike continuous and extensive aquifers found in large, preglacial bedrock valleys south of the study area, buried glacial aquifers in the Fort McMurray area are confined to isolated channels and valleys. Although they do not form a continuous, well-connected network throughout the oil sands region, buried valleys and channels can function as natural pathways for the subsurface movement of water or other fluids at the local scale.

The geological interpretations presented in this study are intended to provide the basis for a hydrogeological characterization of the groundwater contained within buried glacial aquifers in the Fort McMurray region. Recommendations are provided for further characterization of the hydrogeological setting of the drift and upper bedrock units in the region.

1 Introduction

Rapid expansion of existing and new developments in the Athabasca Oil Sands area north of Fort McMurray has generated a wealth of new subsurface geological information that reveals great complexity in the Quaternary sediments overlying the bedrock surface. Foremost is the recognition of local, sand-filled, glacial valley and channel systems eroded into the bedrock surface, the presence of which can have both environmental and economic impacts on oil sand developments.

This study updates our understanding of the distribution and geological properties of buried channel systems in the formerly glaciated landscape of the mineable and in situ–recoverable oil sands north of Fort McMurray (Figure 1). The study is a joint initiative of the Alberta Environment Northern Region (AENV) and the Alberta Geological Survey (AGS) of the Alberta Energy and Utilities Board (EUB) to update the existing AGS maps of buried bedrock and drift channels in the Athabasca Oil Sands mining area and the surrounding in situ recoverable area. There is a sense of urgency in producing these maps so the best possible regulatory decisions and approvals can be made in conjunction with construction and operation of the oil sands megaprojects. Updated regional maps in the public domain are expected to support the following desired outcomes:

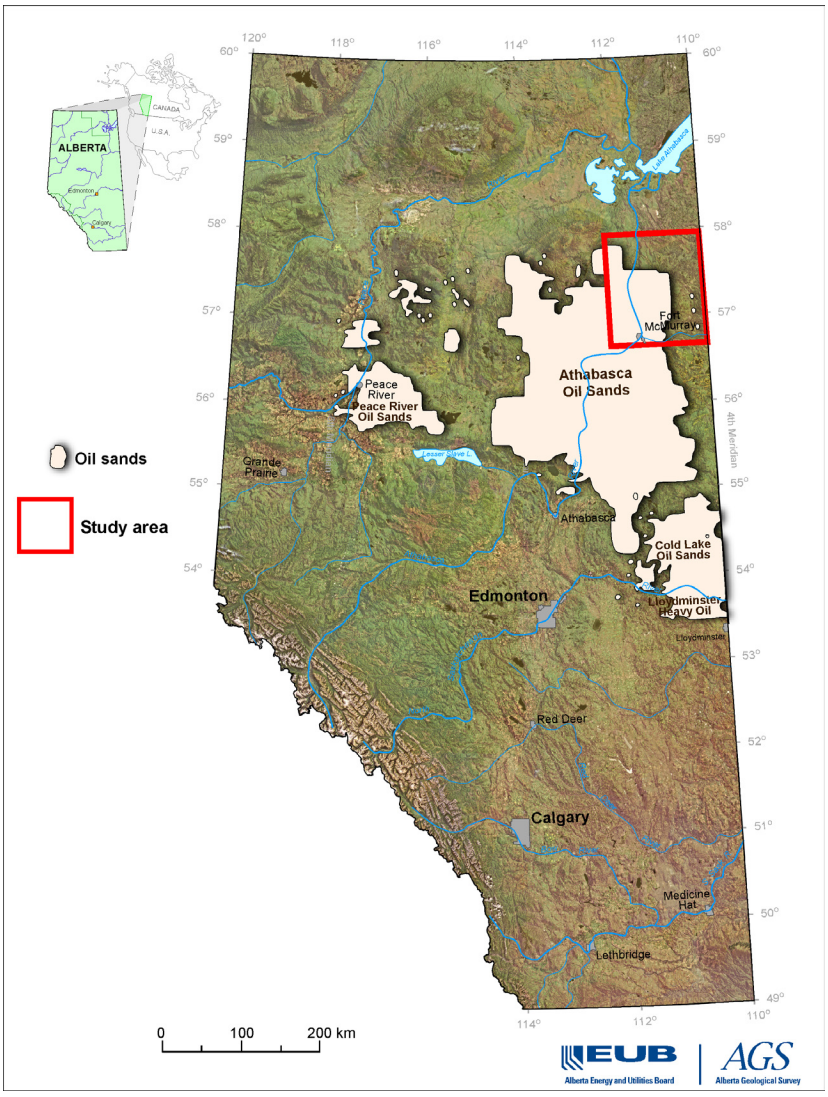


Figure 1. Location of the Athabasca Oil Sands area.

- Reduction of regulatory delays in mine and in situ facility approvals
- Environmental assurance that appropriate remedial measures will be taken by operators in response to surface or subsurface releases of regulated substances
- Recognition and management of cumulative impacts of oil sands mining on the surface water and groundwater via buried channel pathways
- Growing confidence in the AENV and EUB regulatory processes by industry, First Nations and general public stakeholders.

This report presents the interpretation of abundant newly acquired borehole data and information, provided mainly by the bitumen producers in the Fort McMurray region. The abundance of subsurface information now permits the development of detailed maps depicting the bedrock topography, subcrop distribution of bedrock geology units, locations of buried channels and valleys, and nature and distribution of the major aquifer systems contained within the glacial sedimentary sequence above the bedrock surface. These regional interpretive maps also contribute to a better understanding of the origin of channel systems, as well as insight into the timing of the events that were responsible for their creation. More importantly, the maps form the basis from which both regional and local hydrogeological studies can be designed to asses the nature and movement of groundwater in the landscape.

1.1 Relevance of Buried Channels to Oil Sands Developments

Buried channel systems in the Fort McMurray area are classed either as valleys eroded into the preglacial bedrock surface, or as channels nested within the overlying glacial drift. Bedrock channels include both preglacial drainage networks, formed prior to onset of regional glaciation, and glacial meltwater spillways that were incised through pre-existing glacial sediment and into the bedrock. Drift channels are glacial features related to the drainage of meltwater within tunnels at the base of the Laurentide Ice Sheet, or drainage of meltwater along the ice margin, and constitute part of the package of glacial sediments overlying the bedrock surface. Where glacial processes were influenced by bedrock topography, drift channels may overlie, occupy or downcut into older bedrock channels. Where glacial processes acted independently of bedrock topography, drift channels may crosscut bedrock channels or have no spatial association with them at all. Bedrock and drift channels may be infilled at the time of incision, leading to sand-filled channels, or they could have been infilled after the time of incision, leading to clay- or till-filled channels. The physical aspects of these channels, and mechanisms of formation, are discussed in this report.

When sand-filled, these channels contain potable water generally suitable for human consumption. At the same time, they can also act as natural conduits for subsurface migration of fluids associated with oil sands mining operations; e.g., dewatering. If incised deeply enough, these channels can act as windows to deeper aquifers, permitting bedrock-derived waters to commingle with potable near-surface waters. In some areas of in situ oil recovery using steam, such as Steam-Assisted Gravity Drainage (SAGD), channels can be incised deep enough to affect the protective cap rock above injection steam chambers in the oil sands.

Modern streams and rivers in the Athabasca Oil Sands area both reoccupy and crosscut bedrock and drift channels, increasing the risk that any contaminants inadvertently released into these buried channel systems may reach surface-water bodies before natural attenuation processes can mitigate their negative effects. Mapping the subsurface distribution of these channel systems delineates the intersections of paleochannels along modern stream banks and identifies areas of potential surface water–groundwater interaction.

The locations of buried channels can be difficult to predict because they can trend obliquely to modern-day land surfaces, have little to no surface expression, or be so narrow as to fall between the spacing of conventional resource-evaluation boreholes. As a result, mapping of these features requires a relatively high density of borehole information, combined with field examination of outcrops, where present-day rivers may have incised into buried channel systems.

1.2 Previous Work on Bedrock Topography and Buried Channels

The bedrock topography and major bedrock channels have been mapped previously by the AGS (Andriashek, 2000) or their consultants (McPherson and Kathol, 1977). The last major update was completed in 1996 with a hydrogeological study of the Birch Channel, which trends east from the Underground Test Facility to the Athabasca River. That study relied on drilling information available from the late 1980s and early to mid-1990s. Earlier AGS studies relied on much older and sparser datasets. Due to the large amount of drilling since then, the previous maps have become substantially out of date and do not reflect new knowledge gained from recent industry drilling, geophysical surveys and excavations.

Bedrock and drift maps for individual oil sand lease areas have been prepared by a number of different companies in support of Environmental Impact Assessments (EIA) and facility applications to both AENV and EUB. These maps usually terminate at the proponents' lease boundaries or areas of interest. A number of interpretive geology reports have been prepared by consultants to individual oil operators, but no operator(s) have presented any regional geological synthesis.

A more recent study of buried bedrock channels and glacial aquifers was completed by the AGS for the in situ–recoverable oil sands area south of the present study area, between Cold Lake and Fort McMurray (Parks et al., 2005; Andriashek, 2002).

2 Scope of Study

2.1 Introduction

The primary objective of this study was to acquire, compile and interpret abundant recently generated borehole data to create a dynamic model of the near-surface geology of the oil sands area, focusing on the distribution of buried channels on the bedrock surface and within the overlying glacial sediments. Of immediate concern is the management of surface-water and groundwater resources, as the region is undergoing one of the most intense industrial developments in North America. Although water-resource management is not the focus of this study, it is clear that delineating and mapping buried potable glacial aquifers will play an important part in the collective understanding of surface-groundwater interactions, and the overall management of water in the region. For this reason, the underlying theme of this report is to view the geological setting from the perspective of the intrinsic permeability of the geological sediment (i.e., its capacity to either transmit or retard the movement of water in the landscape).

The outcomes of this work are depicted as digitally derived maps and a report to be disseminated for public, industry and, most importantly, government regulatory use. It is anticipated that this model will form the basis for future work on developing a more comprehensive glacial-drift stratigraphy, which can be applied to other issues such as aggregate resources, urban development and other land uses, as well as providing the framework for assessing the near-surface hydrogeology of the region.

2.2 Extent and Physiographic Setting of Study Area

The study area is constrained to the surface-mineable and in situ–recoverable oil sands deposits that lie north of Fort McMurray. This encompasses an area of about 18 000 km^2 in Townships 88–100, Ranges 1–15, west of the 4th Meridian (latitude 56.75°–57.75°, longitude 110°–112.5°; Figure 2). The area includes parts of four National Topographic System (NTS) map sheets: the northern part of NTS 74D, most of NTS 74E, the northeastern part of NTS 84A and the eastern part of NTS 84H. The Clearwater River and the Athabasca River form a natural boundary along the south, and Muskeg Mountain and the Birch Mountains form natural boundaries to the east and west, respectively.

The major physiographic features depicted in Figure 2 are digital renderings of map units derived from Pettapiece (1986) that were subsequently draped on a 50 m resolution digital elevation model (DEM) derived from data collected in 2000 by NASA's Shuttle Radar Topography Mission (SRTM). Figure 3 provides an oblique 3-D view of the topography derived from the SRTM DEM. The most notable feature is the broad lowland in the central part of the study area, referred to here as the Athabasca River lowland (comprising the Embarras, Dover, Kearl Lake, Buckton and Johnson Lake plains; Pettapiece, 1986). This lowland is flanked by the prominent highlands of the Birch Mountains to the northwest, and the less pronounced Muskeg Mountain to the east. Surface elevations range from 220 m above sea level (m asl) along the floodplain of the Athabasca River to 650 m asl on Muskeg Mountain and 850 m asl in the Birch Mountains. Less prominent but notable physiographic features are the Fort Hills, located south of McClelland Lake in the north-central part of the area and included as part of the Johnson Lake Plain, and the locally high-relief features that constitute the Firebag Plains on the eastern edge of the area along the Alberta–Saskatchewan border. The relationships between these physiographic features and the underlying bedrock topography will be addressed in more detail in a subsequent part of the report.

Surface drainage radiating from the uplands is captured by the High Hill, Steepbank, North Steepbank, Muskeg, Firebag, MacKay, Dover and Ells rivers. These tributaries supply the Athabasca and Clearwater rivers, which are incised into the Athabasca plain. The central lowland region is generally characterized by numerous wetlands that are poorly connected to the surface drainage, although this natural drainage has been affected by local surface-mining operations.

Fort McMurray is the major settlement in the area, followed by the small aboriginal community of Fort MacKay. More than half of the study area is currently leased for oil sand development (Figure 4), with road access being restricted to the major oil sand operators (Figure 4). Surface-mineable operations account for about one-third of the leased area, primarily within the Athabasca River lowland where depth to pay is relatively shallow. In situ recoverable operations, mostly SAGD, account for the remaining two-thirds of the lease area in the flanking uplands. Interestingly, the present-day surface-mine excavations are sufficiently deep to be captured as steep-walled depressions on the SRTM DEM.

3 Data Sources, Management and Methods of Interpretation

3.1 Data Sources

Three-dimensional maps of the bedrock topography and elements of the Quaternary stratigraphic sequence within the oil sands area north of Fort McMurray were constructed using data from a number of sources. Borehole log information (lithologs and petrophysical logs), augmented by field-based outcrop mapping, provided the important data for defining the major bedrock geological units in the study area, constructing the topography of the pre-Quaternary bedrock surface, and defining the channel aquifer systems within the glacial drift.

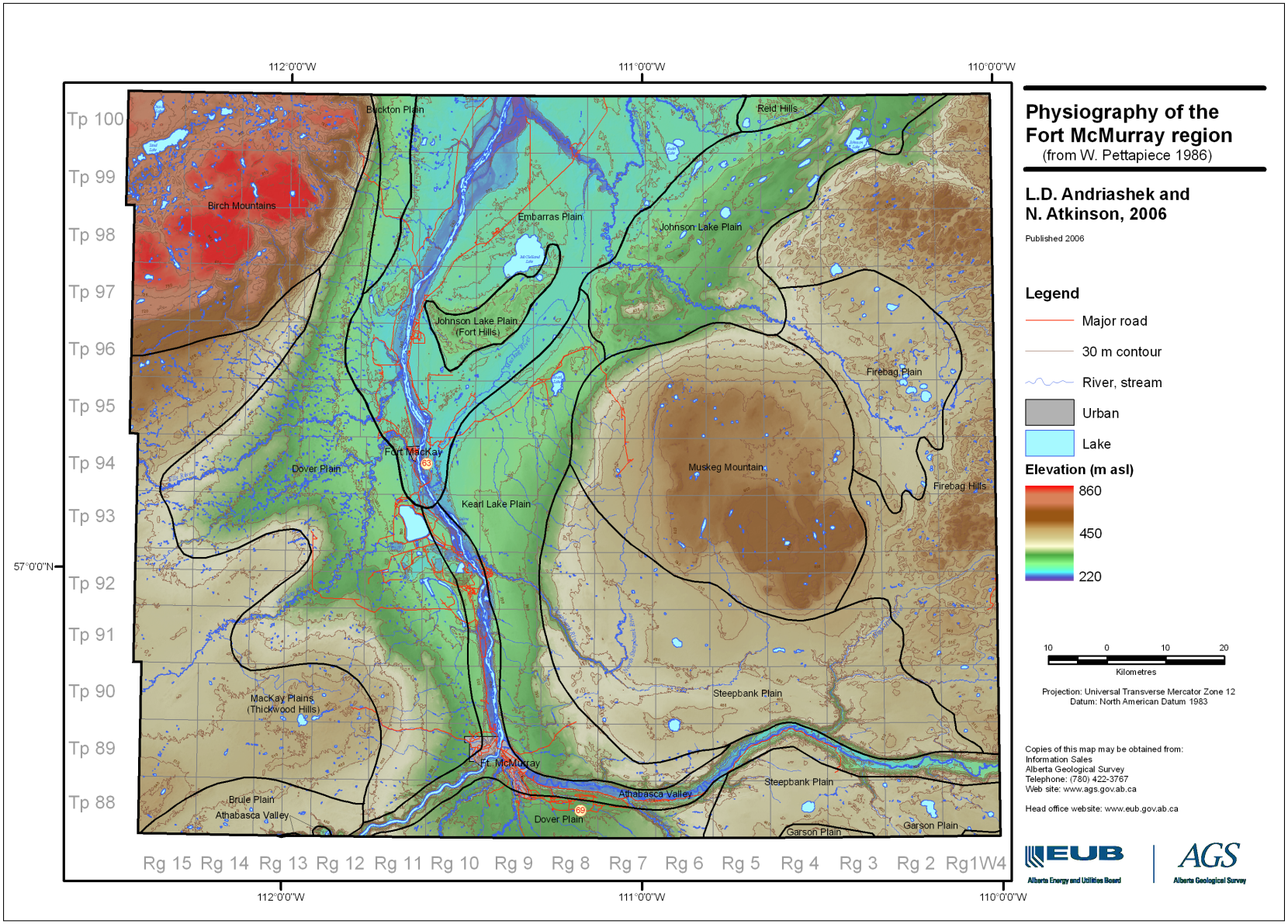


Figure 2. Physiography and topography of the Fort McMurray region.

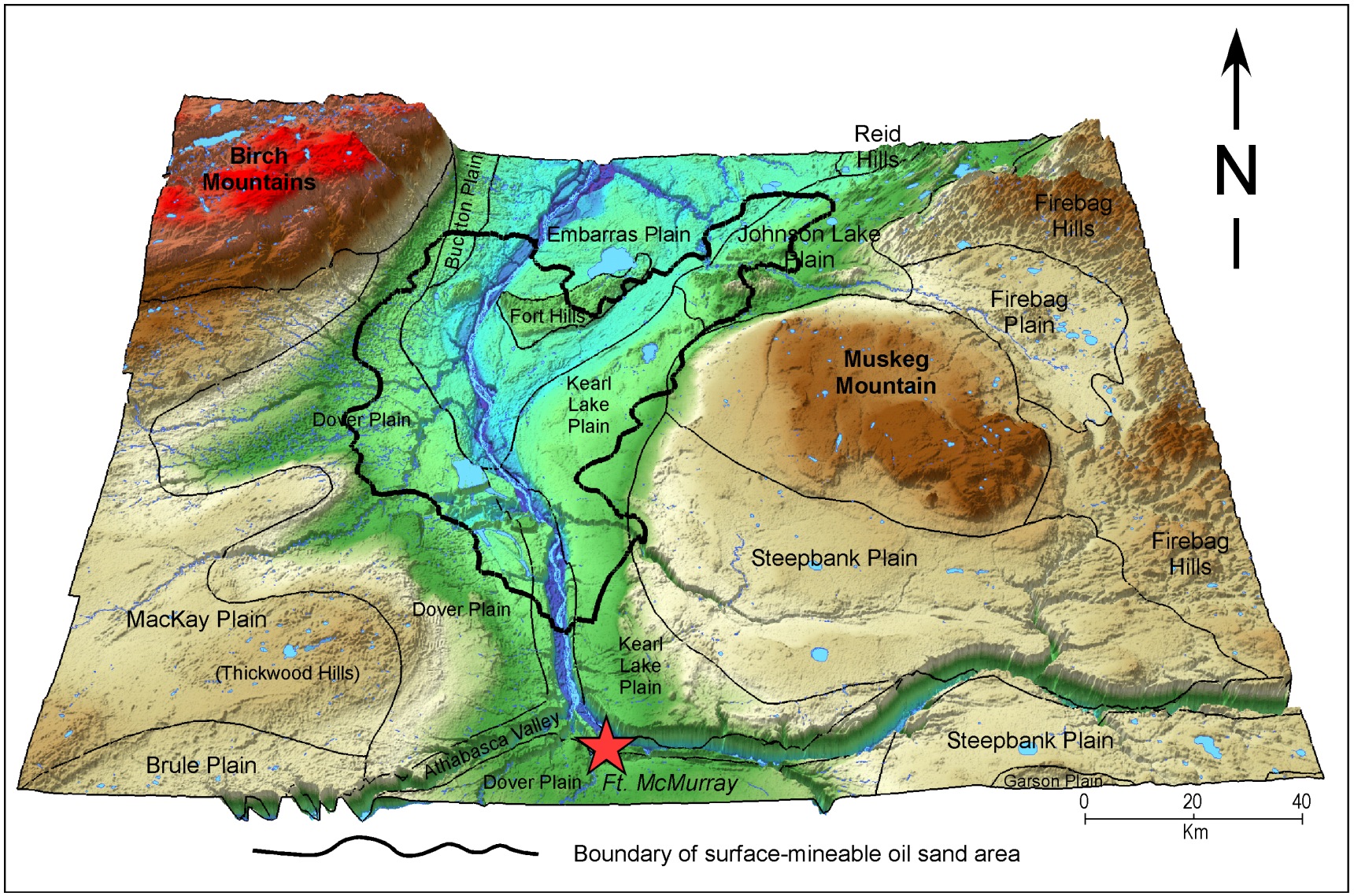


Figure 3. Oblique 3-D rendering of digital elevation data derived from NASA's Shuttle Radar Topography Mission (SRTM), Fort McMurray region.

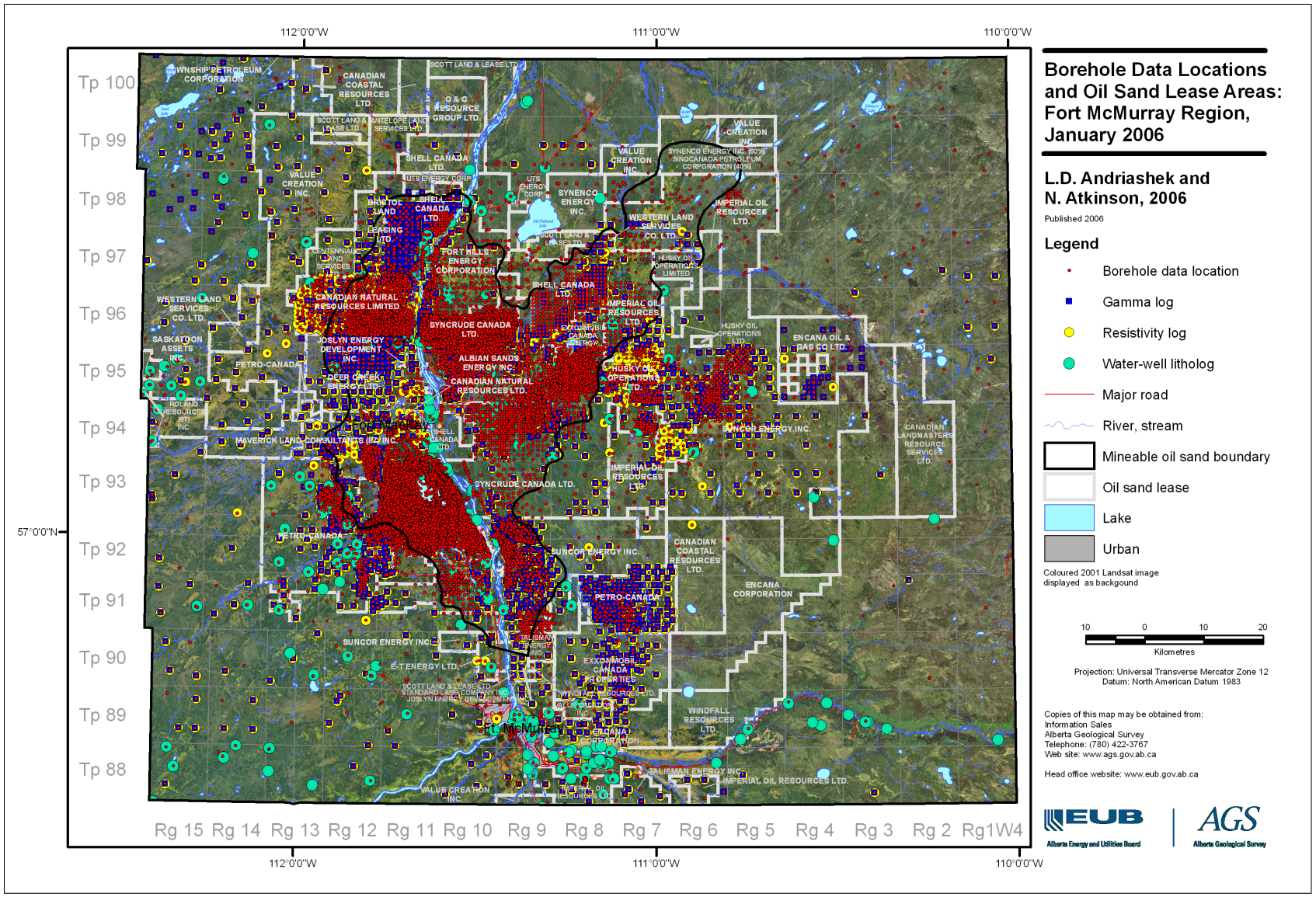


Figure 4. Locations of oil sand lease areas and distribution of borehole data (superimposed on LANDSAT image), Fort McMurray region.

Prior to this project, AGS data holdings for the Quaternary stratigraphic sequence amounted to about 2500 borehole logs and surface outcrop descriptions. A request that industry provide data from their private holdings yielded about 35,000 new borehole records (Figure 4). These records have greatly increased the number of geological unit boundary picks and correspondingly improved interpretation of the geology in the region. Of these, about 30 000 boreholes include borehole lithologs, about 3000 include digital petrophysical logs available from private vendors, and the remainder consist of an assemblage of stratigraphic logs and water-well lithologs. The distribution and density of the data are highly varied, with most of the data clustered around major surface-mine operations (Figure 4). For example, mine-design boreholes in some lease areas are completed on spacings as dense as 75 m, whereas borehole spacing outside the lease areas can range from 7 to 10 km.

Additional information was derived from digitized paper files in AGS data holdings, particularly from maps included in EIAs submitted by industry to government regulatory agencies. Raw data supplied by external sources were incorporated directly into the AGS database, recognizing that there may be errors in the geospatial attributes of the data or in the quality of the actual interpretation. Changes or corrections to these data were made only when supported by other information.

Interpretations of geological formation or unit tops were made from a range of sources, including new formation picks made by AGS from oil and gas industry petrophysical logs, tables of stratigraphic picks supplied by geologists at individual oil companies, borehole litholog descriptions from various drilling methods on oil sands leases, and a minor number of borehole litholog descriptions from the water-well-drilling industry. Collectively, the logs provide sedimentological or lithological interpretations of the well cuttings, and downhole geophysical data recorded in both open-hole, uncased conditions (resistivity, spontaneous potential) and cased-hole conditions (gamma-ray logs). These records, which in some cases comprise a legacy of paper files, were reviewed by AGS staff for completeness of geospatial information before being digitized, and entered into a single relational digital database (Microsoft® Access™) using a standardized data entry procedure.

As a final comment, hydrogeological information pertinent to the glacial-drift stratigraphy in the region was not collected during this study, nor was this information provided by industry.

3.2 Data Management

Borehole information supplied by industry was submitted in varied formats and converted to a standard format before being entered into a relational database prior to geological modelling. The database model is relatively robust, linking tables of geospatial data, borehole completion information, geological data (stratigraphic and lithological) and data quality through a series of formally defined relationships and queries that enable the interpreter to mine the database for the information needed to model individual geological units. Much effort was expended to standardize and convert the input sources to this common data structure, and data validation, culling, and screening became an iterative process during the course of the project. The result is that this region of the Athabasca Oil Sands now has one of the most populated databases of upper bedrock and Quaternary geology information available in Alberta.

In the normal course of defining the stratigraphy, borehole logs (petrophysical and lithological) provide the input data from which stratigraphic interpretations, or ‘picks’, are made. It is these pick values, not the original lithological data, which are used in the construction of the geological model. Geological records associated with a single borehole can contain stratigraphic picks from numerous sources and of varied quality, so each pick is subjectively ranked with respect to its reliability before being entered into the database. The database is then sorted (queried) by these rankings, to ensure that only the best quality data

are returned to be used in the modelling process. The use of this method of classifying the data, based on subjective ranking, ensures that unnecessary or problematic data are not used in the geological model.

The modelling software used to generate the maps and cross-sections for this study was dynamically linked to the database. This linkage not only permitted the posting of map data to be automatically updated as deletions or additions were made to the database, but it conversely enabled the database to be updated dynamically as changes to interpretations were made on the maps and cross-sections.

3.3 Methods of Interpretation

3.3.1 Digital Modelling

Digital maps of the surfaces and thicknesses of geological units were created by 3-D interpolation of stratigraphic pick data using VIEWLOG™ modelling software. Besides being able to view data in various forms (e.g., digital petrophysical logs, lithologs and graphical figures), the software creates digital models of surfaces that, when stacked in proper stratigraphic order, provide a 2.5-dimensional rendering of the subsurface geology. This is important to understanding the geology of the region because the package of stacked surfaces can be digitally sliced in any number of ways to provide views of the subsurface that otherwise would be difficult to visualize or comprehend. Also, because cross-section renderings are dynamically linked to the modelled surfaces, geological unit boundaries and margins can be validated in both plan and cross-section views. This ensures that the modelled surfaces of lower geological units do not violate three-dimensional space by crossing the surfaces of higher units. Furthermore, the model can be used as a predictive tool that provides insight into what the stratigraphic framework may look like in areas where data are absent. Lastly, boundary edges and geometries can be better defined by the application of a digital model than if defined by hand-drawn lines.

Geographically, the x and y co-ordinates of the digital model developed for this study were constrained to the area defined by UTM Zone 12 co-ordinates 412625–561725E, 6272272–63999664N (NAD 83). The z co-ordinate (depth) encompassed that part of the geological column extending from the top of the McMurray Formation to the present-day land surface. Given the abundance of closely spaced data generated on individual lease holdings, a 100 m grid-cell size was chosen as the most appropriate resolution to interpolate the elevation of each geological surface throughout the project area. This yielded a grid of 1490 columns by 1274 rows, for a total of about 1.9 million cells of data. It should be noted that, although this grid density was suitable for depicting modelled surfaces at a regional scale, the selected grid-cell size prevented any features smaller than 100 m from being depicted on the modelled surfaces.

One of the major challenges in modelling this area related to the non uniform, clustered distribution of the data (Figure 4). A varied data density yields modelled surfaces that have a correspondingly varied degree of confidence. Not only does confidence vary as a result of borehole density, but there is also variability in the amount or type of data recorded at each borehole site. For example, not all stratigraphic units were present or could be interpreted at a given site, so there were numerous stratigraphic pick values for some geological formations and very few for others. This differing degree of data density can affect resolution of the digital model, requiring modelled surfaces with poor data density to be adjusted or constrained to overlying or underlying units that have greater data control. Figure 5 depicts the sequence in which the numerous surfaces of the model were generated. It illustrates that, unlike the normal bottom-up approach typically used to construct stratigraphic models, the highest priority was given to modelling those surfaces that either had the greatest amount of data or about which there was the greatest understanding regarding the processes by which they were formed. Unconformable surfaces, such as the present-day land surface and the pre-Quaternary surface (bedrock topography),

were considered to be the most critical surfaces in the model because they constrained the modelling of all other geological units.

Each of the resulting digital grids of the geological surfaces generated by the software underwent a process of validation and, if necessary, correction, ultimately to be combined into a single 2.5-dimensional rendering of the stratigraphy of the region. These grids of digital unit surfaces are considered to be the most important product generated in this study as they can be input into other geological and hydrogeological models developed by industry and other government agencies.

3.3.2 Application of Synthetic Data to Create Realistic Modelled Surfaces

The initial spatial distribution of each geological surface, including the unconformable bedrock surface, is determined from the x, y and z co-ordinates of the stratigraphic picks in the database. A number of modelling algorithms were evaluated for their ability to perform the interpretations before the inverse distance method was selected. In this study, the method applied a linear least-squares estimation algorithm to model each geological surface in every 100 m grid cell, including those far removed from point data locations.

Typically, the initial modelled surfaces did not acceptably portray the geologist's conceptual understanding of the subsurface. Discontinuous or narrow linear elements, such as glacial meltwater channels, were particularly difficult to model because modelling algorithms compute cell values by interpolation methods, whereby the x, y and z values in each grid cell are influenced, in part, by values in neighbouring cells. This often leads to an underestimation or smoothing of the actual geometry of a local feature. Furthermore, no algorithm can produce a realistic model where data are absent, particularly across areas of relatively high relief. Nevertheless, such problems can be addressed, in part, by refining the modelled surface with digitized hand-drawn contours or polylines (each of which has geospatial x, y and z values), herein referred to as 'synthetic' data.

In areas of poor data control or where modelling algorithms underestimated the subsurface topography, such as along the thalwegs of bedrock valleys and channels, hand-drawn contours, or polylines, were introduced to constrain or refine the geometry of the modelled surface. This is akin to hand drawing a contour map except that, in this method, every click of the digital drawing tool creates a synthetic data node with the same z value (elevation) but different x and y values. These node data were stored in the map file, independent of the stratigraphic pick values in the database, but could be invoked along with the pick values in the database to provide additional information during the modelling process. Constraining the subsurface was therefore accomplished very quickly by modelling polyline node data to generate a new grid, or by modifying existing polyline nodes whenever additional data became available.

An additional technique used to further refine the modelling of unconformable surfaces, such as deep incisions in the bedrock topography, involved the creation of synthetic polyline node data from digital lines drawn along geological cross-sections. Due to high local relief of deeply incised channels and valleys, their morphology and configuration were frequently underestimated by the algorithms. Therefore polylines defining the base and sides of each valley were drawn on cross-sections along, and at successive increments away from, each valley thalweg. Unlike hand-drawn contour lines drawn in plan view, in which each polyline node has the same z value, each node on hand-drawn cross-section lines can have a different z value. The density of these synthetic data can be controlled by increasing or decreasing the node spacing through a command in the software, to enable the geometry of the channel aquifer to be well constrained. These synthetic data were tested by comparing and adjusting their values to 'real data' from nearby borehole log information. An iterative contour propagation and validation process eventually

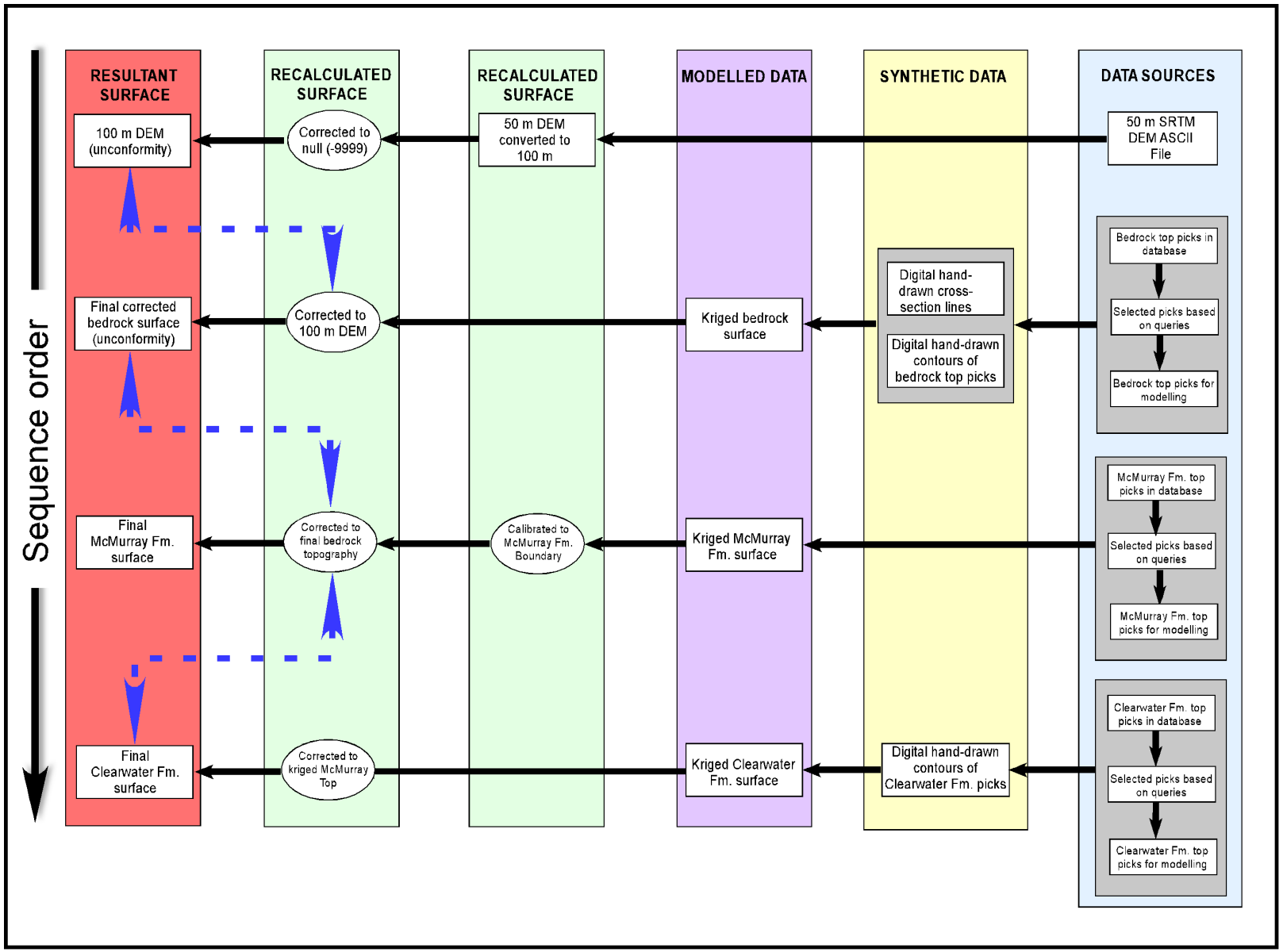


Figure 5. Work flow used to construct structural and unconformable surfaces for the three-dimensional geological model of the Fort McMuray region.

produced a suite of synthetic values that honoured both real data from boreholes and conceptual understandings of geometries of subsurface landscapes created by different geological processes.

In summary, synthetic data, generated in both plan and cross-section view, were not obtained from any type of direct observation but created according the geologist's conceptual view of the most likely geometry of the channel form. The gridding algorithm still honoured each stratigraphic pick in the database, but erroneous interpolations of complex geological conditions were constrained by the synthetic data. The resulting surfaces not only respect the borehole data but also the conceptual understanding of the stratigraphy and geological evolution of the subsurface.

3.3.3 Verifying and Refining the Model — Grounding the Model in Reality

The resulting three-dimensional stratigraphic model of the Fort McMurray region has been tested and refined by field mapping, and by the systematic inspection of geological cross-sections constructed across the project area. Aerial surveys were flown by the authors to locate key stratigraphic sections exposed throughout the project area. Stratigraphic logs generated from the field descriptions were used to verify the geological model and to refine the surfaces of each geological unit. In addition, observations and descriptions of the sediments exposed at outcrops and man-made exposures provided valuable insights regarding the genesis and intrinsic hydraulic properties of the sediment.

Verification of the model was performed by constructing cross-sections through the stratigraphic succession to ensure that each of the modelled surfaces was nested properly and honoured the well picks. Inconsistencies or errors in the geometry of any of the geological surfaces were evaluated and, whenever necessary, the reliability of the picks constraining that surface were checked in the modelling database. In the case of unreliable data, logs were either reinterpreted by the authors or excluded from the modelling dataset. Alternatively, problems with the algorithms associated with the method of interpolation were resolved by introducing synthetic data into the modelling. After each phase of testing, algorithms were re-gridded and each of the geological surfaces was re-kriged.

These techniques combined the authors' knowledge of the regional geology with the computational power of a GIS to create maps superior to those produced by either approach alone.

4 Bedrock Geology

A brief description of the bedrock geology is provided here to set the framework for understanding the relationship between the Quaternary glacial sedimentary succession and the underlying bedrock topography and geology. This relationship is best depicted graphically (Figure 6) by means of a stylized cross-section constructed in the Western Canadian Sedimentary Basin in the northeastern part of the province.

The subsurface distribution of bedrock geology units in the study area is constrained by three major unconformities, shown as wavy lines in Figure 6. These are the pre-Devonian unconformity on the surface of the Precambrian Shield; the sub-Cretaceous unconformity on the surface of Paleozoic rock units; and the Quaternary unconformity on the surface of Cretaceous rocks, represented by the present-day bedrock topography. Of greatest interest to this study are the uppermost bedrock units, consisting of Lower Cretaceous rocks that have been exposed and eroded during the interval from the Tertiary to the present.

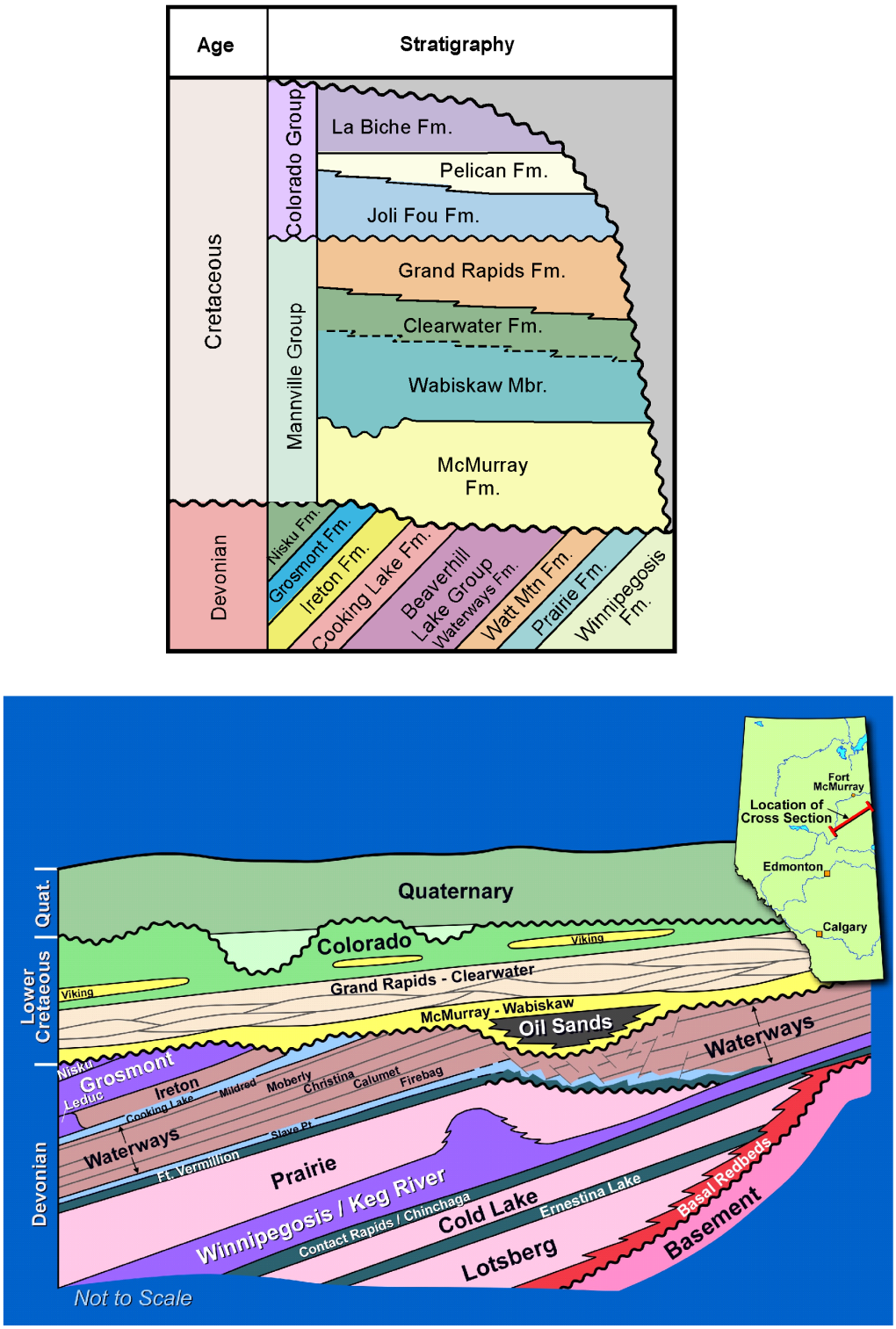


Figure 6. Bedrock stratigraphy in the Athabasca Oil Sands area, northeastern Alberta.

4.1 Mannville Group

The Mannville Group consists of a suite of heterogeneous clastic sedimentary units that lie unconformably in large valley systems eroded into Paleozoic carbonate units (Mossop and Shetsen, 1994). In the Fort McMurray area, the Mannville Group comprises three major formations: the lowermost McMurray Formation, the Clearwater Formation and the uppermost Grand Rapids Formation. These three formations host most of the oil sands in the study area.

4.1.1 McMurray Formation

The McMurray Formation comprises mainly fluvial and estuarine point-bar deposits, composed mainly of sand (Langenberg et al., 2003). Historically, the McMurray Formation has been divided into three informal members, the Lower McMurray, the Middle McMurray and the Upper McMurray, but more recently the distinctions between the Middle and Upper McMurray are not considered feasible on a regional scale (Langenberg et al., 2003). Sedimentary rocks of the Lower McMurray member are composed of conglomerate, sand, silt and shale (Carrigy, 1973), which were deposited by northward-flowing braided fluvial systems that infilled topographic lows on the underlying sub-Cretaceous unconformity (Carrigy, 1973). The topographic lows were progressively infilled with uniform quartz sand of the Middle McMurray member, which later became oil impregnated. The subsequent interaction between fluvial and estuarine environments resulted in a high degree of sediment heterogeneity. In places, coal and mudstone overlie the McMurray Formation, which is inferred to record widespread flooding events prior to marine transgression. Dissolution of underlying evaporite deposits, and subsequent collapse during sedimentation, provided additional complexity to the sedimentary record. In much of the study area, the lowermost Lower McMurray sedimentary rocks that occupy the deep parts of the erosional unconformity are water bearing. Elsewhere, the Lower McMurray member is saturated with bitumen of moderate to high grade (Langenberg et al., 2003). The surface of the Lower McMurray has an unconformable, irregular topography that shows the effects of erosion by Upper McMurray estuarine channels (Langenberg et al., 2003). The Upper McMurray is characterized by estuarine or bay-filled sand and mudstone associated with marine transgression, resulting in a relatively flat surface (Langenberg et al., 2003).

4.1.2 Clearwater Formation

The Clearwater Formation represents transgressive marine sediments deposited by an invading sea. The upper part of the Clearwater Formation is not found in the study area, but the middle part comprises gypsum-bearing grey shale, with minor siltstone and ironstone, deposited in an open-shelf marine environment (Carrigy, 1973; Appendix 1, Figure 83). The lower part of the formation contains the Wabiskaw Member, a dirty to shaly glauconitic sandstone that lies conformably on the McMurray Formation. Within outcrops along the Clearwater River, the top of the formation has been observed to be transitional, and interfingers, with the overlying Grand Rapids Formation (Carrigy, 1973; Kramers and Prost, 1986).

4.1.3 Grand Rapids Formation

The Grand Rapids Formation consists of a clastic sedimentary sequence that prograded northwest into the Boreal Sea in response to an influx of sediments following increased tectonism in the Cordillera to the southwest (Kramers and Prost, 1986). The depositional model is described as a “barrier island/beach coastal plain complex deposited in a wave-dominated, high energy shoreline” (Kramers and Prost, 1986). Shoreline positions are believed to have either prograded seaward or shifted landward in response to basin subsidence caused by isostatic loading and variable sediment influx (Kramers and Prost, 1986). Three massive sand units, each representing episodic transgressive-regressive cycles related to tectonic

pulses in the Cordillera, are mapped within the Grand Rapids Formation southwest of the study area. Moving progressively northward, the formation comprises interbedded, fine-grained sandstone, siltstone and mudstone, with clean sandstone beds that are up to 10 m thick in places (Cotterill, 1996). The base of the formation has a transitional contact with coarsening-upward sedimentary rocks (silt) of the underlying Clearwater Formation, and differentiation on the basis of petrophysical log interpretation can be challenging. In contrast, the contact with the overlying Joli Fou Formation is disconformable and sharp (Cotterill, 1996).

The bulk of the Grand Rapids Formation is composed of fine-grained quartzose and feldspathic sandstone described as having a 'salt-and-pepper' appearance (Hamilton et al., 1999). Laminated siltstone and shale with thin coal seams are also present. Most of the sandstone is noncemented to poorly cemented, although spherical calcareous concretions up to 3 m in diameter are observed in section (Carrigy, 1973). The formation is porous and permeable, as indicated by the numerous small springs that occur at the contact with the underlying Clearwater Formation (Carrigy, 1973).

4.2 Colorado Group

4.2.1 Joli Fou Formation

The Joli Fou Formation consists of dark grey fossiliferous marine shale deposited by a major transgression of the Boreal Sea, which returned to cover most of Alberta (Kramers and Prost, 1986; Hamilton et al., 1999). Contact with sandstone of the underlying Grand Rapids Formation is defined by a relatively sharp break on petrophysical log signatures. The formation is disconformably overlain by the Pelican Formation, and the erosional surface between the two shows significant relief (Cotterill, 1996). The Joli Fou Formation is recognized west of the Athabasca River in the Birch Mountains, but its extent east of the Athabasca River remains unclear. An outlier of the Joli Fou shale is likely present in Twp. 93, Rge. 4, W 4th Mer. As will be discussed in the section of drift thickness, however, there are other factors that can influence the interpretation of clay-rich beds in that part of the study area.

4.2.2 Pelican Formation

The Pelican Formation consists of fine-grained quartzose sandstone and glauconitic siltstone, interpreted to be reworked Grand Rapids Formation sand deposited in an offshore marine-bar complex (Kramers and Prost, 1986; Hamilton et al., 1999). The formation comprises well-washed, variably shaly, fine- to medium-grained glauconitic sandstone, with pebbly to conglomeritic beds near the top of the unit. In the Birch Mountains, as much as 50 m of unconsolidated, light beige to white, quartzose, medium-grained sand have been mapped in outcrops along the northeast side of mountains (Cotterill, 1996). The extent of the Pelican Formation east of the Athabasca River remains uncertain.

4.2.3 La Biche Formation

The La Biche Formation consists of dark grey and brown shale and silty shale that conformably overlies the Pelican Formation (Cotterill, 1996). The La Biche Formation includes two important stratigraphic markers: the Base of Fish Scales horizon (a radioactive shale) and the Second White Specks horizon. In the central part of the province, these marker horizons have been assigned formal formation status (Bloch et al., 1993). The La Biche Formation is mapped within the Birch Mountains west of the Athabasca River, but is not thought to subcrop to the east.

5 Surficial Geology

5.1 Introduction

The discussion of the bedrock topography and buried channels will be preceded by recent updates on the surficial geological sediments that rest on the bedrock surface. For the purposes of the following discussion, it is useful to explain how surficial geology maps are constructed and the type of information that they are intended to convey. This will be followed by comments on some of the challenges previous workers have experienced in classifying the surficial sediments in the study area.

Surficial geology maps are designed to portray a blend of information on the physical properties of sediments at or near the surface, the form and nature of the landscape in which they are found, and their mechanisms of formation. All of these concepts are tied into the map unit, and map units are differentiated by these attributes. A key point is that not all of these attributes are required to create a map unit: a surficial geology map unit can be defined by a single attribute in the absence of other information.

A further point worth discussing is the ambiguity that often results when genetic terms, which are used to describe how a unit was created, are used to describe the physical characteristics of that unit. This is especially evident with the word 'till', which is often used interchangeably to describe both composition and genesis. In the strictest sense, till is a genetic term used to describe sediment deposited directly by, or from, a glacier. Implicit in the term's meaning, however, is that the material is composed of well graded, nonsorted, heterogeneous particle sizes ranging from clay to boulders, all of which are captured by the lithological term 'diamict'. Thus, a regionally extensive diamict is interpreted as till, deposited by a glacier, if no other geological process can equally well explain the genesis and composition of the material. The term 'till', however, is not synonymous with 'diamict', and only indicates that the sediment was deposited, or significantly modified and altered, by glacial ice.

Composition and genesis can also be inferred from other surrogate information such as morphology of landscapes from airphoto analysis, without any evidence of ground truthing or field examination of sediments. The major difficulties that arise in mapping surficial geology occur where attributes regarding the physical nature of the sediment are in conflict with the origin of the sediment. The morphology of a landscape may infer genesis by one geological process, whereas the composition and internal structure of the material might imply genesis by another process. Lack of clarity on these issues is further compounded by the adoption of ambiguous terminology. Such has been the case in the project area, as discussed below.

5.2 Challenges in Classifying the Surficial Geology of the Study Area

Approximately 80% of the surficial geology in the study area, represented by NTS areas 74D and 74E, was mapped by the AGS in the early 1970s (Bayrock, 1971; Bayrock and Reimchen, 1974; Figure 7). A subsequent study was undertaken on behalf of the AGS to evaluate the surficial geology of the proposed mining areas (McPherson and Kathol, 1977), but the report and maps have not been published or widely distributed. Most of the study area is mantled by materials that can be characterized as having been deposited directly by glacial ice (till, ice-contact moraine), by water associated with the melting and wasting of glacial ice (lacustrine deposits, fluvial outwash deposits), or by wind modification of water-laid deposits (eolian deposits). Although the occurrence and distribution of each type of deposit is influenced by former ice-marginal positions, their distribution also coincides with major physiographic features. As might be expected, water-laid deposits of glaciolacustrine and glaciofluvial origin are found primarily in the lowest parts of the landscape, along the margins of the Athabasca and Clearwater rivers, whereas the uplands are mantled by till.

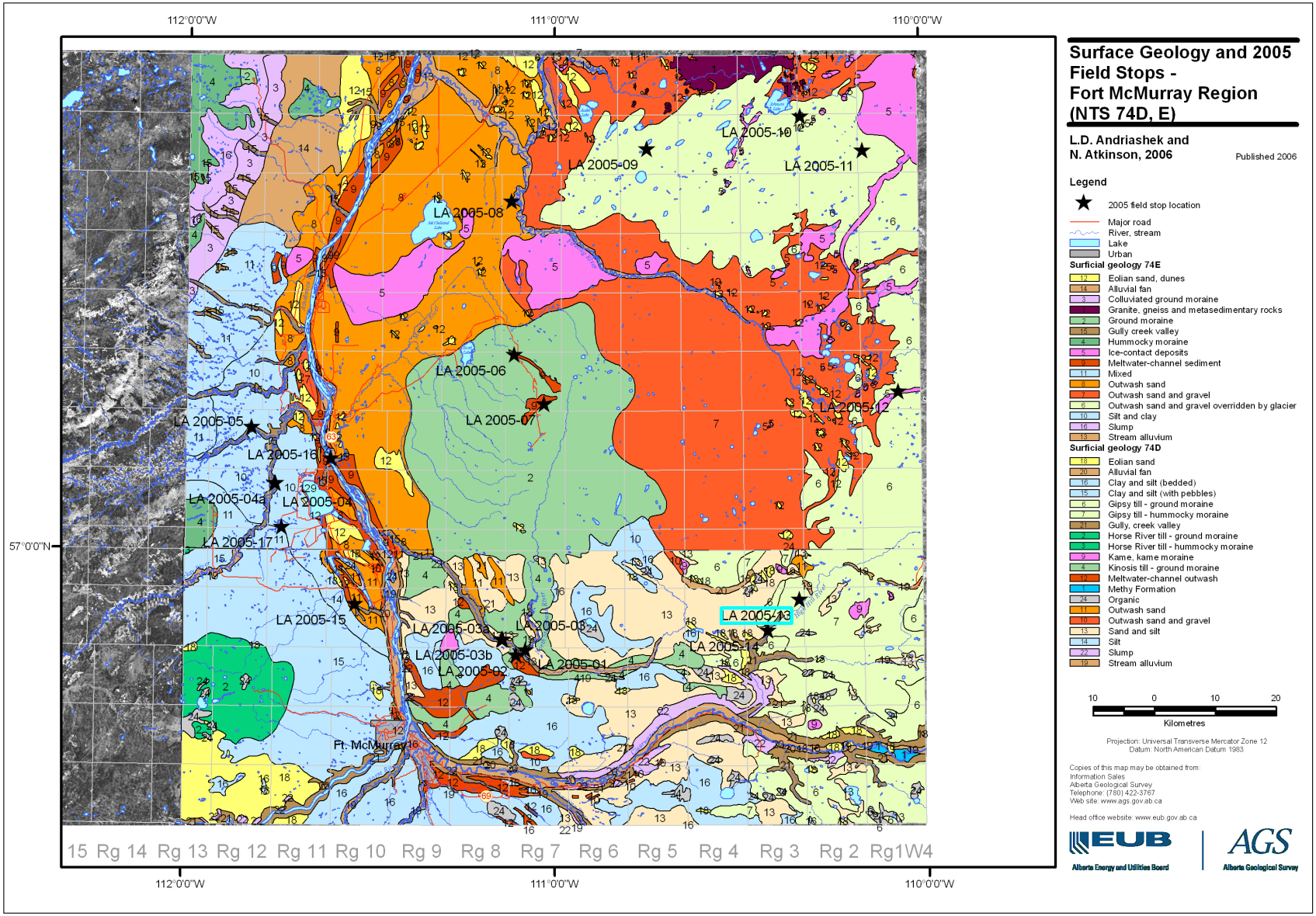


Figure 7. Synoptic surficial geology map showing stops made during the 2005 field season.

Figure 7 highlights, however, some significant irregularities in the classification and distribution of surficial sediments in the region. Firstly, the discordance of some map-unit boundaries along the contact of map areas NTS 74D and 74E attests to some fundamental differences of interpretation, by the same author, regarding the genesis of the sediment. This is most evident in the eastern part of map area, where an extensive deposit mapped as outwash sand and gravel in NTS 74E (Figure 7, unit 7) terminates abruptly at the join between the two map sheets, juxtaposed against sediment classed as till or moraine (Gipsy till). What appears to be an obvious map boundary error in fact illustrates one of the shortcomings of a map that attempts to document simultaneously the physical properties *and* genesis of surface sediments. In the discussion regarding the nature of the sediments of these two map units, Bayrock (1971) and Bayrock and Reimchen (1974) described both as being composed primarily of sand (up to 90%) with a silt matrix. In NTS area 74E, Bayrock (1971) interpreted this sand as being water laid, whereas, in NTS area 74D, the sand was classed as glaciogenic on the basis of sediment-landform associations, having been glacially reworked into drumlins and flutings (Bayrock and Reimchen, 1974). Bayrock wrestled with the dilemma of trying to account for sandy materials that appeared to have been deposited by flowing water, with a landscape that clearly showed the effects of having being modified and sculpted by active ice. His solution was to classify the adjacent landscape (unit 6 in NTS area 74E) as "outwash sand and gravel overridden by glacier." This term captures the evolution of a landscape that was originally formed by glaciofluvial processes to one that was subsequently modified by glacial processes. Because the last major geological agent that acted on the landscape was glacial and not fluvial, however, the equivalent map unit directly to the south in NTS area 74D was classified as till (Gipsy till), even though the material is not a heterogeneous assemblage of particle sizes (i.e., diamict) but composed mainly of sand, with a silt matrix.

The nuances of geological classification are not one of just academic discussion. Decisions regarding land use, surface and groundwater use, and geotechnical properties of sediments for purposes of locating large facilities are all based, in part, on information conveyed on geological maps. Fundamental differences in the understanding of what information is being conveyed on surficial geology maps can lead to significantly different decisions being made regarding land use. The latter part of this report illustrates how reclassifying the surface sediments on the basis of their inherent permeability, and not genesis, can profoundly change the interpretation of the nature of surface water and groundwater interactions in the study area.

5.3 New Observations Regarding the Near-Surface Geology

Much new geological information has been generated in the thirty years since the regional surficial geology maps were published. Individual companies have conducted mapping surveys on their own leases as part of the requirements to fulfill EIA's, and the amount of subsurface information has therefore increased significantly with exploration drilling. In the summer of 2005, the AGS conducted a field program to examine exposures of surficial materials to identify previously unknown outcrops of buried glacial channels and also to characterize the properties of the near-surface glacial deposits. Locations of 17 field stops are shown in Figure 7 and field descriptions of outcrops are included as lithological descriptions, strip logs and photos in Appendix 1. Representative samples of sediment were collected at many sites and analyzed for grain-size distribution, matrix carbonate content and geochemistry. These are included as reference tables in Appendix 2.

The following section discusses some new insights regarding the composition, distribution and genesis of the Quaternary landscape and sediments that are considered to influence the regional distribution of glacial aquifers within the study area.

5.3.1 Quaternary Stratigraphy along the Steepbank and North Steepbank Rivers

Field stops LA2005-01, LA2005-02, LA2005-03 are river outcrops located at or near the junction of the North Steepbank and Steepbank rivers in the south-central part of the study area (Figure 7). This is a remote location that can only be accessed in summer by helicopter. These outcrops were visited to establish the thickness of glacial drift in that area, and to determine if these sites represent outcrops of a buried channel aquifer that was previously mapped from regional borehole information. The outcrops demonstrate that drift thickness exceeds 30 m in the area, and that the exposed part of the stratigraphic assemblage consists of three major units: 1) glacial sand or sandy diamict of varied thickness overlying 2) till of varied grain size overlying 3) an assemblage of sand with till beds of varied thickness (Appendix 1).

Although the map of Bayrock and Reimchen (1974) map shows adjacent areas to be covered by glaciofluvial deposits, the surface sand–sandy diamict at each of the three sites shows evidence of weak folding and deformation, suggesting that the area was overridden by glacial ice or that the sediments were deposited by debris flows resulting from ice-melt collapse in an ice-proximal environment. More information regarding the nature and genesis of the sediments exposed within these outcrops is provided in the discussion of the Lewis Channel in section 7.3.8.

5.3.2 Paleoflow Directions of Buried Channel Deposits Along the MacKay and Dover Rivers

Stops LA2005-04 and LA2005-05 are outcrops located along the MacKay and Dover rivers, respectively (Figure 7), and have been described in a previous study (Andriashek, 2000). Until recently, outcrop LA2005-04 was interpreted to be an exposure of the buried Birch Channel. It appears now that this outcrop probably represents an exposure of the newly mapped buried North Spruce Channel, which trends directly south of the outcrop site. The Birch Channel, however, likely merges or intersects with the North Spruce Channel somewhere near the outcrop. In general, both outcrops show a similar stratigraphic sequence consisting of 1) glaciolacustrine sediment overlying 2) till overlying 3) a thick (10–15 m) assemblage of fluvial sediments ranging from silt to boulder beds, resting on bedrock (Appendix 1, Figures 55–67).

Both outcrops were revisited to obtain additional information on sedimentary structures and paleoflow directions in the lower sand unit, which might provide insight into the genesis of the channel. Dip directions recorded in high-angle beds within the upper 10 m of exposed sand at outcrop LA2005-04 show that the dominant flow direction during deposition was to the southwest, with some variance to the west and northwest (Appendix 1). Dip directions in the buried Willow Channel sediments (outcrop LA2005-06) range between southwest and northwest, and indicate a dominant flow to the west (Appendix 1, Figures 68–74).

5.3.3 Confirmation of a Meltwater Channel Deposit Located by Remote Sensing

An airborne resistivity survey recently conducted by industry along the northwest flank of Muskeg Mountain identified an area that is composed of highly resistive sand and gravel. Stop LA2005-06 is a section located within a gravel pit excavated at the northwestern end of this highly resistive unit (Figure 7). This section exposes as much as 20 m of glacial sand and gravel overlying a 2–3 m thick boulder bed that rests on a till floor (Appendix 1). Till was not observed adjacent to the pit, suggesting that the sand and gravel unit lies at the surface and is therefore depicted on the surficial geology map as a glacial meltwater channel deposit. However, pervasive deformation in the upper ~15 m of the section, recorded by large- to micro-scale folds, chevron-fold structures, and diamict injected into the sand and gravel (see photos and field descriptions, Appendix 1), demonstrates that the site was overridden by westward

flowing ice. It is therefore likely that some or much of the highly resistive material recorded elsewhere by the airborne survey consists of sand and gravel buried by a discontinuous till cover. If so, then this meltwater channel deposit may be more appropriately referred to as a buried channel aquifer.

5.3.4 Distribution of Buried Glacial Lake McMurray Lacustrine Deposits — Pink and Grey Clay

Savigny's (1998) interpretation of the surficial geology of the Athabasca River lowland highlights the sequential development of Glacial Lake McMurray during the late stages of Late Wisconsinan deglaciation in the region. Associated with this glacial lake was the deposition of deep-water glaciolacustrine sediments consisting of rhythmically bedded grey-brown and pink silt and clay, outcrops of which are exposed along the Firebag River in the northern part of the study area. As the ice margin retreated northward, water from south of the study area began to flow northward, forming a delta on the southern margin of Glacial Lake McMurray. Associated with this prograding delta was the deposition of sand with minor silt, clay and gravel on top of the glaciolacustrine silt and clay deposits.
Stop LA2005-08, an outcrop located along the southwestern bank of the Firebag River, reveals about 11 m of dominantly sand with minor silt, clay and gravel, which overlie >3.5 m of laminated grey and pink glaciolacustrine clay interpreted to be Glacial Lake McMurray deposits. It is uncertain whether the sand at this section is part of the deltaic sequence or represents fluvial sediment deposited by the Firebag River, but it seems most likely that the clay represents Glacial Lake McMurray sediments, as described by Savigny (1998). The role that this thick sequence of buried silt and clay is believed to play in the glaciotectonic history and genesis of major landforms of the area is discussed in section 8.2.1.

5.3.5 Glacial Outwash Deposits Modified by Active Glacial Ice — Outwash or Moraine?

Stops LA2005-09, LA2005-10, and LA2005-11, located in the northeast, are situated in Bayrock's (1971) map unit "Outwash sand and gravel overridden by glacier". Field observations confirm a glaciofluvial origin for this material, which comprises well-sorted medium sand with a few boulders and cobbles (Appendix 1, Figures 78 to 80). The streamlined morphology of the landscape (flutes and drumlins, Figure 2) indicates that these glaciofluvial deposits have been glacially modified (cf. Bayrock, 1971). In no place, however, was till observed to overlie the sand.

One of the prominent aspects of this landscape is the relatively high relief of local features, in places 70–80 m and as high as 100 m (LA2005-11). On the basis of sediment-landform associations, it appears that the entire sedimentary sequence is composed of coarse-grained sediment, dominantly sand with stones. If this observation is correct, it means that the thickness of glacial drift in much of the northeastern part of the study area likely exceeds 70 m and, in places, perhaps more than 100 m. Unfortunately there are no exposures of bedrock to confirm the true thickness of the sediments in the area.

The high local relief of these sediments contributes to enhanced surface runoff and erosion, resulting in unstable and poorly vegetated slopes. Numerous wind-faceted cobbles and boulders (ventifacts), observed on exposed or poorly vegetated surfaces, including those of eskers (Appendix 1, Figure 81), attest to extended periods of destabilized land surfaces in this part of the study area (Appendix 1, Figures 78 and 82).

6 Bedrock Topography and Subcrop, and Drift Thickness

The topography of the bedrock surface represents one of the major unconformities in the geological record within the Western Canadian Sedimentary Basin. Understanding the geometry of this unconformity is critical to understanding the distribution of glacial aquifer systems, as this surface forms the basin for the deposition of sediments from subsequent glaciations. Yet, for a number of reasons, this surface can be quite difficult to define, resulting in uncertainty that propagates upwards into the

understanding of the overlying glacial-drift stratigraphy. This section discusses how the bedrock surface was constructed, the challenges in interpreting the data, areas of uncertainty regarding the interpretation, and the thickness of unconsolidated drift cover above the bedrock.

6.1 Challenges in Interpreting the Bedrock Surface

The construction of the bedrock topography map (Figures 8 and 9) relies heavily on stratigraphic pick information derived from borehole logs previously interpreted by other geologists, or from logs that were interpreted in this study. The scope of this study did not permit each stratigraphic pick value provided by external sources to be evaluated against the source borehole log. Rather, all picks were incorporated into the database as provided. In some instances, the interpretations derived from these external sources could not be reconciled with other data and were therefore excluded from the final modelling datasets. As background to the interpretation of the bedrock topography, useful information was gleaned from a comprehensive study of not only the bedrock topography but also the overlying drift stratigraphy in an earlier report on the geology of the Athabasca Oil Sands area prepared for the AGS (McPherson and Kathol, 1977).

The greatest challenge in constructing the bedrock topography map stems from the absence of high-quality data. Data are either non uniformly spaced, or of a highly subjective nature. For example, Figure 8 shows that, although borehole data are abundant around the surface mines in the central part of the study area, they are few or clustered in the in situ–recoverable areas adjacent to the mineable leases. Data points are located north, east and south of Muskeg Mountain, reflecting the absence of exploration where oil sands reserves are considered to be negligible. Unlike data from the surface-mineable area, which commonly consist of lithological descriptions of auger drill cuttings, data in the in situ–recoverable area are of a lesser quality, consisting mainly of petrophysical logs that either terminate at the bottom of steel casing and therefore do not extend to surface (e.g., resistivity logs), or extend farther up hole but are recorded through, and distorted by, steel casing (e.g., gamma logs). In general, gamma logs recorded through casing are the most abundant subsurface information source for mapping the bedrock surface in areas outside the mine leases.

In addition to the problem of sparse data within the in situ–recoverable areas, in very few cases can interpretations from petrophysical logs be supported with the core or drill cuttings that are needed to calibrate the log signature to a rock type. As a consequence, it can be difficult to differentiate sandy surficial sediments from bedrock units with similar sandy properties, especially if only one type of log is available. This is particularly problematic in interpreting the bedrock surface in the Muskeg Mountain area, where glaciogenic sandy sediments are difficult to distinguish from sandstone of the Grand Rapids Formation, or even from sandy facies in the upper part of the Clearwater Formation. Moreover, as discussed in section 8.2.3, defining the bedrock surface across Muskeg Mountain may be further complicated by glaciotectonic processes which are believed to have acted in the region. Seismic profiles have proven to be useful in establishing the bedrock-drift contact in such areas, but these data are generally confidential and therefore not available in the public domain. Furthermore, there is only fragmentary information relating to drift thickness and bedrock topography in the northeastern part of the study area. These data indicate that there are significant differences in the elevation of the bedrock surface, ranging from exposed Precambrian Shield (Twp. 100, Rge. 3–4) to areas directly southeast where the bedrock is buried by >100 m of glaciogenic sand (Twp. 99, Rge. 1). Unfortunately, in the areas of thick sand, the few borehole petrophysical logs that are available do not permit the contact between Quaternary sand and oil-free sand of the underlying McMurray Formation to be differentiated.

For these reasons, the bedrock topography map could not be constructed throughout the entire study area, and a large area in the northeast remains unmapped (shown in white in Figures 8 and 9). Additionally, a

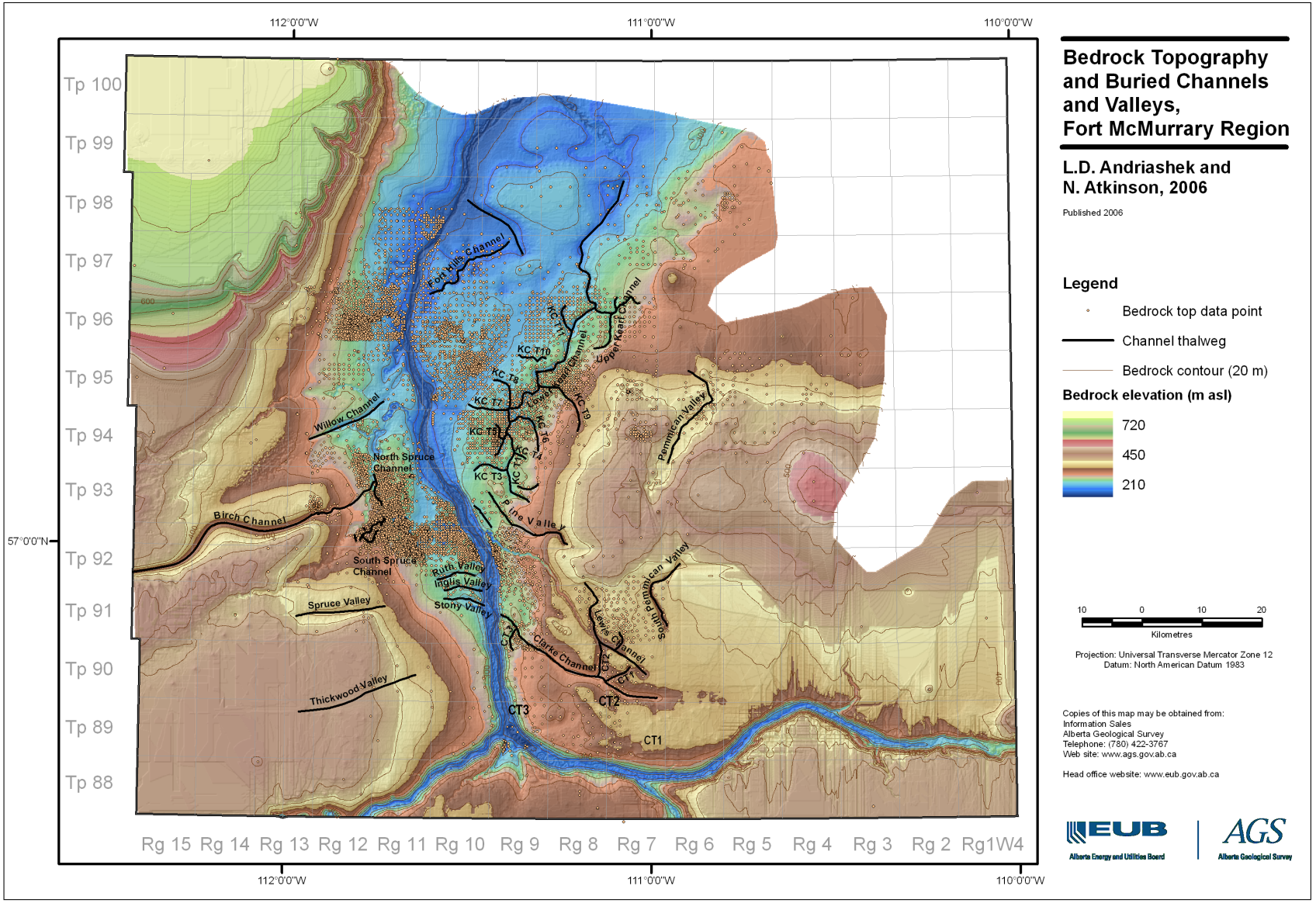


Figure 8. Bedrock topography, and buried channels and valleys, Fort McMurray region.

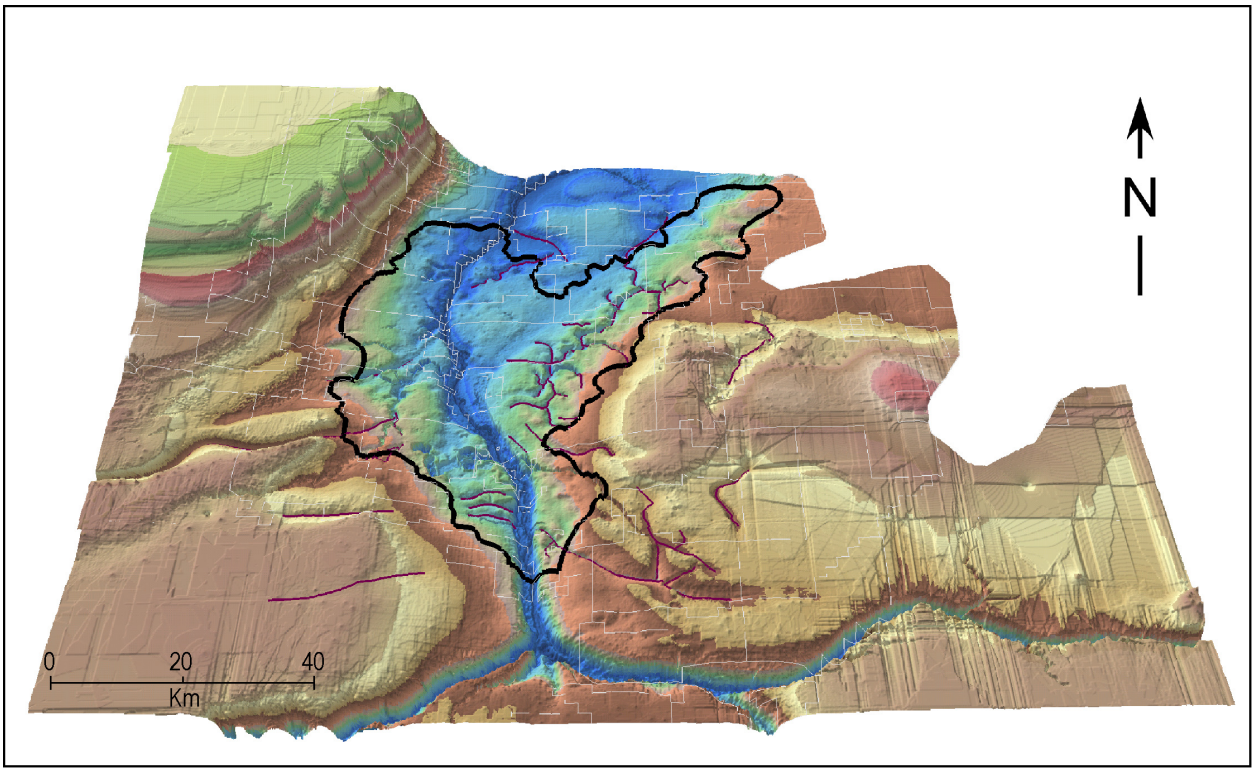


Figure 9. Oblique 3-D rendering of bedrock topography in the Fort McMurray region, showing channel and valley thalwegs, mineable surface oil sand boundary and lease boundaries.

paucity of information along the Clearwater River results in spurious interpolations of model grid values, resulting in aberrant or unrealistic contours. The need for additional work on mapping the bedrock surface will be addressed in subsequent sections.

6.2 Modelling the Bedrock Surface

Considerable effort was devoted to mapping the bedrock surface as accurately as possible to ensure that small but important features, such as incised channels, could be represented on the regional map. An inverse-distance kriging algorithm was applied to model about 66 500 data points, consisting of 9 650 bedrock top values and about 57 000 synthetic data derived from polyline nodes of hand-drawn, digital contour lines. This difference between borehole and synthetic data emphasizes the extent to which the model reflects the authors' interpretation of the subsurface. The resultant kriged surface was then evaluated against other geological surfaces, such as the SRTM DEM of the present-day land surface, to ensure geospatial integrity. If necessary, the kriged bedrock topography was corrected to ensure that the bedrock surface was not erroneously projected above the modern landscape. This 'corrected bedrock surface' was subsequently constrained by an author-defined bounding polygon, to ensure that it was not interpolated across parts of the project area where data are absent. Thereafter, the corrected bedrock surface was only displayed across those parts of the project area that lie within the bounding polygon. In areas where data are absent or too sparse to generate a meaningful surface, the digital grid was assigned a null value (-9999).

6.3 Interpretation

The topography of the bedrock surface largely mirrors the present-day landscape, where major physiographic features such as the Birch and Muskeg mountains and the Athabasca River lowland are dominantly bedrock controlled (McPherson and Kathol, 1977). The bedrock surface shows a considerable range in elevation, from 720 m asl in the Birch Mountains to ≤220 m asl within the thalweg of the present-day Athabasca River (Figures 8–13). The bedrock surface is exposed along all of the major rivers and streams in the Athabasca River lowland, and the geometry of the drift-bedrock contact is well defined by the intersection of the bedrock surface with the SRTM DEM. Metamorphic and igneous rocks of the Precambrian Shield that outcrop in the extreme northeastern part of the study area (Twp. 100, Rge. 3–4; Bayrock 1971) are not depicted on the bedrock topography map but are shown on the surficial geology map. Future updates to the geological model will need to incorporate present-day surface topography values into the model of the bedrock topography in that part of the study area.

The bedrock surface attains its lowest elevation along the thalweg of the present-day Athabasca River, although there remains some uncertainty regarding the depth to bedrock beneath the channel. Anecdotal information (C. Froese, pers. comm., 2006) indicates that, in places, the channel may be 20–40 m deeper than the modern river, but it is uncertain if this reflects local collapse features resulting from salt dissolution (McPherson and Kathol, 1977) or erosion along a continuous channel. If the latter, segments of the present-day Athabasca River may occupy a pre-existing buried channel.

As discussed previously, there also remains some uncertainty regarding the bedrock topography beneath Muskeg Mountain and areas to the north and east, primarily because of the scarcity of high-quality data. Current interpretations place the bedrock surface in the Muskeg Mountain area as high as 535 m asl (Figure 8), within the upper part of the Grand Rapids Formation, or possibly higher, in the lower part of the Colorado Group. North of Muskeg Mountain, the DEM shows a regional depression (Twp. 95–97, Rge. 1–5), demarcated as the Firebag Plain physiographic unit (Figure 2). There are insufficient data to map the bedrock surface in this area; however, based on the general model that the present-day land surface reflects the underlying bedrock surface, it can be assumed that the bedrock topography is also depressed in this area. Likewise, there are insufficient data to permit accurate mapping of the bedrock topography within the Thickwood Hills, in the southwestern part of the study area (MacKay Plain physiographic unit). Nevertheless, there are abundant high-quality data in the Athabasca River lowland that allow the bedrock surface to be mapped at a relatively high resolution. Important local-scale bedrock features, such as karst collapse of the underlying Waterways Formation along the Athabasca River lowland, are known to affect the bedrock topography (McPherson and Kathol, 1977), but these have not been captured on the regional bedrock topography map.

Valleys and channels incised into the bedrock surface reflect the cumulative history of erosion from the Tertiary to the present. In fact, the Athabasca River channel can be considered to be a bedrock channel, as the river is actively incising the exposed bedrock beneath and along the channel margins. From the perspective of groundwater and aquifers, however, the most interesting features are those incised valleys and channels that are buried and masked by glacial sediment. These are herein referred to as buried channels and valleys, and their origin, physical characteristics and distribution within the subsurface form the basis for the discussion in section 7. At least 27 buried bedrock valleys or channels have been mapped in the study area, and it is likely that others will be encountered as more intensive exploration continues in the in situ–recoverable oil sands area (Figure 8). Some channels, such as the Birch, Willow and Kearl (previously referred to as the ‘OSLO’ or the ‘Pleistocene’ Channel) had been mapped previously (Andriashek, 2000; Horne and Seve, 1991). The remainder are newly mapped or defined in this report.

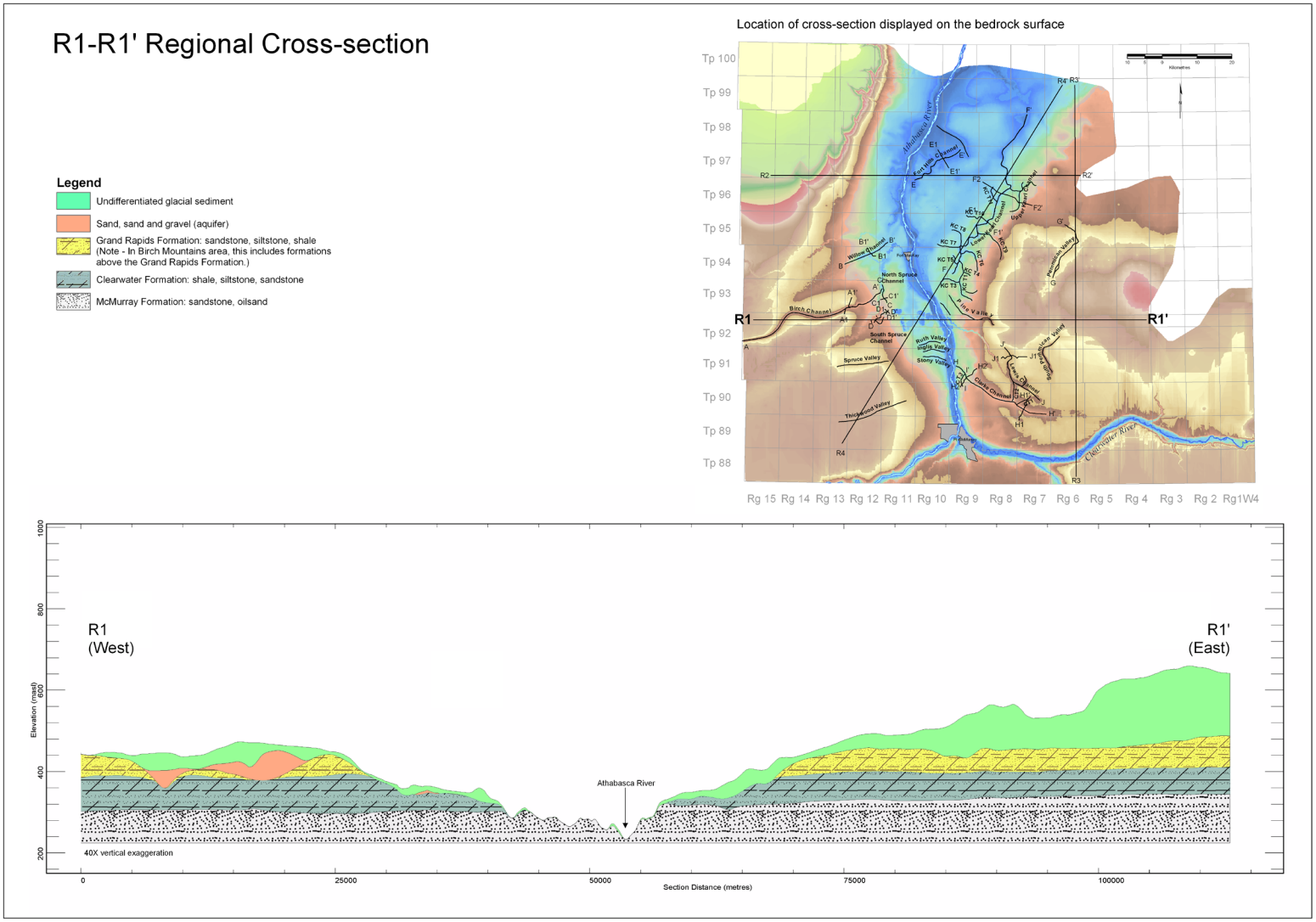


Figure 10. Regional cross-section R1–R1', illustrating the bedrock topography across the Athabasca River valley.

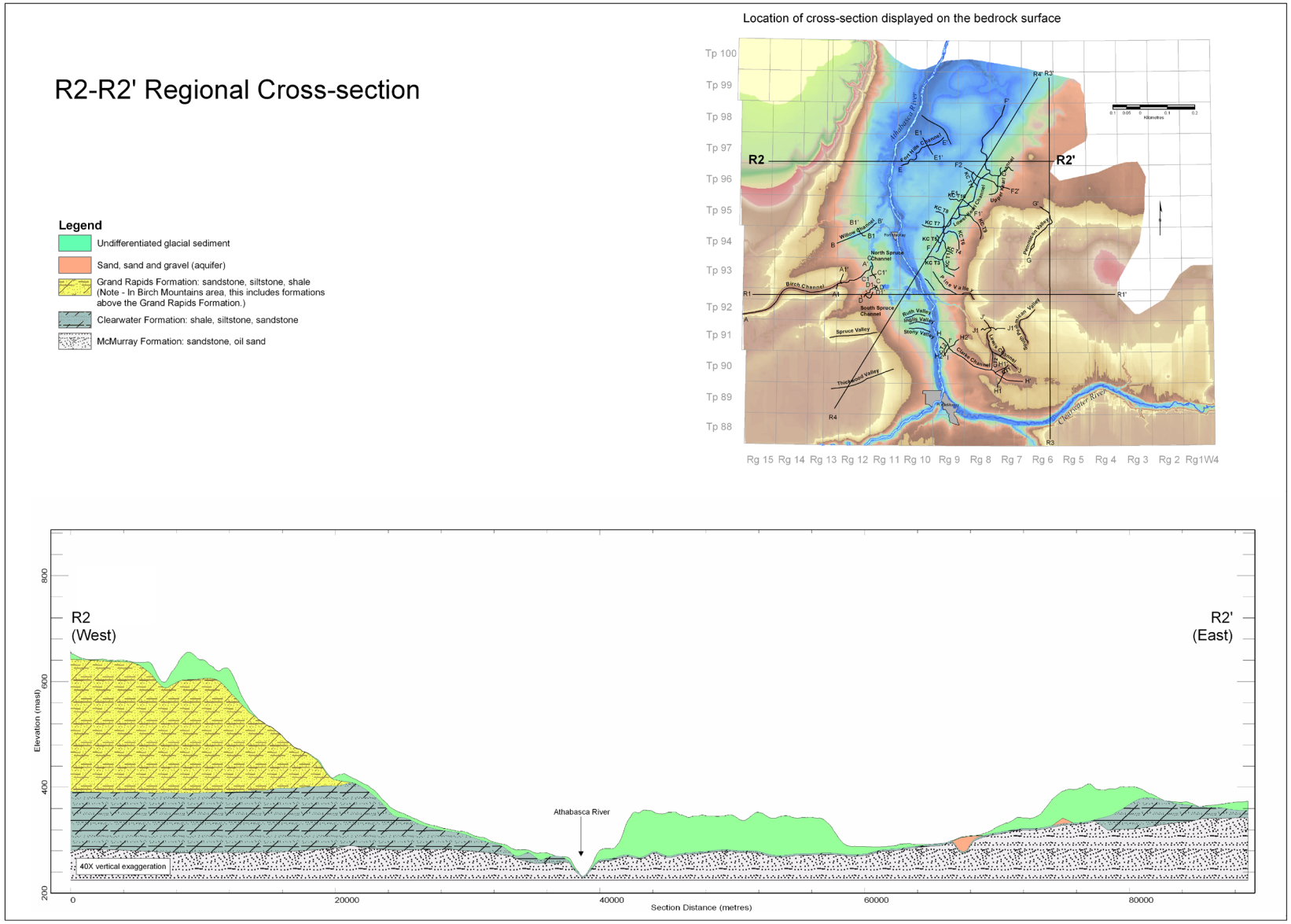


Figure 11. Regional cross-section R2–R2', illustrating the bedrock topography across the Athabasca River valley.

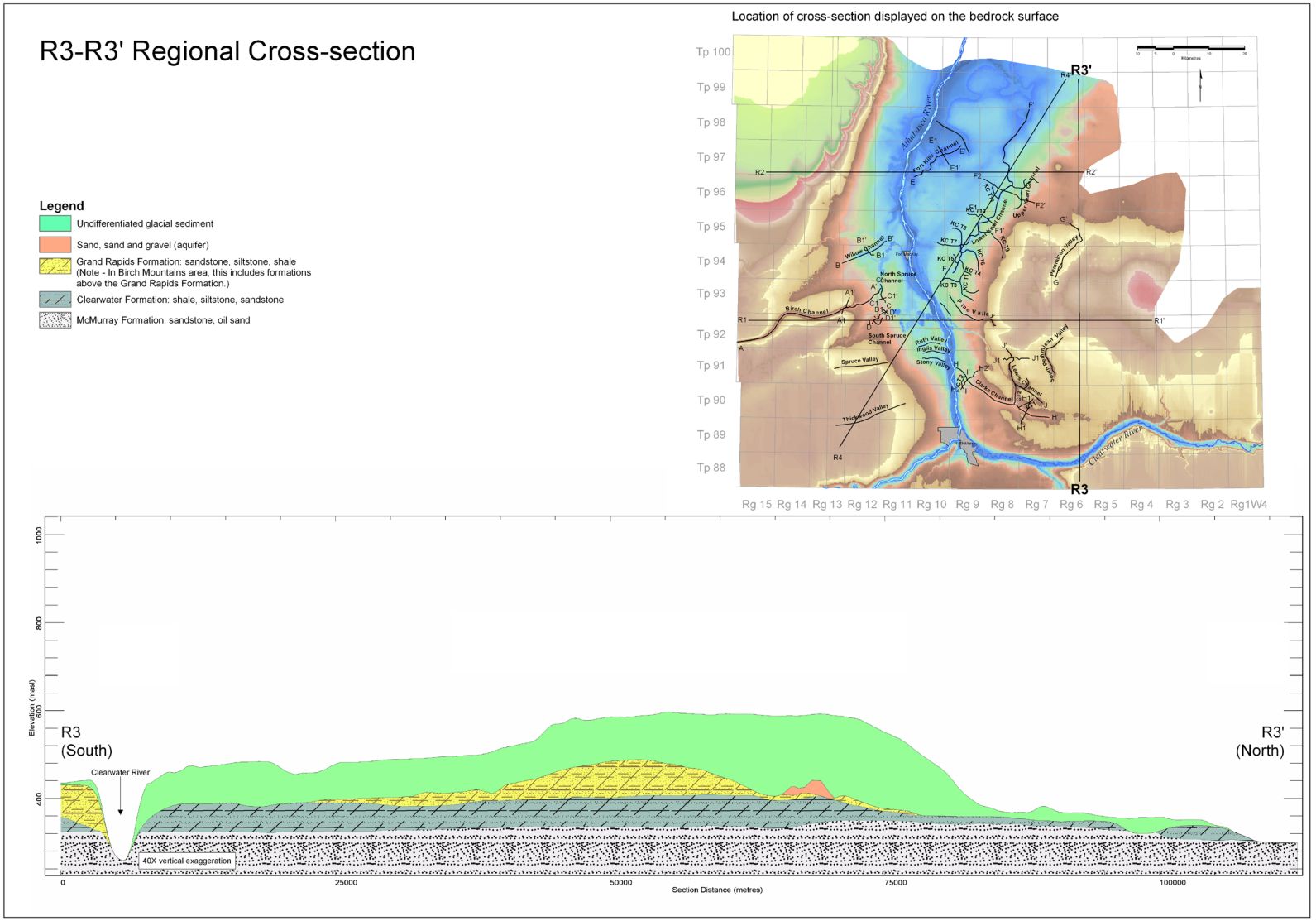


Figure 12. Regional cross-section R3–R3', illustrating the bedrock topography across Muskeg Mountain.

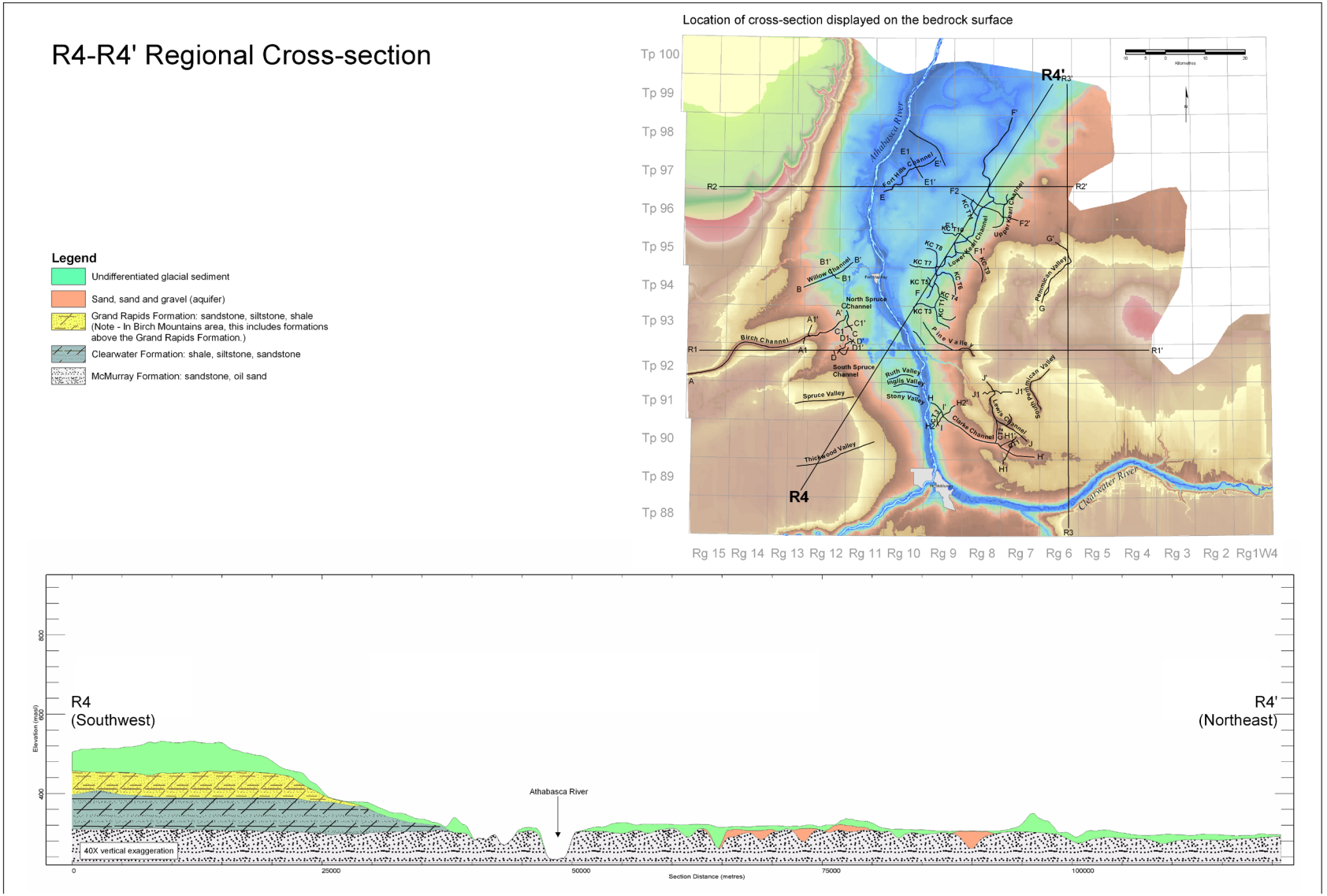


Figure 13. Regional cross-section R4–R4', illustrating the bedrock topography along the Athabasca River valley and into the Thickwood Hills.

6.4 Bedrock Subcrop

In addition to increasing the understanding of the bedrock surface, there is also great interest in understanding the bedrock geology directly beneath the glacial drift, particularly in areas where glacial aquifers may lie directly on bedrock aquifer units. A detailed bedrock subcrop map, showing the subsurface distribution of the major bedrock units in the area, is depicted in Figure 14. A number of deeper geological formations are known to subcrop or outcrop in the study area, such as the Devonian along the Athabasca and Clearwater rivers, and higher units of the Colorado Group in the Birch Mountains to the west and possibly in the Muskeg Mountains to the east. In this study, however, there were only sufficient data to construct detailed structure and erosional surface maps for two bedrock geological units, the McMurray and Clearwater formations. The erosional surfaces of all units higher than the Clearwater Formation are represented as one, the bedrock topographic surface.

The structural and erosional surface of the McMurray Formation was modelled by inverse-distance kriging of about 19 800 borehole picks. The resultant surface was then fitted to a bounding polygon that constrained its extent to only where the bedrock surface is defined. Lastly, this constrained structure top was compared to the bedrock topography and corrected to ensure that it was not projected above the bedrock surface (Figure 5). If such cases were encountered, the value of the bedrock surface was assigned to the value of the corrected McMurray Formation surface. The difference between the original structure map and the erosional surface map yields a subcrop distribution map (Figure 14).

Because there are about 30% fewer stratigraphic pick values for the Clearwater Formation (about 6 970 values) than for the McMurray Formation, an additional ~45 800 synthetic data values were used to model the topography of the Clearwater Formation. As with the McMurray Formation, the extent of the initially modelled Clearwater Formation surface was constrained by a bounding polygon that ensured its subcrop was defined only where the bedrock surface was mapped. This constrained surface was then compared to the top of the McMurray Formation to ensure that it was not projected below the McMurray surface. In any instance where this occurred, the value of the McMurray Formation top was assigned to the adjusted Clearwater top, effectively creating a stratigraphic pinch-out. This adjusted Clearwater Formation surface was subsequently compared to the bedrock topography to ensure that it was not projected into the overlying drift (Figure 5). As before, the value of the bedrock surface in such instances was assigned to the top of the Clearwater Formation, and a comparison of the original surface with the erosional surface yields a subcrop distribution of the Clearwater Formation.

Figure 14 shows that, except within incised bedrock valleys and channels, the exposed surface of the McMurray Formation lies between 310 and 320 m asl in the south, and decreases northward to about 240 m. The subcrop contact between the McMurray Formation and the Clearwater Formation lies between 280 and 300 m on the west side of the Athabasca River valley, and between 310 and 320 m on the east side of the valley. The exposed surface of the Clearwater Formation decreases from about 390 m along the flanks of the Birch and Muskeg mountains to about 280–330 m in the Athabasca River lowland. The exposed contact between the Clearwater Formation and the overlying Grand Rapids Formation generally lies at about 390–400 m.

Previous work in the Birch Mountains recognized that the structural surface of the Grand Rapids Formation rises from west to east, to a maximum elevation of about 490 m (Cotterill, 1996). With the possible exception of an outlier of the Joli Fou and possibly Pelican formations in the highest parts of Muskeg Mountain, the 490 m elevation means that the Grand Rapids Formation represents the uppermost bedrock unit to subcrop east of the Athabasca River, and its surface thus defines the bedrock topography. In the Birch Mountains, west of the Athabasca River, stratigraphically higher units of the Colorado

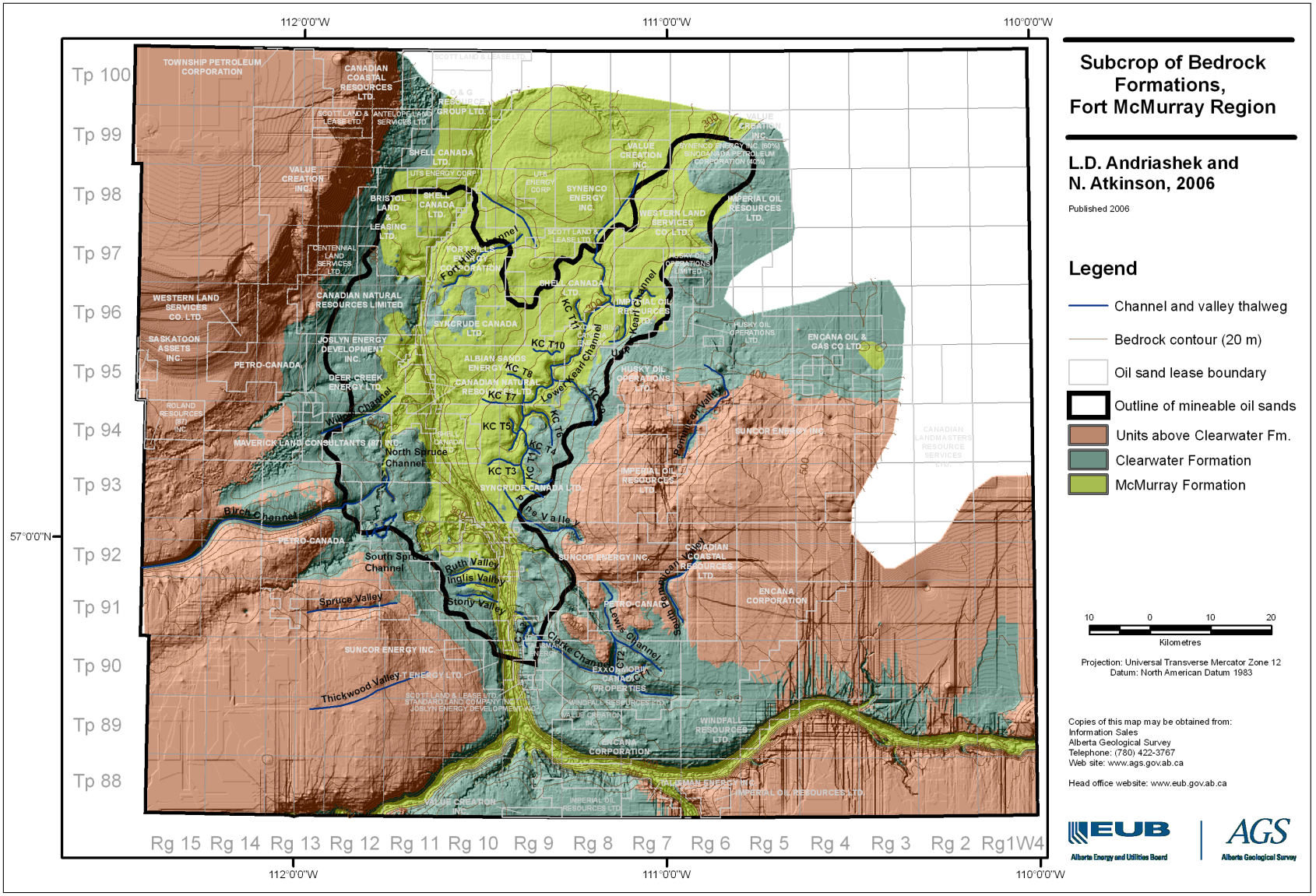


Figure 14. Subcrop of bedrock geological units beneath glacial drift, Fort McMurray region.

Group form the bedrock surface, but these units have not been differentiated in this study. Compared to the subcrop interpretations presented on the bedrock geology map of Alberta (Hamilton et al., 1999), Figure 14 provides a more detailed geometry of the post-Cretaceous erosion of the geological units in the region. From the perspective of interaction of near-surface groundwater with bedrock aquifers in the mineable oil sands area, the most significant addition to Hamilton et al. (1999) is the delineation of numerous glacial channels, such as the Kearl Channel and its tributaries, which are incised into the McMurray Formation. This increase in resolution of the subcrop surface is not surprising, considering that the mineable oil sands area contains an abundance of closely spaced borehole data.

6.5 Drift Thickness

In this report, the term 'drift' refers to all unconsolidated sediments that lie atop the bedrock surface, irrespective of age or genesis. For the most part, it is believed that glacial and postglacial sediments constitute most of the drift in the study area, although it is speculated that bedrock within parts of the Birch Mountains is capped by preglacial fluvial sediment.

Mapping drift thickness is important because it identifies areas with the potential to contain thick sequences of the sand and gravel that constitute an aquifer system. Conversely, in areas of thin drift, potential pathways can be highlighted where surface water interacts with bedrock units. Unlike the construction of geological surfaces, in which stratigraphic pick values and synthetic data are interpolated using kriging algorithms, isopachs (thickness maps) are constructed by simple subtraction of modelled geological surfaces. In the case of the drift isopach, the modelled bedrock surface (unconformity) is subtracted from the DEM of the present-day land surface (unconformity) to produce a map that reflects thicknesses related to variations in either or both surfaces. In this regard, the drift isopach is sensitively dependant on the accuracy of the modelling of each surface.

The results from this study show that drift thickness in the Athabasca Oil Sands area north of Fort McMurray varies significantly, from <1 m to >200 m (Figure 15).

A comment is necessary to clarify any ambiguity regarding areas of thin drift displayed in Figure 15. The large white area in the northeastern part of the study area reflects the absence of data relating to bedrock topography (and, hence, drift thickness), and does not represent an area of no drift. Areas shown in white within the coloured portion of the map, however, do correspond to areas of thin to no drift (0–1 m). Not surprisingly, these areas occur along the present-day Athabasca and Clearwater rivers and their tributaries, where bedrock is exposed along the valley walls and adjacent toplands (Figures 10–13; Appendix 1, Figures 84–86). Thin drift also occurs along the eastern flank of the Birch Mountains, where bedrock of the Colorado Group is exposed or mantled with a discontinuous veneer of till or colluvium. Although drift within much of the Athabasca River lowland is also thin (1–10 m), it is laterally extensive, except in areas where late-glacial fluvial scour has eroded down to bedrock (e.g., Twp. 94–96, Rge. 9–10; Figure 15). The erosion of drift and the subsequent excavation of oil sand from open-pit mines are also reflected in the isopach, as areas of zero drift thickness.

Areas of thick drift reflect one of two depositional environments: 1) the accretion of material atop bedrock uplands, or 2) the infill of depressions or features previously scoured into the bedrock surface. In the former case, thick accumulations of drift on a relatively level bedrock surface might be expressed as topographic highs in the present-day landscape. In the latter case, there may be no surface expression to indicate thick fill at depth. Figures 10, 12 and 14 show that the thickest accumulation of drift occurs as an accretion on top of Muskeg Mountain, where >200 m of sediment have been mapped. Although the morphology of Muskeg Mountain is influenced by high relief in the bedrock topography (Figures 8 and 12), this morphology has been enhanced by sediment accretion. Although data are sparse and

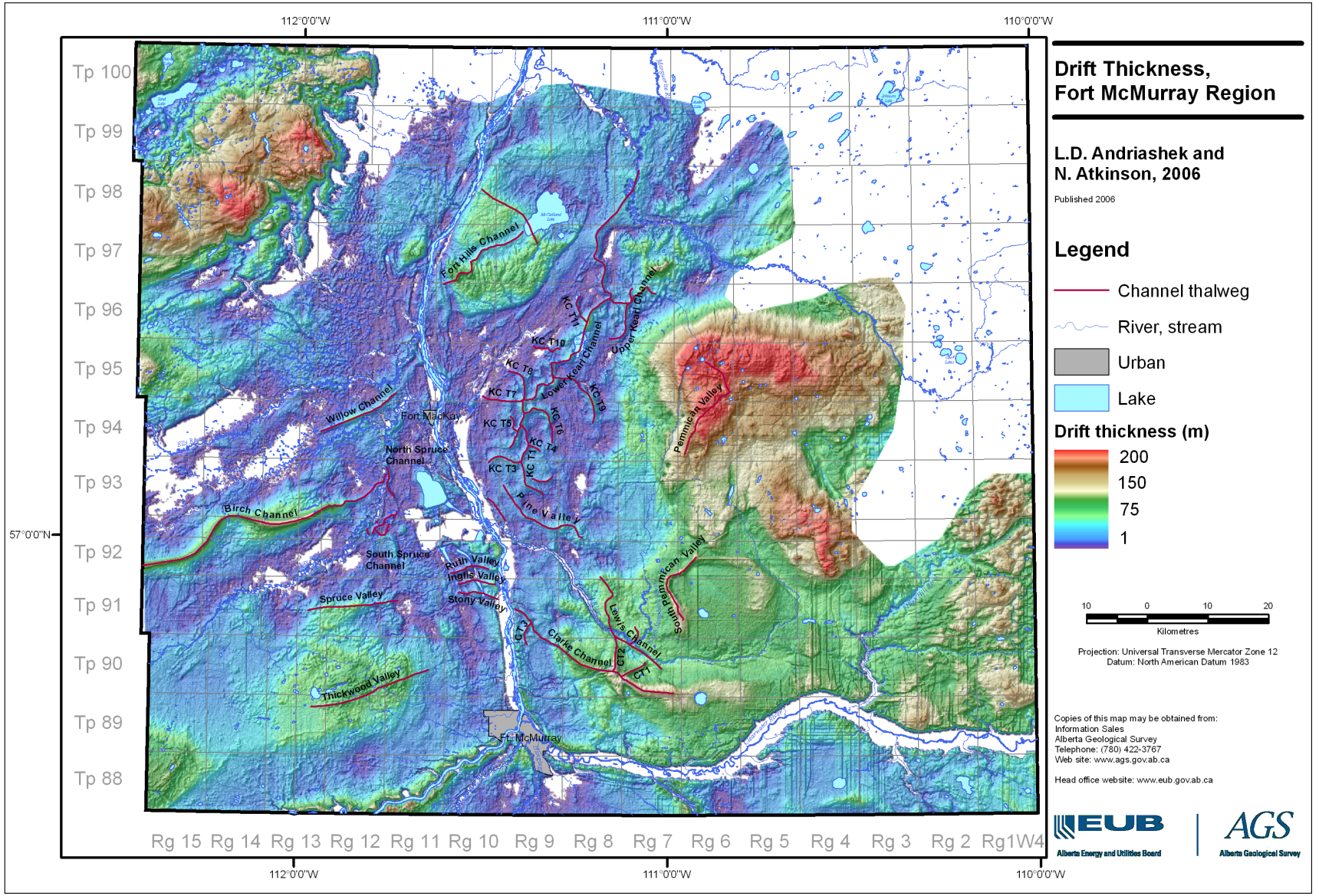


Figure 15. Thickness of drift above the bedrock surface, Fort McMurray region.

understanding of the bedrock topography is more speculative, the authors suggest that thick drift has been similarly accreted on the bedrock surface in the Birch Mountains (Figure 15). Other areas of thick accretion on a relatively level bedrock surface include

- an east-trending morainal complex northwest of Muskeg Mountain, which includes the Fort Hills, where 50–75 m of drift are mapped on an undulating to shallowly incised bedrock landscape (Figures 2, 8 and 15);
- the area between the Clearwater River and Muskeg Mountain and farther east, where 80–100 m of drift are mapped; and
- northeast of Muskeg Mountain where, although not shown on Figure 15, >80 m of drift were observed in the sandy morainal complex situated in Twp. 96–100, Rge. 1–5.

Infill of buried bedrock valleys and channels represents the second depositional environment for thick drift, and these are the primary focus of this study. Channel infills are illustrated in Figure 15 as sinuous to linear ridges of thick drift, which mirror the geometry of the underlying bedrock channel. Although not nearly as extensive as the broad areas of thick drift on Birch and Muskeg mountains, drift thickness in some bedrock channels is significant, with 100 m or more of infill occurring within segments of the Birch, Clarke and Lewis channels, and above the South Pemmican Valley (Figures 8 and 15). Other channels with significant infill (25–50 m thick) include the complex of channels associated with the Kearl Channel along the eastern edge of the Athabasca River lowland, the Willow Channel, and the channel complex referred to as the North and South Spruce channels in Twp. 92, Rge. 11 (Figures 8 and 15).

There was no attempt during this study to establish a regional stratigraphic framework for the entire drift sequence, although a framework was developed by MacPherson and Kathol (1977) and site-specific frameworks have been developed at the scale of individual oil sand leases. The focus of this study was to map just the buried drift aquifers that lie in bedrock valleys and channels.

7 Buried Channels, Valleys and Aquifers

Buried bedrock valleys and channels are the foci for the deposition of coarse sediments that make up potable aquifers within the Fort McMurray region. This section describes the physical characteristics of buried valleys and channels, their geometry, genesis and nature of sediment infill, and includes a general discussion of the relationships between the aquifer systems within the region.

7.1 Channels Versus Valleys

Although sometimes used synonymously, especially in the context of landscapes modified by fluvial processes, the terms ‘channel’ and ‘valley’ in this study denote erosional features that were formed in different fluvial environments. The differentiation between the two is based on the relative width to depth of the erosional form, the nature of the sediments contained within, and the inferred history of formation. In terms of geometry, buried channels generally have a well-defined channel form, with steeper sidewalls and greater depth to width ratios than valleys. Buried channels are inferred to have been eroded by glacial meltwater flowing under hydraulic pressure at the base of an ice sheet (herein referred to as a subglacial environment) and, in most but not all cases, coarse sediment rests on the channel floor. In contrast, buried valleys are broader with shallow valley walls, are not as deeply incised, and may or may not contain extensive fluvial deposits on their floors. Buried valleys are believed to have been formed by subaerial drainage that preceded the onset of glaciation, but preglacial valleys in reality are commonly the foci for multiple fluvial erosional and depositional events over time, and seldom represent a single

event. As new subsurface information becomes available in the study area, the distinction between the two may become less apparent.

Drift aquifers within buried valleys and channels were mapped from borehole lithologs, or from petrophysical log traces where lithologs were unavailable. In some settings, it was possible to differentiate various lithological units within the channel fill sequences, which, although locally correlative, were not mapped in this regional study. Where the channel fill sequence consists of a single unit of thick sand and gravel resting on bedrock, the top of the sand and gravel was assigned as the aquifer top. In some settings, however, it appears that more than one depositional event occurred within the channel, resulting in a thick sequence of stacked deposits. The top of the highest unit within the sequence was assigned as the aquifer top, even if the deposits were not stratigraphically equivalent along the length of the channel. In some areas, the top of buried sand and gravel extends beyond the confines of the channel and rests not on bedrock, but on pre-existing till. In these areas, the subsurface distribution of the aquifer does not necessarily conform to the geometry of the underlying bedrock channel. Furthermore, it was not possible to the map the surface of the till that underlies the sand and gravel along the channel margins. Consequently, when calculating the aquifer thickness by subtracting modelled surfaces, the top of the immediately underlying modelled surface was used in the calculation, in this case the bedrock topography. The result is that, in a few places, erroneously thicker values were assigned to the aquifer along the channel edge.

7.2 Buried Bedrock Valleys

As many as eight buried bedrock valleys have been mapped in the study area, and it likely this number will increase with further exploration in the region. Before these are discussed detail, some general comments can be made regarding their position in the bedrock landscape. Almost all buried valleys are interpreted as regional drainage networks that developed on the bedrock surface prior to glaciation. They represent erosional features that developed in response to subaerial drainage along the steepest slopes on the bedrock surface. For the most part, they emanate from watersheds on the bedrock landscape, trending towards topographic lows, or occur in areas where locally steep bedrock relief accelerated the rate of erosion, such as along gullies on the flanks of major streams and rivers. In the absence of any other information, any fluvial sediment present within the valley floor is interpreted to be derived locally, reflecting the composition of the underlying or nearby bedrock units. To date, there is no information that indicates the presence of preglacial Tertiary sand and gravel (Empress Formation unit 1; Andriashek, 2002) on the floors of any of the buried valleys in the study area. If new information were to reveal that the sediment has a glacial source, then the valley might be classified as a buried glacial channel.

7.2.1 Pemmican and South Pemmican Valleys

It is likely that numerous valley systems have developed on the flanks of the major bedrock uplands in the study area but remain hidden by thick drift. This study has mapped two valleys emanating from Muskeg Mountain, herein named the ‘Pemmican Valley’ and ‘South Pemmican Valley’ (Figure 8). There remains some uncertainty regarding the geometry of both valley systems. Data quality is poor, consisting primarily of gamma-ray logs recorded through casing, and information on the composition of the drift and the underlying bedrock is scarce. Further, as discussed previously, the Muskeg Mountain area represents the northeastern limit of the Grand Rapids Formation, which can be indistinguishable from sandy drift on petrophysical log traces.

The Pemmican Valley transects the central part of Muskeg Mountain along a north-south axis. The valley is relatively wide, and the depth of incision into bedrock is about 20–25 m, resulting in a high width-to-depth ratio (~155, Table 1). It has a shallow gradient, and its elevation decreases northwards from about

405 to 375 m asl over a distance of about 20 km. Notably, the gradient is opposite to the slope of the present-day topography (Figure 2). The valley is infilled by a thick (200 m) sequence of drift (Figures 12 and 15). Gamma log signatures indicate that a unit of coarse-grained sediment, interpreted as fluvial sand and gravel, occurs on the bedrock surface along the thalweg of the Pemmican Valley (Figure 16). The correlation of this sand and gravel unit was complicated by the inability to differentiate it from sandstone of the Grand Rapids Formation, and by glaciotectonic processes that acted subsequent to its deposition. The influence of glaciotectonism on the composition of drift at Muskeg Mountain will be discussed in section 8.2.3.

Table 1. Properties of buried valleys and channels, Fort McMurray region.

Channel/valley name	Length (km)	Width (km)	Depth of incision into bedrock (m)	Width: depth ratio	Starting elevation (m asl)	Ending elevation (m asl)	Gradient (m/km) '-' denotes opposite to DEM slope direction
Birch Channel	46	2.8	75-80	36	355	320	0.8
Clarke Channel	31	2.0	25-50	80	345	300	1.5
Clarke Channel T1	5	1.0	20	53	375	340	7.3
Clarke Channel T2	6	3.0	45-50	64	378	336	7.5
Clarke Channel T3	4	1.0	25	47	330	295	8.8
Lewis Channel	21	2.4	30	83	390	375	0.6
Fort Hills Channel	18	1.4	10	140	260	245	0.8
Kearl Main Channel	60	1.0	20	53	290	260	0.8
Upper Kearl Channel	11	1.5	25	60	325	305	1.8
Kearl Channel T1	14	1.1	15	85	334	289	3.2
Kearl Channel T2	4	1.0	5-10	136	339	317	6.0
Kearl Channel T3	6	1.3	10	118	296	300	-0.7
Kearl Channel T4	2	1.1	20	52	315	296	8.6
Kearl Channel T5	3	0.8	25	35	285	293	-2.5
Kearl Channel T6	7	0.8	35	24	325	255	10.0
Kearl Channel T7	7	0.9	5-10	150	285	273	1.8
Kearl Channel T8	6	1.2	15	75	271	284	-2.0
Kearl Channel T9	12	0.8	20	44	369	286	6.9

Table 1. Properties of buried valleys and channels, Fort McMurray region. (continued)

Channel/valley name	Length (km)	Width (km)	Depth of incision into bedrock (m)	Width: depth ratio	Starting elevation (m asl)	Ending elevation (m asl)	Gradient (m/km) '-' denotes opposite to DEM slope direction
Kearl Channel T10	5	0.5	5	100	303	289	2.8
Kearl Channel T11	5	0.8	20	46	281	278	0.6
North Spruce Channel	6	0.6	30	20	310	300	0.9
South Spruce Channel (north branch)	5	0.3	20	48	345	310	5.0
South Spruce Channel (south branch)	5	0.5	15	35	341	339	0.4
Inglis Valley	6	0.9	10	104	300	275	4.0
Pemmican Valley	20	3.4	25	155	374	405	-1.5
Pine Valley	17	1.3	10-30	81	410	310	6.0
Ruth Valley	8	1.2	10	80	300	280	2.5
South Pemmican Valley	14	1.7	20	81	385	375	0.7
Spruce Valley	16	1.9	20	95	420	380	2.0
Stony Valley	6	1.3	10	144	305	290	2.5
Thickwood Valley	21	1.0	10	100	455	390	3.0
Willow Channel	14	1	25-30	58	330	275	3.6

The South Pemmican Valley extends south from the Muskeg Mountain bedrock highland, decreasing from about 385 to 375 m asl over a distance of about 15 km (Figure 8, Table 1). Since this valley lies at the limit of data availability, the geometry of its margins remains uncertain, particularly along the eastern flank, which appears to broaden eastward. The valley is estimated to be at least 1.5–2 km wide, and the depth of incision into bedrock is about 20 m. As much as 120 m of drift lies above the valley floor (Figure 15). The valley is interpreted to be floored on shale of the Clearwater Formation but, as discussed previously, mapping the bedrock topography and valley geometry is complicated by the difficulty in differentiating coarse-grained sediments from sandstone of the Grand Rapids Formation. Gamma log signatures indicate that a coarse-textured unit rests on the Clearwater Formation (Figure 17). In the absence of additional information, this is interpreted as a fluvial unit, although sandy till or sandstone would produce a similar log signature. Certainly the differences in profile from adjacent gamma logs indicate that the sediment has a variable composition, which is generally not typical of fluvial sand and gravel (Figure 17).

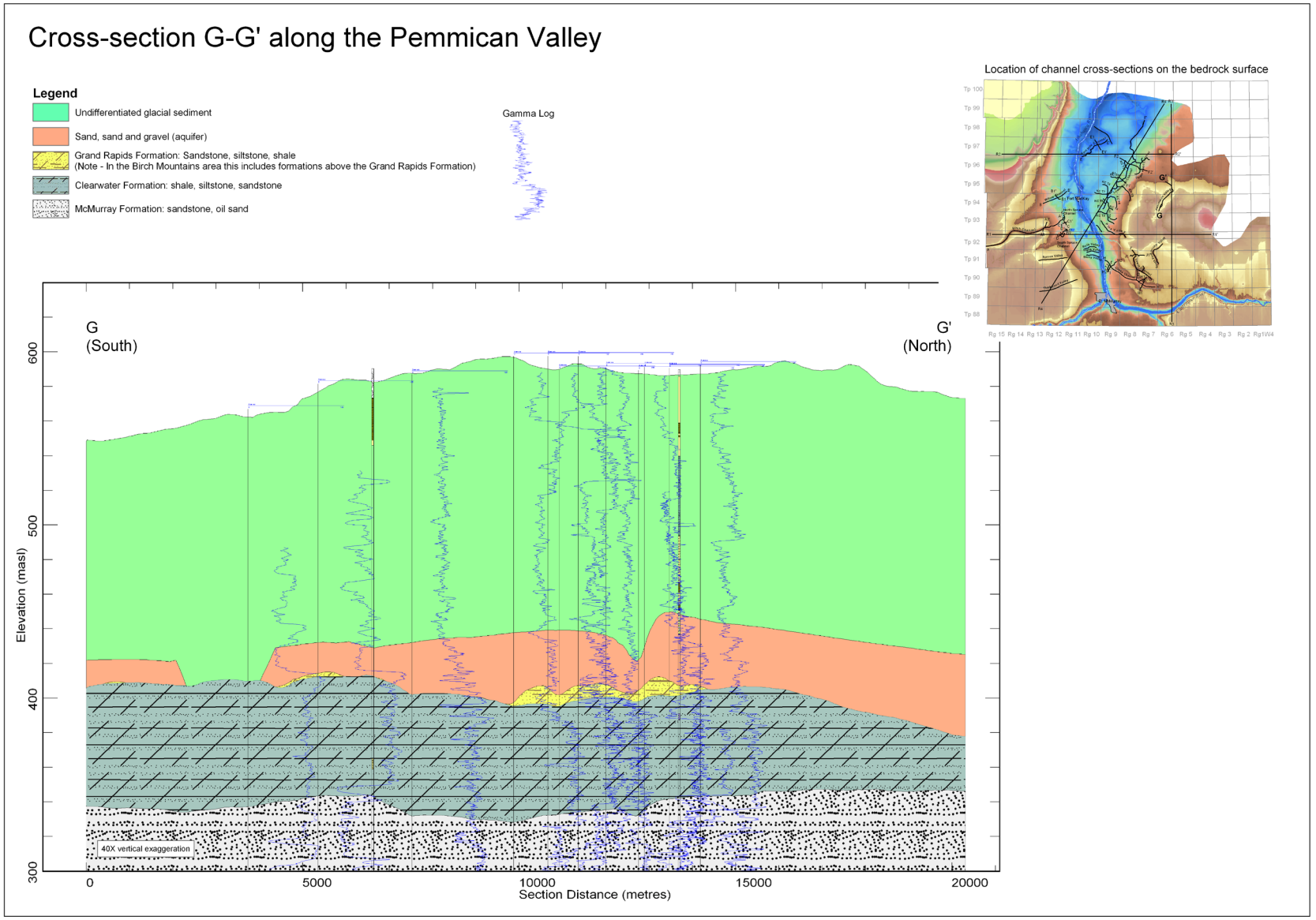


Figure 16. Geological cross-section along the Pemmican Valley, Fort McMurray region.

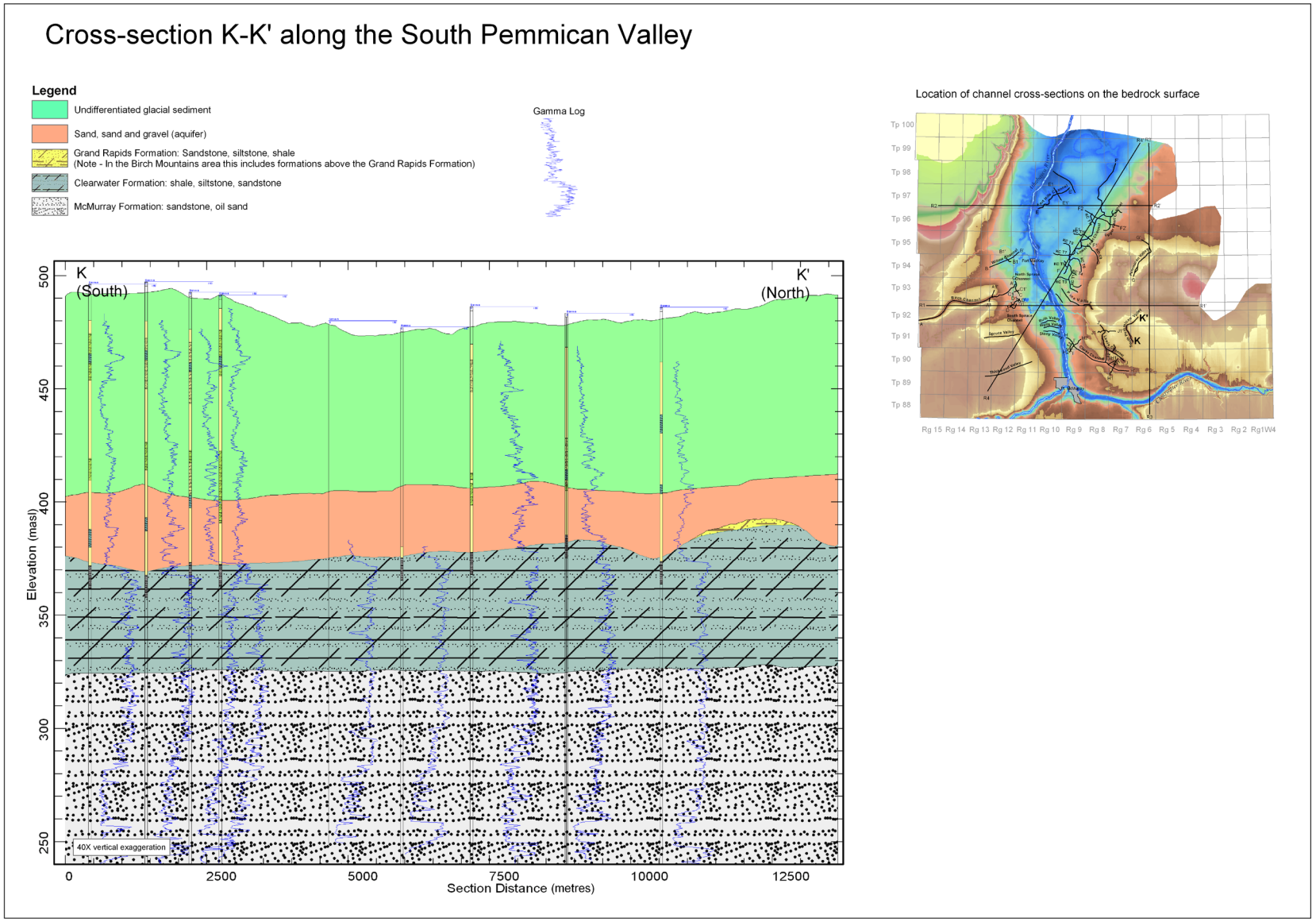


Figure 17. Geological cross-section along the South Pemmican Valley, Fort McMurray region.

7.2.2 Pine Valley

The location and subsurface geometry of the Pine Valley was interpreted from a small number of petrophysical (mainly gamma ray) logs; as a result, confidence in the interpretation is low. The Pine Valley lies along the west flank of Muskeg Mountain (Figure 8). It descends from about 410 m asl to about 310 m, where it enters the Athabasca River lowland. The valley is about 17 km long and 1.5 km wide, and depth of incision into bedrock ranges from 10 to 15 m in the northwest, where it incises 15 m into the Clearwater and McMurray formations, to as much as 30 m in the southeast, where it erodes into the Grand Rapids and Clearwater formations on the edge of Muskeg Mountain (Table 1, Figures 1 and 15).

Drift thickness above the valley floor ranges from about 25 m in the northwest to about 50 m in the southeast (Figure 15). In the absence of borehole lithology records, the composition of the drift within the valley remains unknown.

7.2.3 Thickwood and Spruce Valleys

The Thickwood and Spruce valleys are mapped in the southwestern part of the study area, trending east from the bedrock upland that underlies the Thickwood Hills–MacKay Plains physiographic unit (Figures 2 and 8). As both valleys were mapped from sparse data, there is only a rudimentary knowledge of their geometry and associated sediment infills. Both valleys are interpreted to be floored on bedrock of the Grand Rapids Formation (Figure 14).

The Thickwood Valley, the more southerly of the two, is about 20 km long and 1 km or more wide. The valley descends from about 450 m asl at its western end to about 390 m at the east, and is incised about 10 m into the Grand Rapids Formation (Figure 8). As much as 80 m of drift were mapped above the valley floor (Figure 15). A single borehole litholog located along the north flank of the Thickwood Valley (Twp. 90, Rge. 12) recorded as much as 70 m of sand and gravel above the bedrock surface. If this occurrence and thickness accurately reflect the sediments contained within the area, then the valley may contain an aquifer, which presently cannot be mapped.

The Spruce Valley is located 15 km to the north, and similarly trends eastward through the centre of Twp. 91, Rge. 12 (Figure 8). It is about 16 km long and 1–2 km wide (Table 1). The valley descends from about 420 m asl in the west to about 380 m at the eastern edge of the Thickwood Hills–MacKay Plains, and is incised about 20 m into the Grand Rapids and Clearwater formations, resulting in a shallow gradient (~2–3 m/km). The valley is infilled by as much as 65 m of drift (Figure 15). There is insufficient information to map the valley farther east, although it is likely that it links with the buried Stony Valley located to the east (Figure 8). There are no data to indicate the composition of the sediments within or above the valley, and thus no indication of the presence of buried aquifers.

Additional information is required to confirm the location and geometry of both of these buried valleys, and to establish the nature of their associated sediments.

7.2.4 Stony, Inglis and Ruth Valleys

The Stony, Inglis and Ruth bedrock valleys are three subparallel valleys located directly west of the Athabasca River (Twp. 91–92, Rge. 10; Figure 8). They originate within the Athabasca River lowland and all appear to be intersected by the Athabasca River valley. Collectively, these valleys have similar characteristics: they are 6–8 km long and about 1 km wide. The Stony Valley decreases from about 300 m asl in the west to about 285 m in the east, and is incised about 10–15 m into the Clearwater and

McMurray formations (Table 1, Figure 14). Drift thickness in the Stony Valley ranges from 20 m at the western end to as much as 40 m at the eastern end (Figure 15). The Inglis Valley decreases from about 300 m in the west to about 280 m in the east and, at its deepest, is incised about 13 m into the McMurray Formation. Thickness of drift above the valley floor ranges from 15 m in the west to 40 m near the eastern end. The Ruth Valley descends from about 300 m in the west to about 280 m in the east. It is incised about 10 m into the McMurray Formation and is overlain by 15–35 m of drift.

The absence of any borehole lithologs makes it difficult to comment on the genesis and characteristics of the infill of these valleys, or their potential to host buried aquifers. A few gamma and resistivity logs recorded at the bottom of the drift sequence do not indicate thick infill of sand and gravel resting on the valley floors. Given that each of these valleys is truncated by the Athabasca River valley, the authors conclude that they formed prior to the re-establishment of the regional drainage in the Athabasca River lowland, following the last glaciation in the area. If so, then they can be considered to represent headward erosion of gullies that developed along the western flank of the preglacial Athabasca River valley. There is, however, circumstantial geomorphic evidence to suggest instead that all three valleys were eroded by glacial meltwater, flowing either along the former ice margin or in subglacial tunnels at a time when the preglacial Athabasca River valley was ice filled. Each of these channels, particularly the Stony Valley, could possibly represent the western continuation of the buried Clarke Channel, which is located east of the Athabasca River (Figure 8). The subparallel, east-west orientation of the three valleys may reflect episodic erosion along a northward retreating ice margin. Therefore, the potential for thick, continuous deposits of glacial sand and gravel within the Stony, Inglis and Ruth valleys remains high, until proven otherwise.

7.3 Buried Bedrock Channels

There are some unique aspects of the geometry of buried bedrock channels in the study area that warrant discussion. Most buried channels are interpreted as a class of glaciofluvial landform referred to as ‘tunnel channel’ or ‘tunnel valley’. A discussion paper on the various mechanisms of tunnel valley formation (O’Cofaigh, 1996) described tunnel valleys as “large, elongate, over deepened depressions eroded into bedrock or glacial sediment.” Tunnel valleys and channels are not features unique to the study area. They have been recognized in various parts of Canada (Brennand and Shaw, 1994; Beaney and Shaw, 2000; Russell et al., 2003; Sharpe et al., 2004), in the United States (Cutler et al., 2002; Fisher et al., 2005; Kozlowski et al., 2005; Hooke and Jennings, 2006) and in Europe (Piotrowski, 1997; Jørgensen and Sanderson, 2006). A comprehensive discussion of tunnel channel geometry and genesis is beyond the scope of this report, but the reader is encouraged to review the referenced papers to gain additional insights into their properties and modes of erosion.

Tunnel valleys, or channels, exhibit a number of features atypical of channels eroded under subaerial conditions. Some general comments can be made from this and other studies:

- Many tunnel channels are not confined to topographic lows, but can be eroded into the modern drainage and, in some cases, override bedrock highs (e.g., the Birch Channel).
- The gradients of the floors of some of these channels (e.g., the Birch Channel) can trend in the opposite direction to not only the present-day land surface but also the regional bedrock surface.
- Buried tunnel channels typically lack regional continuity: they appear to both begin and end abruptly, over distances as small as 5 km for some channels in the study area.
- Tunnel channels can be as much as 100 km long and consist of relatively straight, isolated segments or an integrated network of braided to anastomosing channel segments that can bifurcate and rejoin.

- Most channels tend to be narrow (≤1.5 km wide) and deep (as much as 100 m), resulting in steep, asymmetrical side walls and depth to width ratios as high as 1:5, as in the case of the Gregoire tunnel channel located directly south of the study area (Andriashek, 2000; Figure 18).
- Depth of channel incision is variable, and overdeepening by fluvial scour can result in undulating and concave longitudinal profiles (O'Cofaigh, 1996).
- Erosion and infill from episodic flood events can produce a complex of stacked and superposed channel segments and associated deposits.

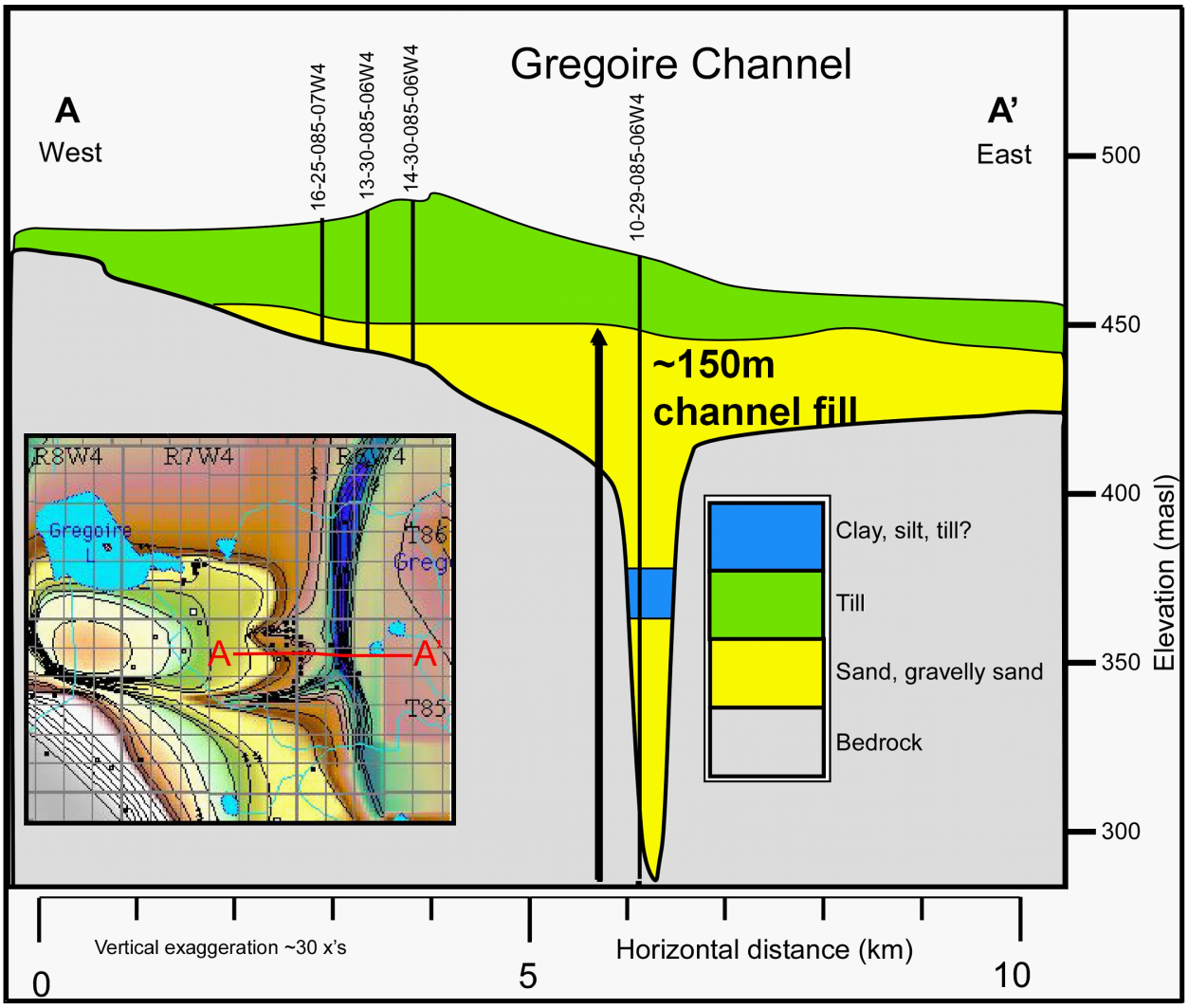


Figure 18. Geological cross-section of the Gregoire tunnel channel, illustrating the narrow and deeply entrenched channel (depth-to-width ratio of about 1:5), Fort McMurray region.

Some general comments can also be made regarding the nature of the sedimentary fill within buried tunnel channels:

- Tunnel channels can be infilled by a variety of sediment types, including till, gravity-flow deposits, glaciofluvial sand and gravel, and suspension deposits. Many, however, are typically filled with thick fluvial sediment (as much as 70 m in the Athabasca study area), which in some cases appears to have been deposited during a single event (Russell et al., 2003).

- In the Fort McMurray region, the channel sediment is generally sand but also contains clay beds and gravel, which includes metre-sized boulder beds. These deposits are indicative of highly varied depositional regimes typical of glaciofluvial environments. O'Cofaigh (1996) stated that till is not commonly found on the floors of buried tunnel channels, which appears to be true for channels in the study area. In rare cases, segments of channels may be completely infilled with till, fine-grained fluvial or lacustrine sediment, or injected slabs of glacially thrust and displaced bedrock.
- Seismic profile and borehole lithology data reveal chaotic inclusions of till and bedrock in some channel-fill sequences, indicating either collapse of the channel sides during sediment infill or glaciotectonic displacement of bedrock into the channel.

As a consequence of their narrow width, abrupt truncations, and possible superposition on topographic highs, the distribution of buried tunnel channels can be difficult to predict from sparse borehole information. Narrow valley segments can easily lie between exploration boreholes, which commonly are spaced 1–1.5 km apart.

Finally, not all buried glacial channels in the study area are believed to have necessarily formed beneath a glacier. Although their form and sedimentology reflect an ice-proximal environment, it is evident that at least some channels were formed by subaerial drainage of glacial meltwater, typical of abandoned glacial meltwater channels found in the present landscape of Alberta.

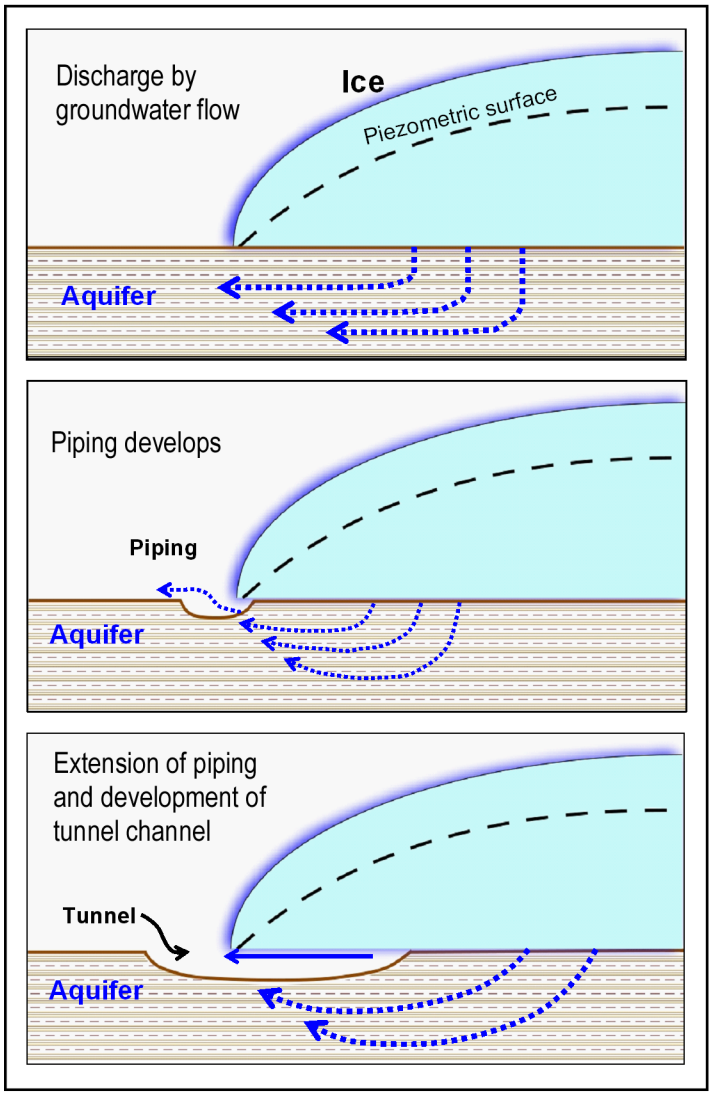
The following sections provide a more detailed description of the geometry and infill composition of channels in the Athabasca Oil Sands area.

7.3.1 Genesis of Tunnel Channels

There is much debate regarding the genesis of tunnel channels, and a summary of those discussions would constitute a paper in itself. There is, however, a consensus that the morphology of tunnel channels indicates that they did not form under subaerial conditions. Rather, subglacial meltwater was the primary erosive agent, with meltwater driven against the regional slope by a hydrostatic head generated by the gradient of the former ice surface. Two mechanisms of formation are briefly summarized here to explain the origin of some buried bedrock channels in the Athabasca Oil Sands area:

1) **Episodic catastrophic flow of ponded subglacial water initiated by piping:** In this model, tunnel channels are formed by episodic outbursts of ponded subglacial meltwater behind the frozen margin of the glacier, and the process of erosion is initiated by piping (Hooke and Jennings, 2006). Ice sheets overriding sediments with high hydraulic conductivity normally discharge subglacial meltwater primarily through the substratum as groundwater flow. If, however, the hydraulic conductivity of the substratum is insufficient to drain all the basal meltwater, as is the case near the ice margin where the glacier bed and underlying ground are frozen (permafrost), excess water will begin to accumulate beneath the ice and lead to elevated basal water pressures. This pressure is directed toward the glacier margin (Figure 19a), where the substrate fails by piping. Headward propagation of the conduit (incipient channel) eventually connects with the subglacial reservoir and the resulting catastrophic outburst enhances erosion, enlarging the subglacial channel (Hooke and Jennings, 2006). Subsequent drainage of the reservoir decreases the flow of water and the channel becomes filled with sediment and ice, plugging up the outlet. This allows the reservoir to refill and the process repeats.

2) **Catastrophic subglacial meltwater floods:** In this model, tunnel channels serve as drainage pathways for short-lived catastrophic discharges of subglacial water (jökulhlaups), which scour into the underlying bedrock. As in the previous model, meltwater accumulates at the base of the



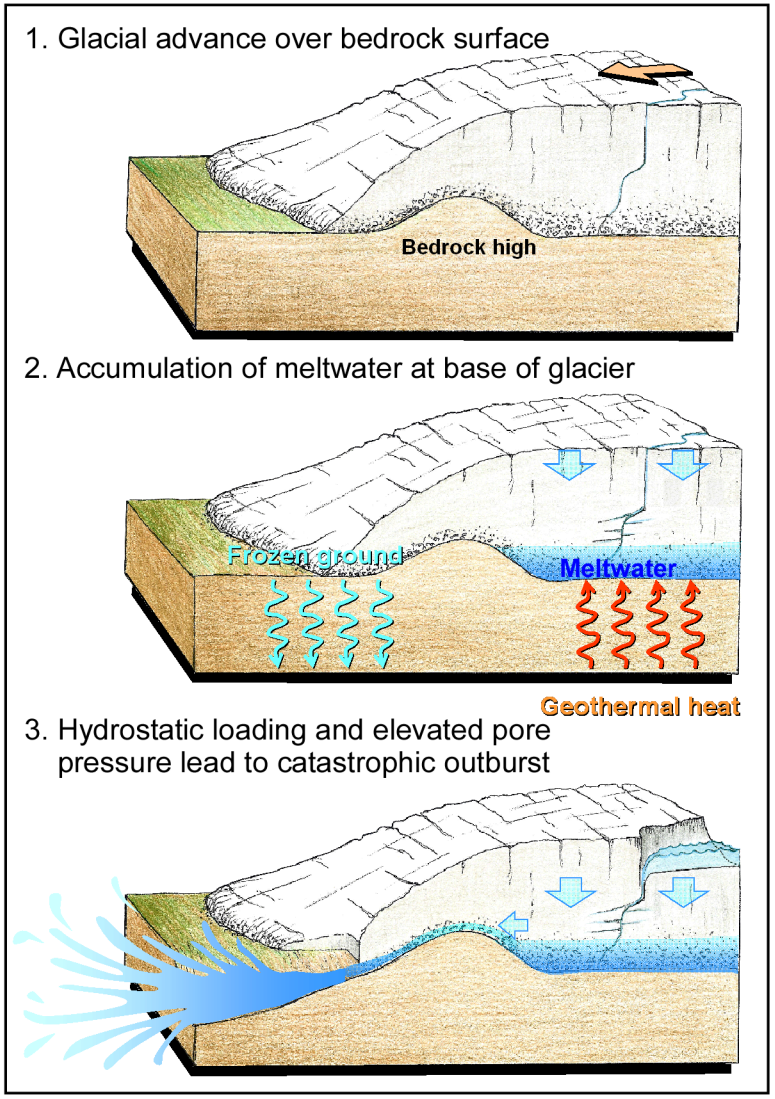


Figure 19. a) Tunnel channel formation by progressive piping of sediment beneath glacier (modified from Boulton and Hindmarsh (1987) in O'Cofaigh, 1996). b) Tunnel channel formation by catastrophic release of subglacial meltwater.

glacier, back from the frozen margin, by way of surface-water percolation and basal ice melt (Figure 19b). Obstructions in the underlying bedrock surface, as well as the frozen glacier margin, inhibit subglacial drainage, enabling the development of ponded subglacial water, which is subjected to elevated pressure by the weight of the overlying ice. The entire tunnel channel system forms simultaneously by incision from a catastrophic flood of high-velocity, channellized subglacial meltwater. Because these systems are driven by hydrostatic head, channels can be eroded on elevated parts of the underlying landscape, and have anastomosing, undulating to scoured longitudinal profiles (O'Cofaigh, 1996). These flood events are interpreted to be overloaded with suspended sediment, which leads to rapid sedimentation directly down-flow (Russell et al., 2003). Common to both models is the rapid drainage of ponded subglacial meltwater under high hydrostatic pressure, and the subsequent entrenchment and infill of the scour feature.

7.3.2 Birch Channel

The Birch Channel is one of better understood channels in the study area, mainly because of the high-quality lithological descriptions of borehole cuttings and a suite of downhole petrophysical logs. A comprehensive description of the channel, and the sediments contained within, was provided by Andriashek (2000), so only a summary is included here.

The Birch Channel lies beneath the MacKay Plains physiographic unit, west of the Athabasca River lowland (Twp. 92–93, Rge. 11–15; Figures 2 and 8). The channel is believed to extend west of the study area, to Twp. 91, Rge. 17, where it extends south to at least the southern part of Twp. 90 (Andriashek, 2000). The Birch Channel has incised through the Grand Rapids Formation and is floored on the Clearwater Formation (Figure 14). Andriashek (2000) suggested that the Birch Channel aquifer outcropped along the east side of MacKay River (Sec. 30, Twp. 93, Rge. 11; Andriashek, 2000, Figure A2-1). That interpretation is now revised based on new information collected during this study: it is more likely that the exposure of buried fluvial deposits on the MacKay River is an outcrop of the buried North Spruce Channel aquifer, which merges with the Birch Channel aquifer near that location.

A number of aspects of the geometry of the Birch Channel support the interpretation that it was formed subglacially. Firstly, the channel is deeply incised (75–80 m) into the highest part of the underlying bedrock, and yet, for much of its channel length, it has an extremely low gradient (0.3 m/km), particularly in the western part of the channel (Table 1, Figure 20). The gradient increases only slightly as the channel enters the Athabasca River lowland. This entrenchment of a deeply incised, nearly flat channel into the bedrock upland is atypical of subaerial erosion but characteristic of erosion by subglacial meltwater under high hydraulic head. A second feature of the Birch Channel that is characteristic of tunnel channels but atypical of subaerial valleys is the relatively low width-to-depth ratio (Table 1, Figure 20). The third aspect that supports the tunnel channel interpretation is the thick infill of glaciofluvial gravel and sand, interbedded with silt and clay as well as diamict (Andriashek, 2000), which indicates rapidly fluctuating flow regimes, typical of subglacial environments.

Figure 21 shows point values of the cumulative thickness of sand and gravel recorded in individual boreholes in the study area, irrespective of whether the sand and gravel is buried or exposed. It illustrates the overall regional distribution of sand and gravel within the drift, which helps define the distribution of buried aquifers. Figure 22 is a buried aquifer isopach map, constructed by first modelling the top of buried sand and gravel that rest on bedrock and then subtracting the bedrock surface from the modelled buried sand and gravel surface. Figures 20 to 22 show as much as 80–90 m of coarse-grained glaciofluvial sediment lying on the bedrock floor of the Birch Channel. The thickness of drift (and channel aquifer) decreases abruptly in the eastern segment of the channel (Twp. 93, Rge. 12), where the channel enters the Athabasca River lowland and is intersected by the MacKay River (Figure 18).

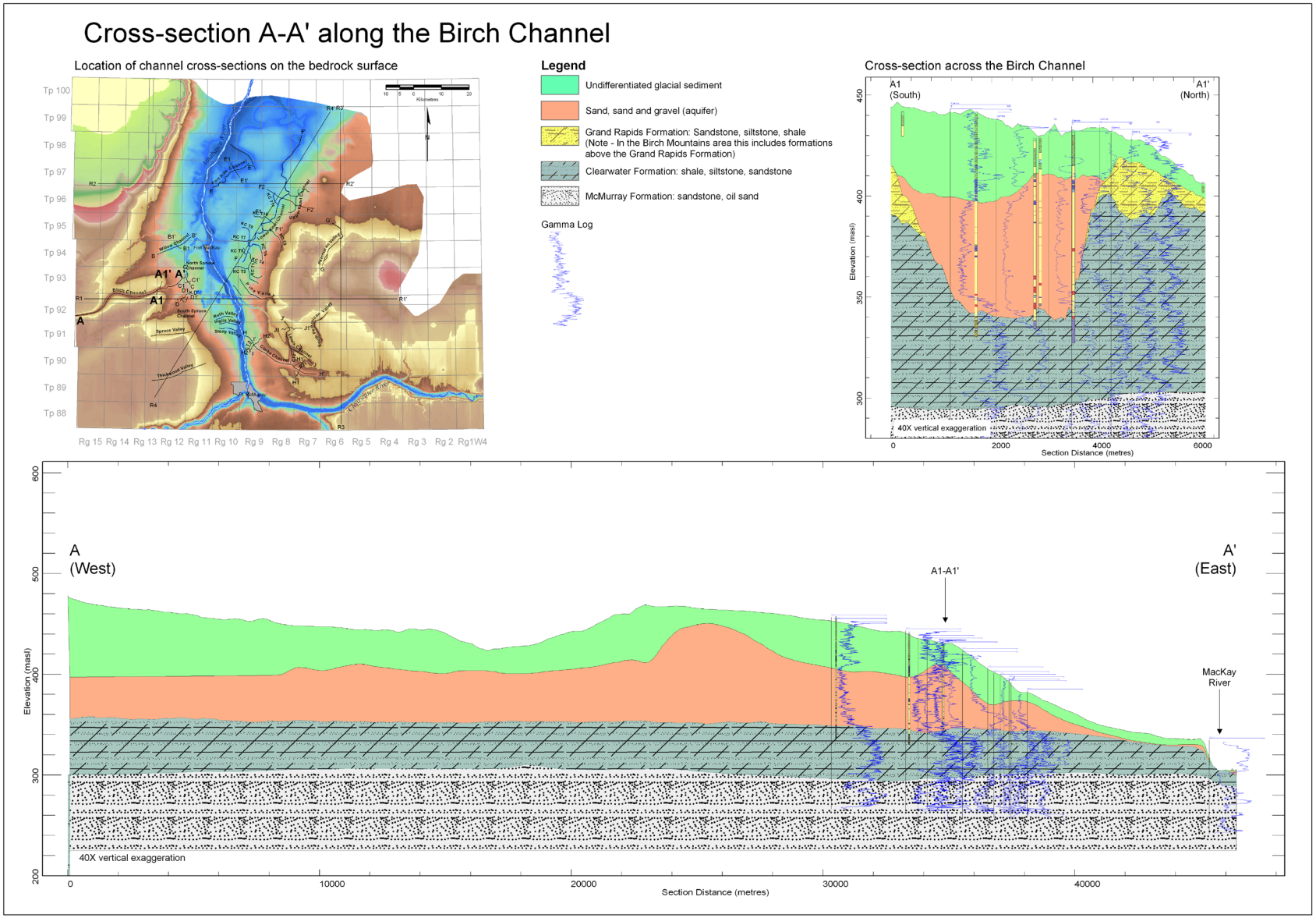


Figure 20. Geological cross-section along the Birch Channel, Fort McMurray region.

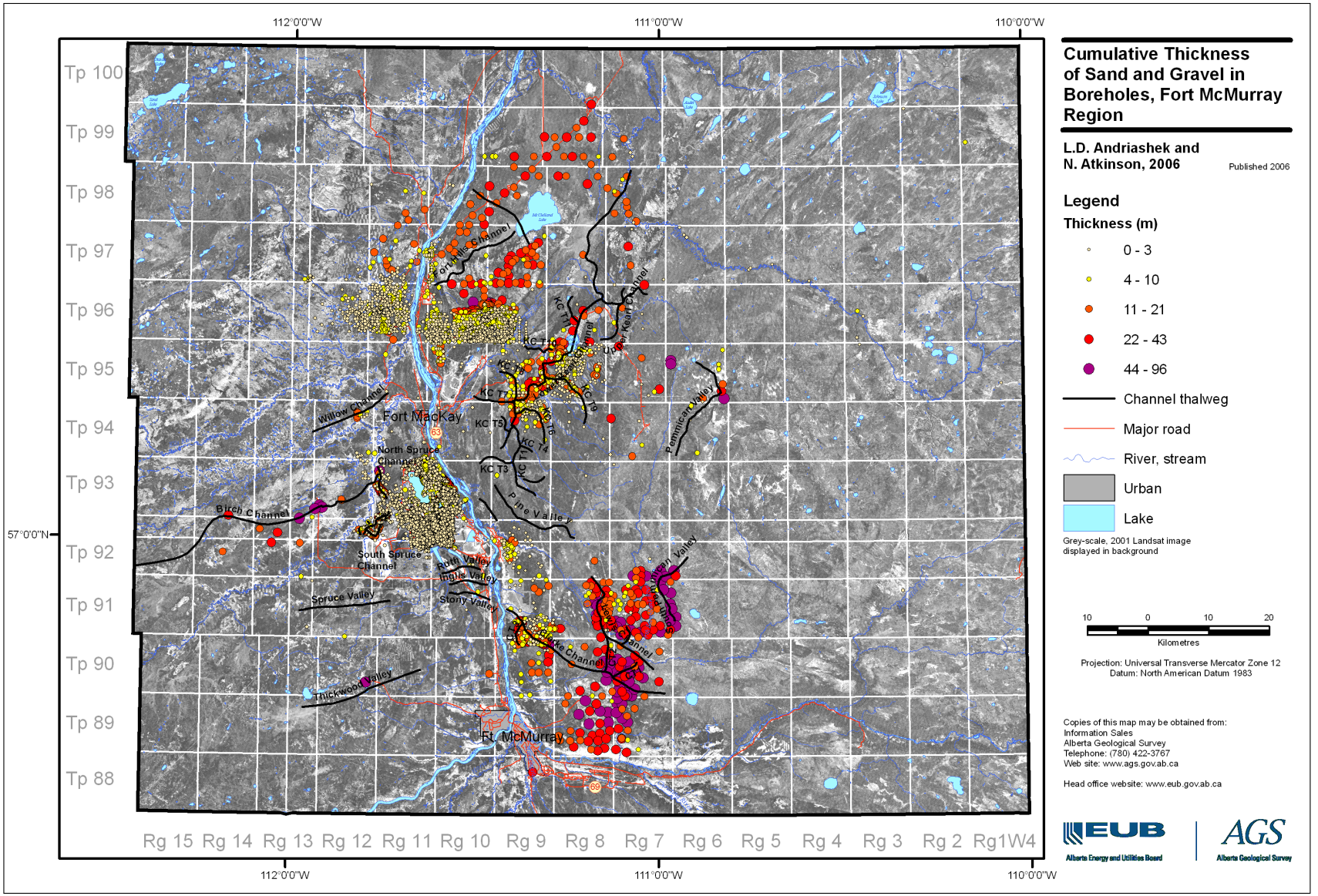


Figure 21. Point values of cumulative thickness of sand and gravel recorded in borehole logs, Fort McMurray region.

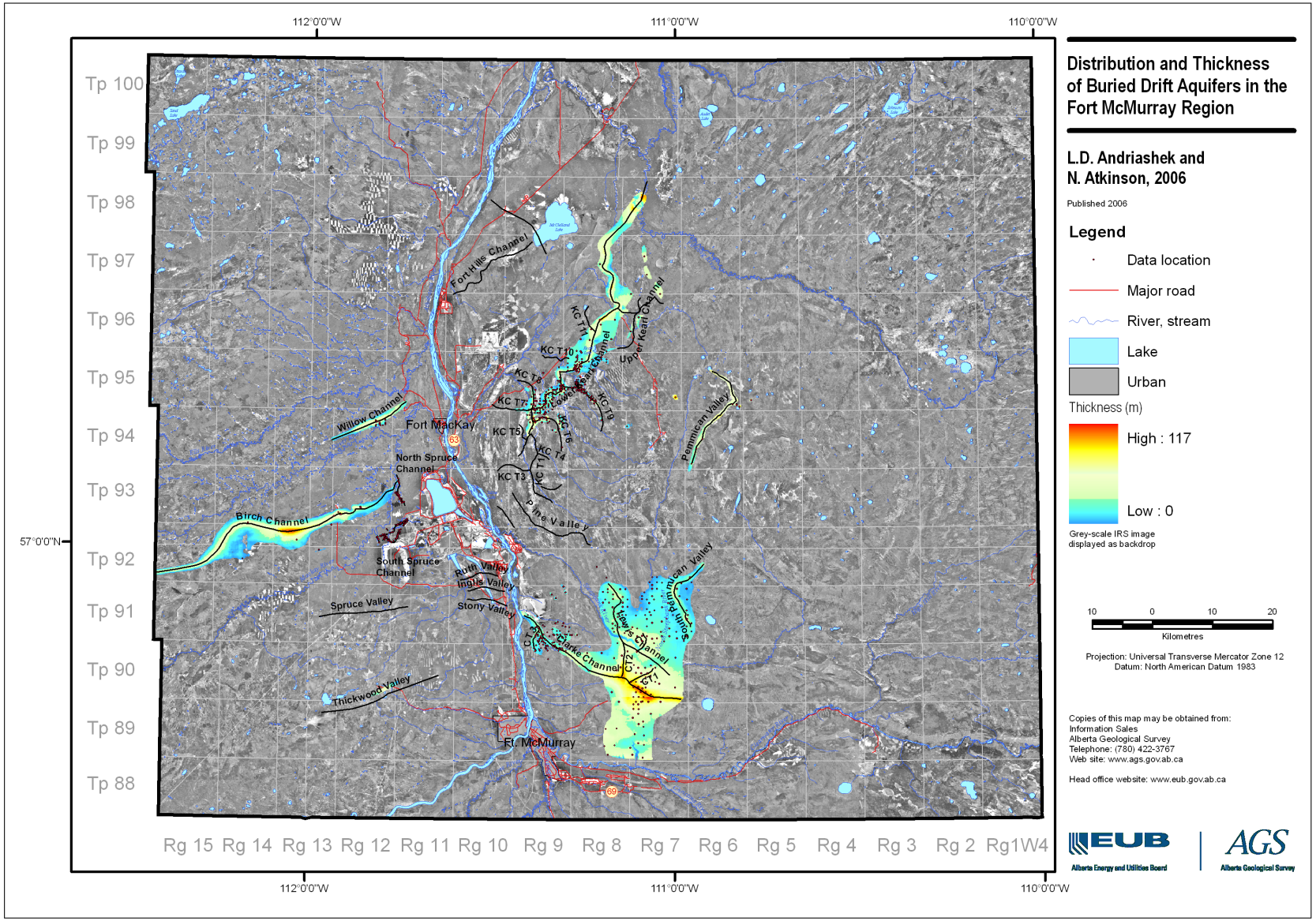


Figure 22. Distribution and thickness of buried drift aquifers in the region north of Fort McMurray.

The Birch Channel aquifer contains potable groundwater (unpublished water chemistry data, AGS data holdings) that has been used as a source of fresh water for steam injection in SAGD oil recovery processes. East of Twp. 93, Rge. 12, the top of the aquifer lies just beneath the present-day land surface (Figure 20) and groundwater discharges into shallow streams and wetlands.

7.3.3 North and South Spruce Channels

An abundance of high-quality, closely spaced borehole data, consisting of shallow-auger lithologs, enables a complex of discontinuous to anastomosing, deeply entrenched bedrock tunnel channels to be mapped directly east of the MacKay River (Twp. 92–93, Rge. 11–12; Figure 8). From these were mapped two distinct but unconnected channel segments, named here the 'North Spruce Channel' and the 'South Spruce Channel'.

The North Spruce Channel trends north for about 6 km, along the western edge of Twp. 93, Rge. 11, directly west of the Syncrude mine tailings pond, where it is believed to merge with the Birch Channel and form a single channel along the east side of the MacKay River (Figure 8). The channel has a relatively shallow gradient for most of its length, decreasing northward from about 310 to 300 m asl over a distance of about 5 km. The channel is deeply entrenched at its northernmost end, however, where it merges with the Birch Channel, bottoming out at about 275 m over a distance of 0.5 km. The channel is relatively narrow (0.6 km) and deeply incised into bedrock (30 m), resulting in one of the lowest width-to-depth ratios (20) of all the bedrock channels and valleys discussed in the report (Table 1). The southern segment of the channel is floored on the Clearwater Formation, whereas its northern end is incised into McMurray Formation oil sand.

Most of the drift within the channel consists of sand and gravel that increases in thickness from 20 m in the south to 50 m within the deeply scoured northern segment (Figures 22 and 23). Beds of till also occur within the channel sand and gravel, but do not appear to be extensive. The channel sand and gravel is capped by thin till, which is overlain by glaciolacustrine silt and clay. Appendix 1 (Figures 57-62) illustrates the textural variability in the channel sediments exposed along the MacKay River, ranging from metre-sized boulders to finely bedded silty sand. Dip directions recorded in high-angle beds within the upper 10 m of sand at outcrop LA2005-04 show that the dominant flow direction during time of deposition was to the southwest, with some variance to the west and northwest (Appendix 1). If a dominantly southwest dip direction is representative of the entire aquifer sequence, then this flow direction is opposite to not only the gradient of the present-day landscape (north), but also to the northerly slope of the channel thalweg. This is significant because it supports the interpretation that these channels were formed subglacially by meltwater driven by a hydraulic head that enabled flow against the regional gradient.

Directly south of the North Spruce Channel are a number of discrete bedrock channel segments that start and end abruptly. Two of these channel segments, though disconnected, appear to represent erosion along a single channel, collectively called the 'South Spruce Channel' (Figures 8 and 24). Another channel segment lies to the east and south of this segment, informally referred to as the south branch of the South Spruce Channel (Table 1). Both segments of the South Spruce Channel complex are about 5 km long and narrow (0.3–0.5 km), have steep side walls, and are deeply incised (10–15 m) into the Clearwater Formation. Overdeepening by fluvial scour at the northern end of the channel has produced an undulating longitudinal profile, as shown in the cross-section constructed along the channel thalweg in Figure 24. Elevation of the channel floor decreases from about 345 m asl in the southwest to about 310 m in the northeast, resulting in a gradient of about 5 m/km. The channel consists of two disjointed segments, however, each of which has a shallower gradient (Figure 24). A notable feature of this channel system is that it terminates abruptly, within the spacing interval of adjacent boreholes (~100 m).

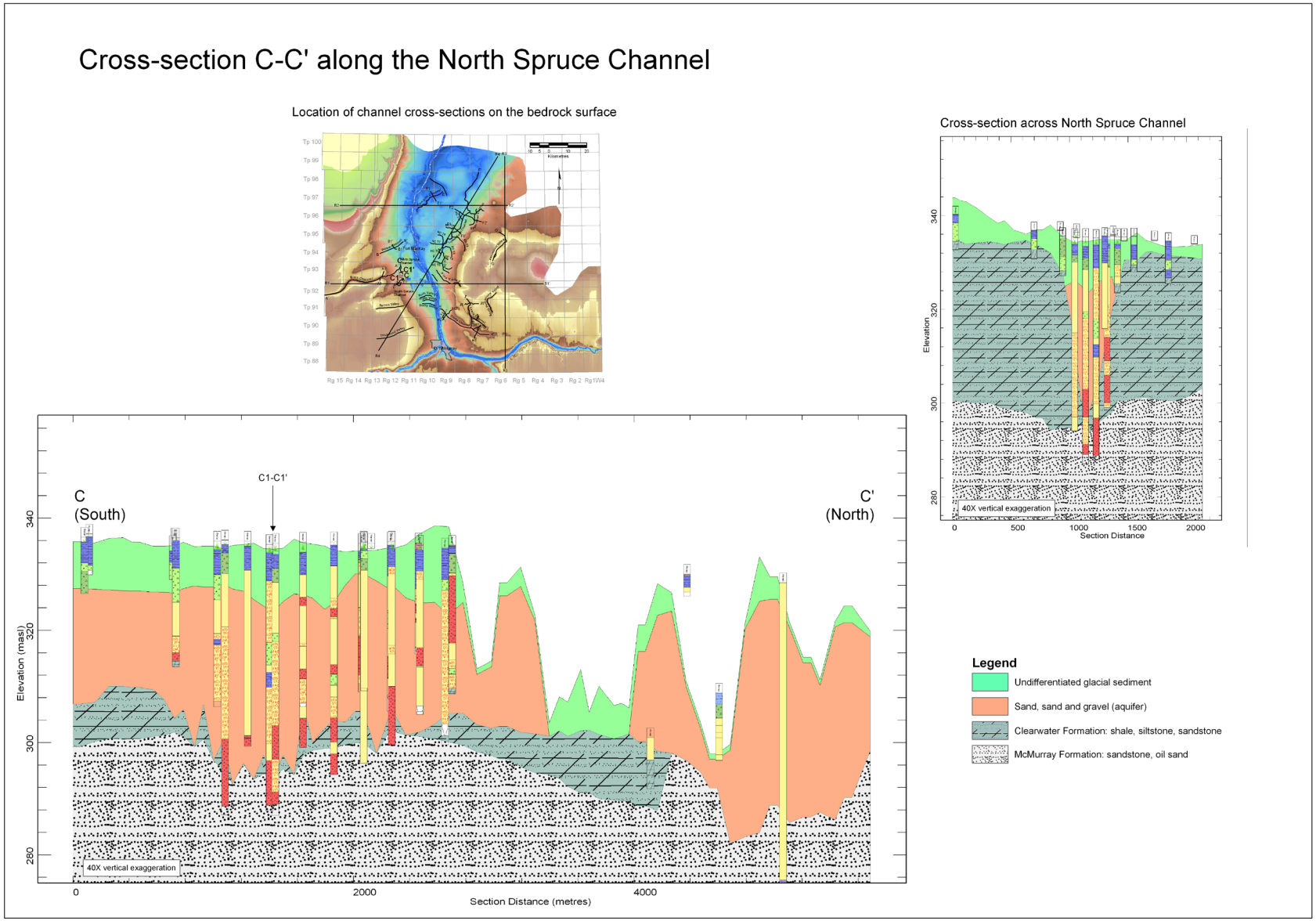


Figure 23. Geological cross-section along the North Spruce Channel, Fort McMurray region.

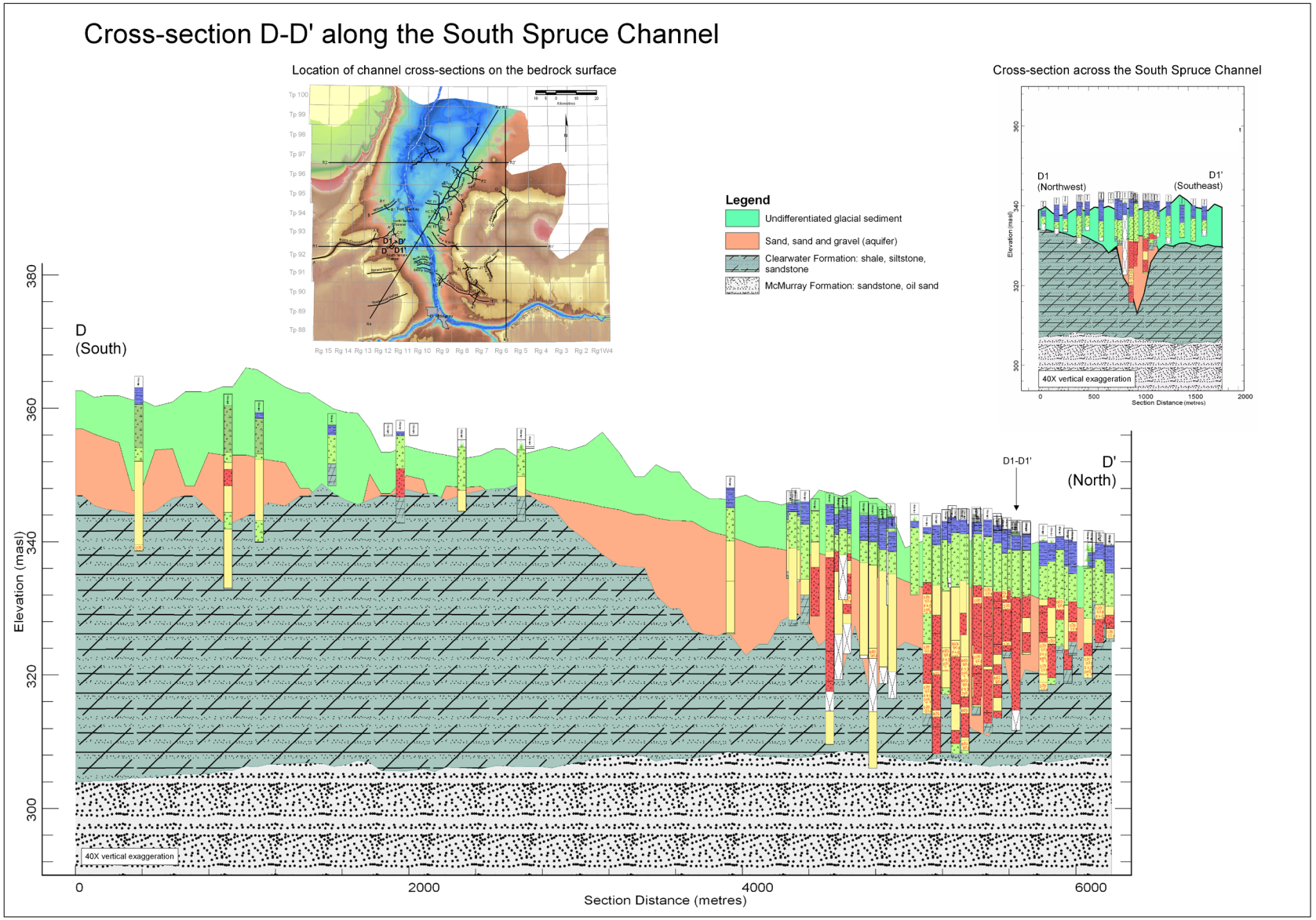


Figure 24. Geological cross-section along the South Spruce Channel, Fort McMurray region.

Like the North Spruce Channel, the South Spruce Channel contains thick sand and gravel (as much as 20 m), overlain by till and glaciolacustrine sediment (Figures 23 and 24). The fluvial sediments within channel have been exposed by recent oil sands mining excavations, revealing a wide range in grain size, from imbricated boulders near the base of the sequence to cross-stratified sand and silty sand near the top (Appendix 1, Figures 87–89). The eastward-imbricated boulders indicate that the dominant flow direction at the time of deposition was to the west, which is consistent with flow direction for the upper part of the fluvial sequence in the North Spruce Channel. As discussed previously, this westerly flow against the regional bedrock slope and the undulating profile of the channel floor support a subglacial origin for the channel and associated glaciofluvial sediments.

Unfortunately, future work on exposures of this channel will not be possible since the South Spruce Channel system has now been excavated by oil sands mining.

7.3.4 Willow Channel

Andriashek (2000) initially described the Willow Channel and its associated sediments. Since that report, new borehole information has increased understanding of the extent of the channel and the nature of its associated sediments.

The Willow Channel is currently mapped for about 14 km across the northwestern part of the study area, trending northeast from Twp. 94, Rge. 12 to the southwest corner of Twp. 95, Rge. 11 (Figure 8). There are insufficient data to map the channel farther west and, although data remain sparse in the northeast, high-quality litholog information confirm the presence and easterly extent of the channel. The Willow Channel is estimated to be about 1 km wide and appears, from gamma log records, to incise bedrock by 25–30 m (Figure 25). The western half of the channel is floored on the Clearwater Formation and the eastern half on McMurray Formation oil sand (Figures 14 and 25). The elevation of the channel floor decreases from about 330 m asl in the west to about 275 m in the east, resulting in a gradient of about 3.5 m/km (Table 1).

Drift thickness above the channel floor ranges between 30 and 60 m (Figure 15), with up to 40 m of sand and gravel resting directly on the channel floor (Figures 22 and 25). Stratigraphic evidence suggests that this is a stacked sequence resulting from several cycles of episodic discharge from subglacial reservoirs. A cross-section constructed across the Willow Channel (Figure 25) shows that the top of the buried sand and gravel appears to be unconstrained by the channel margins, since it mantles the adjacent bedrock surface where it can be correlated with sand that overlies till. If this correlation is valid, and the intratill sand units are not simply isolated beds within the drift sequence, it leads to one of two interpretations regarding the depositional history. In the first scenario, the bedrock landscape was first covered with till into which a channel was later incised. Both the channel and surrounding landscape where then covered with sand and gravel during a single event. All units were later covered by another glaciation that deposited what is now the upper till, as well as the overlying lacustrine sediments. In the second scenario, glacial meltwater eroded a channel in the exposed bedrock, and sand and gravel were deposited within the channel margins. A glacial advance then covered these channel deposits, as well as the adjacent bedrock margins, with till. Subsequent glacial meltwater reoccupied the channel, eroded the previously deposited till within the channel and stacked another sequence of sand and gravel on top of the pre-existing channel deposits, as well as on the till-covered landscape along the channel flanks. As in the first case, a later glaciation covered the entire sequence with till and glaciolacustrine sediment. In either scenario, the stratigraphic record suggests that multiple glacial events influenced erosion and sedimentation in the area, and that the Willow Channel may have been occupied by more than one fluvial system. The thickness of the aquifer along the margins of the Willow Channel, as depicted in cross-

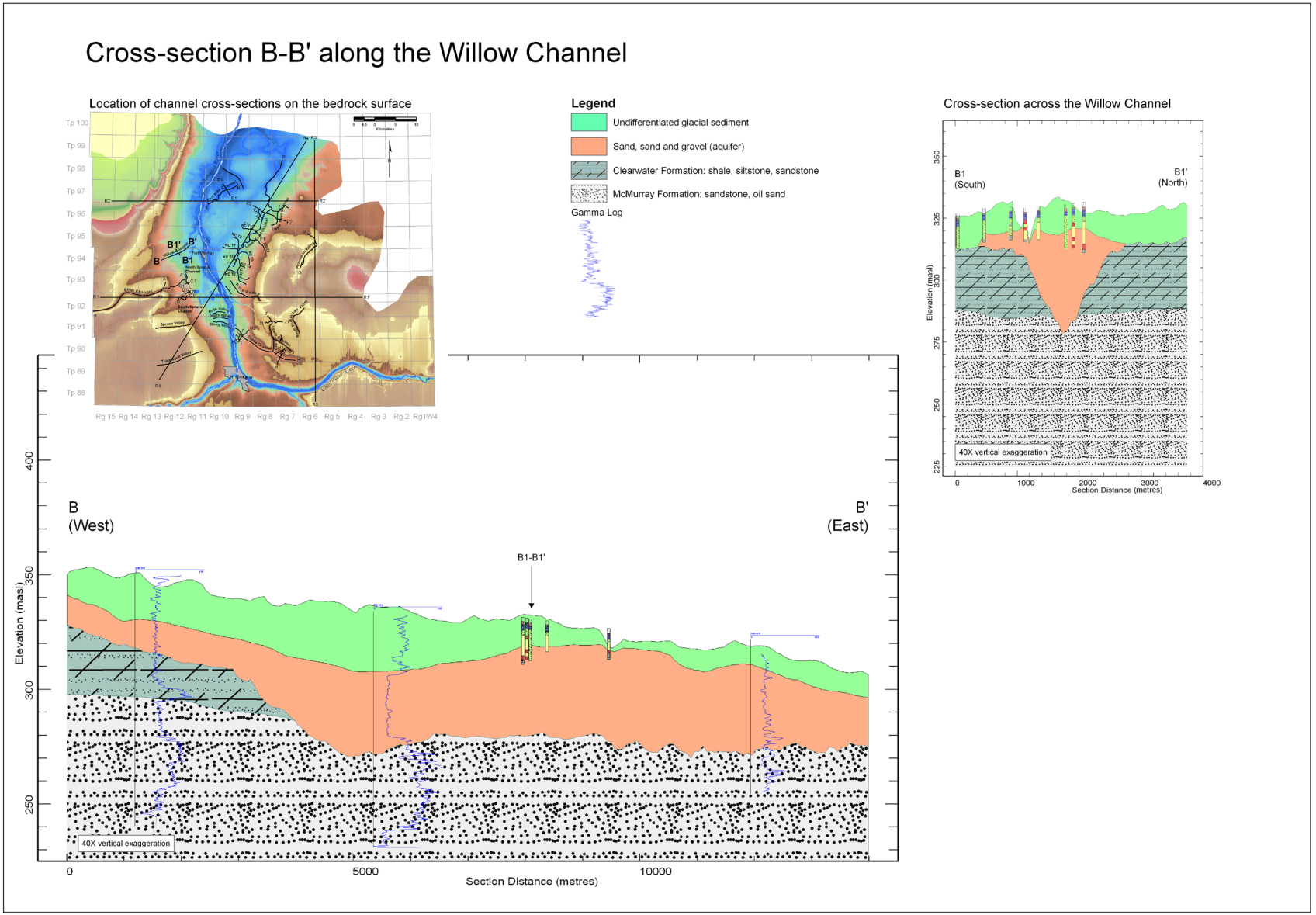


Figure 25. Geological cross-section along the Willow Channel, Fort McMurray region.

section B1–B1' (Figure 25), is an overestimation resulting from use of the bedrock surface (instead of the underlying till surface) in the calculation of the isopach map.

A previously mapped exposure of the Willow Channel sediments, situated along a cutoff meander of the Dover River in the southwest corner of Sec. 26, Twp. 94, Rge. 12 (Andriashek, 2000), was revisited to collect information regarding the sedimentology and direction of flow at the time of deposition. Appendix 1 (Figures 65–67) illustrates the variability in composition of the buried fluvial sediment, from 2–3 m thick beds of boulders to beds of crossbedded sand. Remarkably, the suite of sediments within the Willow Channel, including the bed of boulders nested within fine sand, is almost identical to that in the outcrop of the North Spruce Channel, approximately 10 km to the south. Dip directions of high-angle bedding structures in sand at the Willow Channel outcrop range from southwest to northwest, indicating flow dominantly to the west (Appendix 1). This flow direction is opposite to the gradient of the underlying bedrock channel floor, as well as the gradient of the regional bedrock and present-day topography. Flow in opposing directions, along with evidence of catastrophic high-energy bursts (boulder bed), support a subglacial meltwater origin for some of the fluvial sediments contained within the Willow Channel, and possibly the channel itself.

7.3.5 Fort Hills Channel

The bedrock topography map (Figure 8) shows two channel or valley thalwegs forming a perpendicular pattern beneath the west flank of the Fort Hills, southwest of McClelland Lake (Twp. 97, Rge. 9–10): a northeast-trending channel is herein named the 'Fort Hill Channel', whereas the northwest-trending channel or valley remains unnamed. In a previous study (McPherson and Kathol, 1977), the unnamed channel was projected at least 40 m deeper than shown in this study. This is an area where data are sparse and karst dissolution of the underlying Devonian bedrock is known to occur, so the bedrock topography remains open to reinterpretation.

The floor of the Fort Hills Channel ranges from about 245–260 m asl and, although the overall gradient of the channel floor is to the northwest, the floor has an undulating longitudinal profile (Figure 26). The channel is relatively broad (1–1.3 km) and incised about 10–12 m into the McMurray Formation (Figure 14), resulting in a high width-to-depth ratio (Table 1), more typical of the bedrock valleys described in section 7.2. Drift thickness above the channel ranges from as much as 100 m within the southwestern segment of the channel underlying the Fort Hills to about 40 m in the northeast (Figures 15 and 26).

Abundant high-quality borehole data (lithologs) support a detailed interpretation of the drift stratigraphy within the Fort Hills Channel. These data were acquired late in the study, however, and have not been incorporated extensively into the interpretations in this report. Borehole lithologs depicted on the cross-sections in Figure 26 show the drift to be composed generally of thick sand with discontinuous thick beds of clay, which overlies till, which in turn overlies either bedrock or thick sand on top of bedrock. Unlike the stratigraphic setting of other glacial channels, a widespread, extensive basal sand aquifer is not recognized within the Fort Hills Channel, even though thick sand locally rests on the bedrock surface. What is also apparent is the great variability in lithology and thickness of similar units in adjacent boreholes, particularly in the thick complex that defines the Fort Hills physiographic unit (Figures 2 and 26). The origin of the sediments in the Fort Hills continues to be subject to much debate, having previously being interpreted as an ice-contact kame-moraine complex (Bayrock, 1971; McPherson and Kathol, 1977) and more recently as an ice-thrust complex (Savigny and Leboe, 1998). The characteristics and origin of the sediments in the Fort Hills are discussed in section 8.2.1.

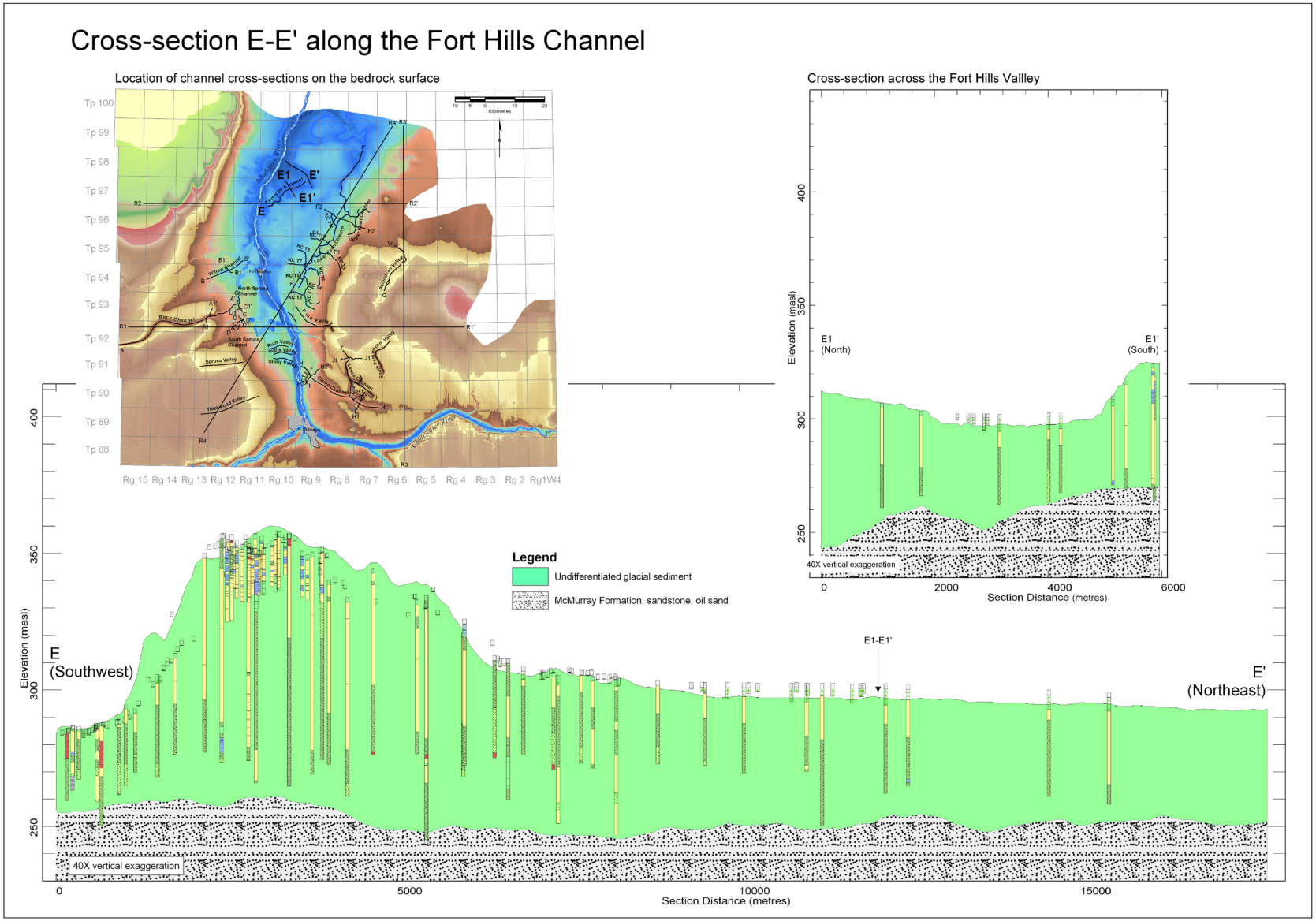


Figure 26. Geological cross-section along the Fort Hills Channel, Fort McMurray region.

Additional work is required to interpret these new data, in order to better define the subsurface geology of the thick drift sequence that makes up the Fort Hills.

7.3.6 Kearl Channel Complex

The Kearl Channel complex consists of a network of up to 11 channel segments that are either disconnected from or crosscut one main channel. The complex is nested at the foot of the west side of the Muskeg Mountain bedrock upland, with the main channel, herein referred to as the 'Kearl Channel', trending north, parallel to the axis of the Athabasca River lowland (Figure 8). Elements of the main channel have been mapped in previous reports (Laubitz, 1989), and a comprehensive summary of the channel geometry, stratigraphy and genesis was presented by Horne and Seve (1991). The reader is encouraged to review these papers.

The abundance of new data now enables a regional interpretation of the entire Kearl Channel complex. For purposes of discussion, the remaining branches or channel segments have been assigned informal names (T1 to T11). Their designation and physical properties are summarized in Table 1. It is uncertain if all channel segments were formed at the same time or by the same process. Some channel segments, especially those trending west, may be preglacial valleys. These include the Pine Valley, which formed by drainage off the west flank of Muskeg Mountain. The main Kearl Channel may be been superposed later, and segments of these preglacial valleys may have been subsequently occupied by glacial meltwater, to further complicate the interpretation of their origin. Most of the discussion here will focus on the Kearl Channel, and the nature of its associated glaciofluvial sediments, as well as those secondary channels that also contain glaciofluvial sediments.

Horne and Seve (1991, p. 77-7) aptly described the geometry of Kearl Channel as "…a series of non-equidistant straight courses, interspersed by gentle meanders and right-angle bends throughout its length. Feeder tributaries tend to re-align the main channel in the direction of the tributary at the junction point." This linked series of channel segments extends 60 km from Twp. 94, Rge. 9 northward to Twp. 100, Rge. 7, where the channel likely intersects the Firebag River (Figure 8). Data are sparse to the north, however, and due to the demonstrated abruptness of some tunnel channel terminations, it is conceivable that the Kearl Channel terminates before the river. Outcrops of the Kearl Channel were not observed along exposures at the presumed intersection with the west bank of the Firebag River (stop LA2005-08; Appendix 1, Figures 75–77), primarily because the river exposure did not extend to bedrock.

The width of the Kearl Channel varies between 0.8 and 1.0 km, although bifurcations increase its width to as much 2 km (southeast corner of Twp. 95, Rge. 9; Table 1). For the southern two-thirds, the floor of the channel is relatively flat, decreasing gently north from about 290 to 280 m asl at a gradient of about 0.25 m/km. The northern third of the channel is steeper, decreasing to 260 m over 15 km, at a gradient of 1.3 m/km. The channel is incised as much as 25 m into the McMurray Formation (Figures 14 and 27). The subparallel relationship between the Upper Kearl Channel and the Kearl Channel (Figure 8), suggests that they are genetically related but formed at different times. A cross-section across both channels (Figure 27) shows that the Upper Kearl Channel occupies a higher elevation, suggesting it became abandoned as meltwater drained preferentially along the larger Kearl Channel.

As with most of the buried channels, the longitudinal profile of the Kearl Channel is undulating and overdeepened by as much as 10 m directly north and south of Kearl Lake (Twp. 95, Rge. 8). Horne and Seve (1991) attributed the overdeepening to plunge-pool action caused by the catastrophic release of meltwater, but similar overdeepening can occur in subglacial tunnel channels. Overdeepening of the channel floor, however, cannot be attributed solely to fluvial erosion. Borehole records show thick beds (4–5 m) of displaced Clearwater Formation shale nested within the channel sand and gravel, suggesting

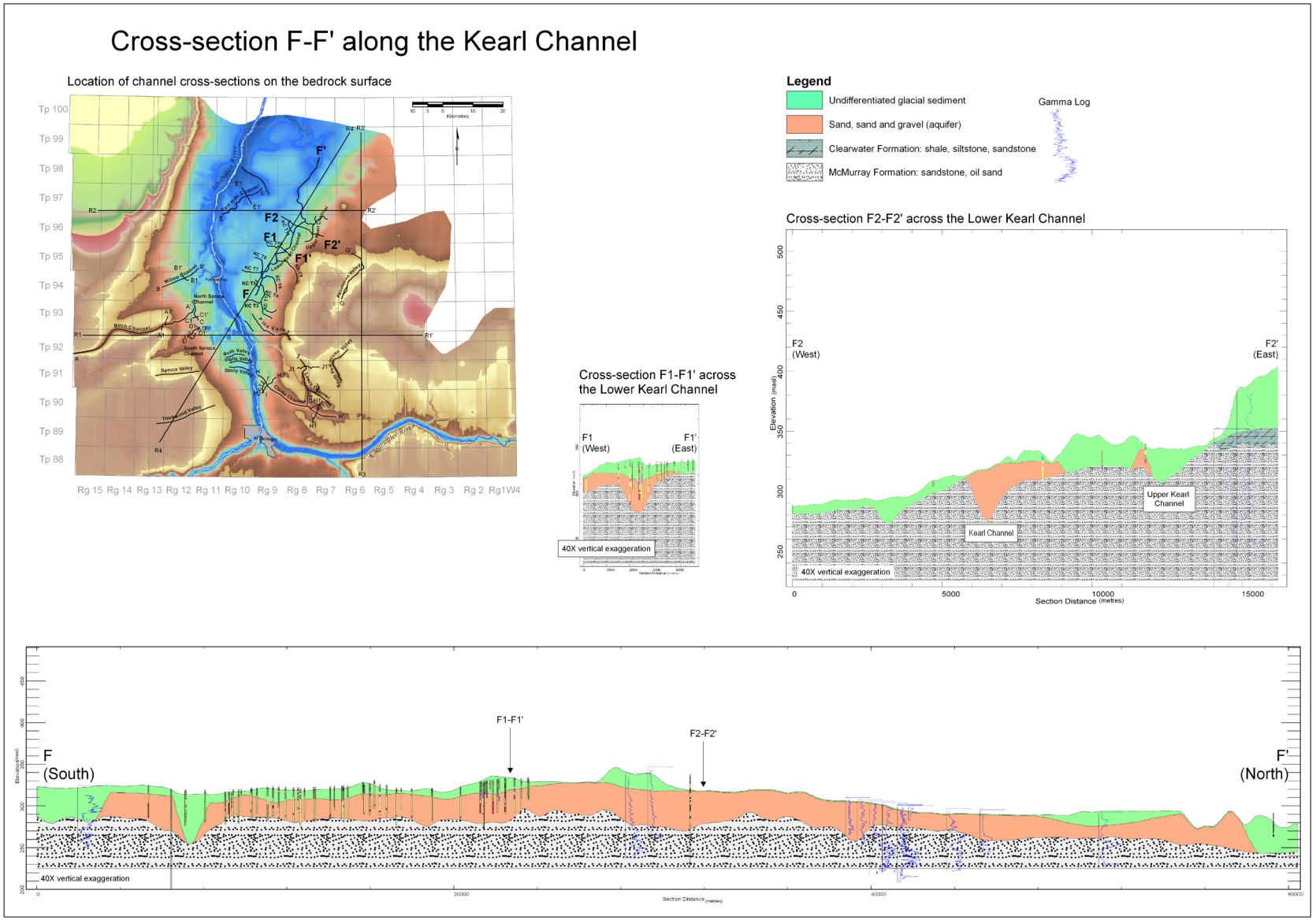


Figure 27. Geological cross-section along the Kearl Channel, Fort McMurray region.

that ice thrusting may have excavated parts of the channel floor. The influence of glaciotectonism on the drift composition within the Kearl Channel is discussed in section 8.2.2.

Figure 15 shows that drift thickness above the Kearl Channel complex ranges between 25 and 70 m, and averages between 30 and 40 m. Figures 22 and 27 show that channel sand and gravel form as much as 75% of the drift sequence, the remainder being till, overlain by glaciolacustrine and glaciofluvial sediments. To explain both the erosion of the channel and deposition of fluvial sediments within the channel, Horne and Seve (1991) suggested that, during formation, channellized water flowed to the south, against the regional topographic gradient, due to the catastrophic release of meltwater from a subglacial lake in the vicinity of McClelland Lake. The authors support this interpretation and argue the up-slope erosion and undulating to overdeepened channel form are evidence of erosion by a subglacial tunnel channel formed in the early stages of that meltwater release.

Some comments are worthwhile regarding the channel stratigraphy and possible affects on the behaviour of groundwater flow. Firstly, the top of the sand and gravel that lies on the floor of bedrock channel appears to be correlative with the top of a sand and gravel unit that rests on till along the flanks of the channel (Figure 27, cross-section F1–F1'). This suggests that a stacked fluvial sequence also occurs within the Kearl Channel. The overbank extension of the aquifer onto a pre-existing till plain, particularly along the thalweg of the Upper Kearl Channel, means that individual sand and gravel beds encountered within boreholes along the flanks of the channel should be evaluated in the context of being part of a much more extensive regional aquifer system. As with the Willow Channel, the thickness of the aquifer along the channel margins has been overestimated in the isopach calculation.

A second comment regarding aquifer distribution and continuity within the Kearl Channel is the localized apparent erosion of the sand and gravel, and subsequent infill with till within the channel (e.g., the south end of F–F', Figure 27). It is uncertain if erosion of the sand and gravel was related to glaciofluvial scour, or to excavational glaciotectonics, prior to the deposition of till. Borehole lithologs along the axis of Kearl Channel and within some of the adjacent channel segments, notably at the west end of channel T9, show glacially displaced bedrock present, either as discrete beds within the sand and gravel or at the base of the till directly overlying the sand and gravel. Three possible mechanisms for bedrock emplacement are considered. Firstly, masses of displaced bedrock entrained in the base of an overriding glacier were physically thrust or injected into the underlying channel sand and gravel. If so, then the upper part of the aquifer sequence may be similarly deformed by glaciotectonism. The second mechanism requires the syngenetic deposition of subglacial sand and gravel and the melt-out of entrained blocks of displaced bedrock from the base of the overlying ice mass. In this case, the displaced blocks of bedrock are conformable with sand and gravel. In the third mechanism, entrained masses of bedrock represent blocks of the Clearwater Formation that slumped from the high-angle slopes formed by fluvial scour of the tunnel channel. The influence of glaciotectonism on this and other features in the northern part of the study area is discussed in section 8.

The final comment regarding the characteristics of the Kearl Channel aquifer is the variability in the thickness of drift overlying the channel sediment, and the high potential for local interaction with near-surface water. If the surface of the top of the aquifer has been modelled correctly, then less than 5 m of surficial sediment, much of which is sandy with high intrinsic permeability, overlies the northern segment of the channel (Figure 27, cross-section F–F'). Although data density in this region is low, leading to reduced confidence in the modelled aquifer surface relative to that further south, the results do indicate a high probability that surface water bodies, perhaps even Kearl Lake, will interact with the aquifer.

With respect to the presence of buried aquifers within the remaining channel segments T1 to T11 (Table 1), the current data indicate that only segments T6, T7, T8, and T9 contain buried sand and gravel within their channel segments. Of these, T9 contains the most continuous buried deposits, and even these have been eroded or disturbed, likely by glacial thrusting at the confluence with the Kearl Channel (Twp. 95, Rge. 8). Horne and Seve (1991) commented that the upper parts of the 'feeder' channels in the east were infilled dominantly with fine-grained material, mainly till with a great amount of Clearwater Formation material. They suggested that subsequent reworking of sediment by glacial meltwater, particularly near the junction with the Kearl Channel, deposited coarse fluvial sediment along the lower portions of the tributary channels. The observations and interpretations in this study support their interpretation.

7.3.7 Clarke Channel Complex

The Clarke Channel complex was first mapped in an earlier AGS study (Andriashek and Meeks, 2000) and has been refined here through interpretation of a variety of data, ranging from dominantly gamma logs recorded through steel casing along the eastern two-thirds of the channel to higher quality water-well litholog records in the western third. Confidential seismic records, made available for viewing from private-company data holdings, provided supporting information for mapping the subsurface position and geometry of the Clarke Channel.

The Clarke Channel complex, the western segment of which has been referred to as the Woodcreek Channel in some industry studies, occurs in the southern part of the study area, north of the Clearwater River in Twp. 90–91, Rge. 6–9 (Figure 8). The Clarke Channel proper is a well-defined, entrenched bedrock channel with a northwesterly trend, subparallel to the axis of both the Clearwater and Steepbank rivers. The channel is referred to as a complex because it includes three bedrock channels or valley segments that, although not necessarily tributaries, intersect with the Clarke Channel. One segment, informally called 'Clarke Channel segment T1' (Table 1), trends southwest to merge with the Clarke Channel in Twp. 90, Rge. 7. A segment located farther to the west, referred to as 'Clarke Channel segment T2', trends north in Twp. 90, Rge. 8, apparently linking the Clarke Channel with the Lewis Channel. The third channel segment, Clarke Channel segment T3, is located even farther west and also trends north, subparallel to the Athabasca River, to merge with the Clarke Channel in Twp. 91 Rge. 9.

The Clarke Channel was mapped over at least 30 km, before the absence of data in the east prevented interpretation farther to the east. The channel floor slopes gradually from southeast to northwest, decreasing from about 345 m asl in the east to 300 m at the intersection with the Athabasca River valley in Twp. 91, Rge. 6 (Figure 28, section H–H'), a gradient of about 1.5 m/km. The lowest point in the channel lies at about 295 m, in an overdeepened fluvial scour at the junction with channel segment T3. The Clarke Channel is about 2 km wide and 20–50 m deep (Figure 28, cross-section H1–H1'). The channel is incised through the Grand Rapids Formation in the east and is floored on Clearwater Formation for its entire length (Figure 14). Thickness of drift above the channel floor is as much as 135 m in the east and decreases to about 40 m in the west (Figures 15 and 28). Any present-day surface expression of the Clarke Channel has effectively been masked by the thick drift cover.

Channel segment T1 extends northeast for about 5 km from its junction with the Clarke Channel in Twp. 90, Rge. 7 (Figure 8). The valley is 0.5–1 km wide, narrowing to the north, and the valley floor decreases in elevation from about 370 m asl in the east to about 340 m at the junction, resulting in a relatively steep gradient of about 7.5 m/km. Depth of incision into bedrock is about 20 m. This morphology suggests that the valley originated due to headward erosion of a bedrock tributary. Thickness of drift above the valley floor ranges between 80 and 100 m.

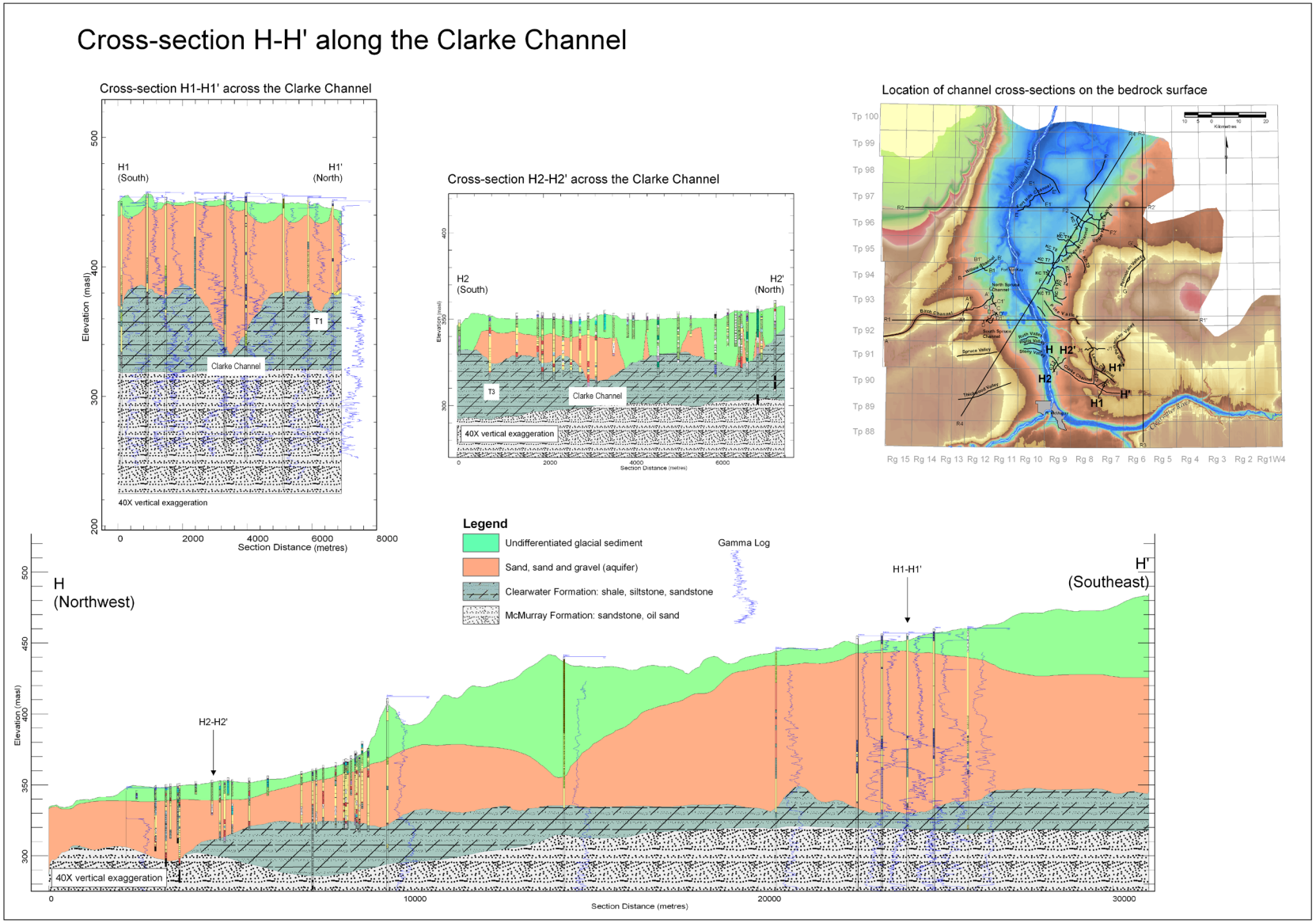


Figure 28. Geological cross-section along the Clarke Channel, Fort McMurray region.

Channel segment T2 extends 6 km north from its intersection with the Clarke Channel in Twp. 90, Rge. 8, where it forms an apparent junction with the Lewis Channel. The elevation of the channel floor ranges from about 380 m asl at its northern end to about 335 m at the south, resulting in a relatively steep gradient of 7.5 m/km (Table 1). The valley is broad (2–3 km wide) and is incised about 35–45 m into the Clearwater Formation (Figure 14). Like channel segment T1, the morphology of T2 likely originated from subaerial headward erosion of a bedrock tributary. Thickness of drift above the channel floor ranges between 65 and 110 m.

The location and geometry of channel segment T3 (Figure 8) are better defined, primarily because of a greater density of higher quality borehole data, consisting of lithologs as well as petrophysical logs. Channel segment T3 trends roughly parallel to the Athabasca River for 4 km in Twp. 91, Rge. 9, where it merges with the Clarke Channel. Detailed mapping in this area showed an apparent fluvial scour on the bedrock surface that continues north beyond the channel segment T3–Clarke Channel junction, suggesting that T3 is part of a northward-trending buried channel system that parallels the east side of the Athabasca River valley. If so, this indicates that the Clarke Channel intersected an older fluvial feature. The elevation of the floor of channel segment T3 ranges from about 325 m asl in the south to as low as 295 m in an overdeepened scour at the junction with the Clarke Channel. This yields a relatively steep gradient of about 8 m/km (Table 1). Depth of incision into the Clearwater Formation is about 6 m at the south end and about 15 m in the north (Figure 28, cross-section H2–H2'). Thickness of drift above the channel floor ranges between 25 and 50 m.

In the introduction of the discussion of buried bedrock channels (section 7.3) a statement was made that some buried glacial channels were formed subglacially, whereas others were formed in a subaerial environment. The authors believe that the Clarke Channel and its three adjoining channel segments represent subaerial channels formed prior to the last glacial event, either along the margin of a retreating glacier front, or through the reoccupation of pre-existing bedrock valleys or possibly pre-existing meltwater channels. Interpreting the Clarke Channel is challenging, not only because of the irregular geometry of the channel and its tributaries, but also due to the nature and extraordinary thickness of the channel infill. Figures 22 and 28 show that thick deposits of coarse-grained sediment, presumably sand, rest on the floors of the Clarke Channel and its tributaries, as well as on the bedrock surface flanking the channels. It is assumed that sand constitutes the majority of the infill because the moraine in the eastern part of the study area is composed of sandy diamict derived from glacially reworked glaciofluvial sand. The differentiation of sandy diamict from channel sand is nearly impossible from gamma log records alone. The level of confidence in the interpretation and correlation of the sediments within the eastern part of the Clarke Channel is therefore lower. Nevertheless, assuming that the interpretation presented in Figure 22 is correct, the thickest aquifer deposits (100 m) have been mapped where channel segments T1 and T2 join the Clarke Channel, in Twp. 90, Rge. 7 (Figure 22, Figure 28, cross-section H–H'). Mapping the aquifer in this eastern part of the Clarke Channel is further complicated by the difficulty in differentiating between coarse-grained glacial sediments and Grand Rapids Formation sandstone. The gamma logs in this area show that there is a high degree of variability in downhole lithology, ranging from uniform sand to sand containing thick beds (20 m) of fine-grained sediment. The origin of the fine sediment is unknown, although it could be slumped blocks of bedrock that failed along steep slopes (i.e., colluvium), glacially displaced bedrock or fine-grained glaciogenic sediment (diamict, clay). A further feature of note is that, in many places, the top of the aquifer lies almost at the present-day surface, mantled by only 2–3 m of fine-grained glacial sediment (Figure 28, cross-section H–H1'). This proximity to the land surface suggests that these may be younger meltwater deposits stacked on top of pre-existing fluvial sediments found at depth within the channel. If so, these younger deposits may form an extensive sheet that exceeds the lateral extent of the deeper channel deposits. This may explain, in part, the broad extent of sand, depicted in Figure 22, that links the aquifers in the Clarke and Lewis channels.

Mapping the aquifer in the western part of the Clarke Channel is facilitated by the availability of abundant borehole lithologs. These data show that the basal sediment generally consists of about 3–4 m of gravel, overlain by as much as 30–35 m of sand and silty sand, capped by about 10–15 m of glaciogenic sediment (Figure 28). The aquifer in the western part of the channel shows a more consistent lithology, lacking the beds of fine-grained material found to the east.

7.3.8 Lewis Channel

The Lewis Channel and its associated sediments were mapped from various sources of data, including outcrop observations at the junction of the North Steepbank and Steepbank rivers (field stops LA2005-01, -02 and -03; Appendix 1, Figures 39–54), a single water-well litholog located in L.S.D. 10, Sec. 26, Twp. 91, Rge. 8, and numerous gamma logs from the petroleum industry. The Lewis Channel lies directly north of the Clarke Channel, trending northwest from Twp. 90, Rge. 7, (roughly along the axis of the Steepbank River), to the southeast corner of Twp. 91, Rge. 8, where it deviates northward to the southeast corner of Twp. 92, Rge. 8 (Figure 8). The channel has been mapped for 20 km, but the subsurface extent of both the southeast and northwest ends of the channel are unknown. Both ends appear to terminate abruptly, but this likely reflects a reduction in data density. The channel can be considered as two distinct elements: a northern segment that slopes southeast to intersect the Steepbank River and a southern segment that slopes northwest to the Steepbank River. Both channel elements are very shallow. The elevation of the channel floor in the northern segment ranges from about 385 m asl at its northwest end to about 375 m at its junction with the Steepbank River, whereas the channel floor in the southern segment ranges in elevation from about 390 m asl in the east to 375 m at its intersection with the Steepbank River. This yields gradients of about 0.5 m/km (Table 1).

Unlike the other glacial channels described in this report, the lateral margins of the Lewis Channel are not well defined. In part, this may reflect the difficulty in defining the bedrock surface in this part of the study area because of the similarity in petrophysical log properties between bedrock of the Grand Rapids Formation and the overlying glacially derived sediments. This is illustrated in cross-section J–J' (Figure 29), constructed across the axis of the northern segment of the Lewis Channel. Nonetheless, the channel appears to be broad (2–3 km) and relatively shallow, incised only 15 m into bedrock. In this regard, its geometry is more characteristic of a broad bedrock valley, similar to that of the South Pemmican Valley, rather than a glacial channel. The channel has incised through the Grand Rapids Formation and, for the most part, rests on the Clearwater Formation (Figures 14 and 29).

As much as 80 m and 40 to 70 m of drift overlie the floor of the northern and southern segments of the Lewis Channel, respectively (Figures 15 and 29). Of this, buried channel sand and gravel make up half to two-thirds of the drift thickness (Figure 22). Field stops LA2005-01 to -03 (Appendix 1, Figures 39–54) are river outcrops visited for establishing drift thickness in that area, and to determine if these sites represent outcrops of a buried channel aquifer mapped previously (Andriashek, 2000). As mentioned in section 5.3.1, these outcrops establish that drift thickness exceeds 30 m in the area and that the exposed part of the stratigraphic assemblage consists of three major units: 1) glacial sand or sand diamict of varied thickness, which overlies 2) till of variable grain size, which overlies 3) an assemblage of sand and till beds of varied thickness. Bedrock was not observed in any of the three outcrops.

Most importantly, these outcrops confirm the presence of the Lewis Channel, as well as the sedimentary properties of the buried aquifer. At outcrop LA2005-01, located on the west bank of the North Steepbank River (directly north of the confluence of the Steepbank and North Steepbank rivers), the stratigraphic sequence of the upper half of the outcrop consists of sand and sandy diamict, overlain by till with a range of grain sizes, from sandy loam at the top to a silt-rich loam that becomes progressively more sand rich at depth (LA2005-01; Appendix 1, Figures 39–44). The lower half of the outcrop is dominantly sand with

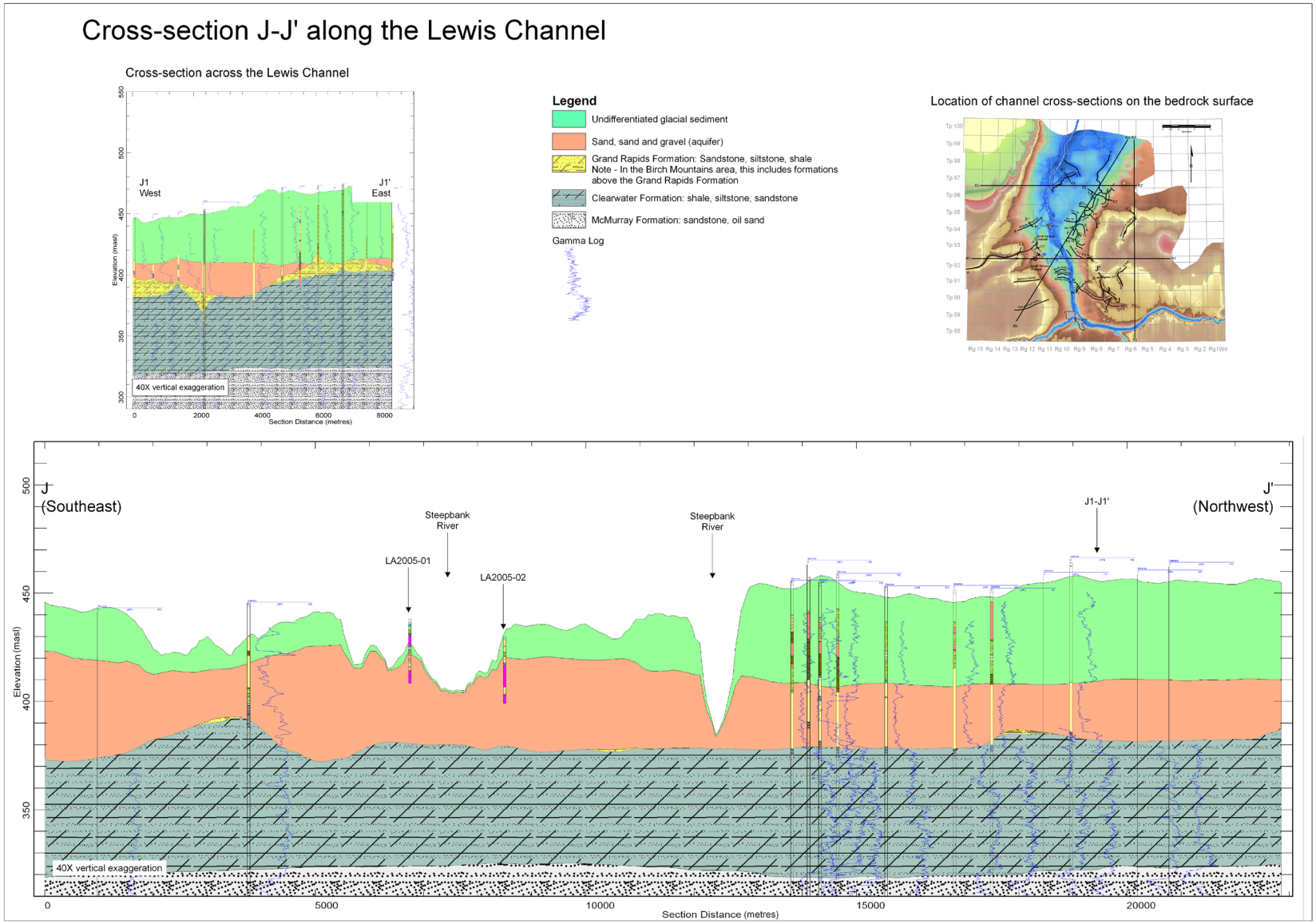


Figure 29. Geological cross-section along the Lewis Channel, Fort McMurray region.

thick (1–2 m) interbeds of till. Sedimentary structures in the sand, such as planar bedding, crossbedding and ripple beds, are interpreted to be of fluvial origin, with bedding planes dipping to the north, northeast and northwest. This indicates that flow along the Lewis Channel was generally toward the north or northwest, similar to the inferred flow direction for the surface meltwater outwash deposits shown by Bayrock (1974).

The stratigraphic sequence in outcrop LA2005-02, located on a hairpin meander on the south bank of the Steepbank River, shows a similar sedimentary sequence except that the deformed surface sand is much thicker and the underlying till is thinner. Although colluvium covers much of the outcrop, exposed sand was observed near river level. Dip directions measured in sand beds 20–25 m below the ground surface indicate flow dominantly to the north or northeast, consistent with northward flow directions measured in the lower sand of outcrop LA2005-01.

Stop LA2005-03, located about 6 km west of LA2005-01 and -02, is a 300 m long outcrop along the north bank of the Steepbank River. Four separate outcrops were described along this exposure (Appendix 1, Figures 51–54). All exhibit a similar sedimentary succession of deformed sandy till in the upper 1–4 m, overlying interbedded sand and sandy diamict for another 5–8 m. Climbing-ripple structures at a depth of about 6 m at one location indicate that flow at the time of deposition was to the west. Thick colluvium covers the lower half of the outcrop.

In summary, the sections along the Steepbank and North Steepbank rivers reveal a thick (>20 m) sequence of sand and sandy diamict buried by till, which in turn is mantled by thin surface sand and sandy diamict. The top of the lower sand and sandy diamict correlates with a lithological break in the gamma log signatures from nearby boreholes, demonstrating that the sand-till interbed sequence within the Lewis Channel extends for at least another 25 m below the base of the outcrop, for a total thickness of 40–45 m (Figure 29, cross-section J–J').

A few comments can be made regarding the great extent of buried sand and gravel that rests on the bedrock interfluves between the Clarke and Lewis channels, and the Pemmican Valley, mapped in the area defined by Twp. 89–91, Rge. 7–8 (Figure 22). Gamma logs record a sandy unit resting on Clearwater Formation shale, which stratigraphically correlates with sand and gravel within the channels. Although the genesis of this sandy material remains speculative, the authors believe it forms part of a laterally extensive fluvial sand that correlates with the buried sand and gravel above the channels. Further work, however, is required to support this interpretation.

Finally, in light of current understanding of the northwesterly drainage of Glacial Lake Agassiz along the Clearwater River valley (Smith and Fisher, 1993; Teller et al., 2005), it is intriguing to consider that the Clarke and Lewis channels may have both functioned as northwesterly drainage routes for ice-dammed meltwater prior to the last glacial advance over the area. A northwesterly flow is certainly supported by the field observations of fluvial sediments in the Lewis Channel. Future reconstruction of the glacial history of the area may need to consider incorporating the subsurface record of these buried channels.

7.4 Discussion

High-quality and closely spaced borehole information affords a unique opportunity for constructing detailed maps of the bedrock valleys and channels within the surface-mineable area in the Athabasca River lowland. What has been most surprising is the number and varied scale of buried channels, ranging in width from as narrow as 100–200 m (North and South Spruce channels) to >1.5 km (Birch Channel). To a large degree, confidence in establishing the numbers and density of channels in the study area is

determined by data availability. In the case of the North and Spruce channels, neither could have been mapped if borehole spacing had exceeded 100 m. If channels of this size are typical of the processes that acted on the bedrock landscape in the study area (or at least within the Athabasca River lowland), then it is conceivable that channels of similar scale remain to be discovered in areas of poor data control. It is interesting, therefore, to speculate that buried channels within the Athabasca River lowland owe their origin to catastrophic flow of subglacial meltwater, and that they form a swarm of features in the study area, some yet to be discovered.

8 Glaciotectonism: Implications for Hydrostratigraphic Interpretations

In the course of the subsurface interpretations, a range of information supported the conceptual view that glaciotectonism has played an important part in the glacial stratigraphic record of the study area. Although much of the conceptual model remains to be validated by observations and/or data, the authors believe there is sufficient indirect evidence to conclude that the composition and internal architecture of the drift sequence have been significantly influenced by glaciotectonic forces. If true, there may be large parts of the study area where it may be difficult to establish a meaningful understanding of the subsurface distribution and geometry of aquifers within the drift sequence.

Evidence of glaciotectonism falls into two categories: surface geomorphic expressions of glacially thrusted landforms, and subsurface information illustrating stratigraphic complexity arising from glacial thrusting. These are discussed in sections 8.1 and 8.2, respectively.

8.1 Geomorphological Evidence for Glaciotectonism

8.1.1 Fort Hills–McClelland Lake Hill-Hole Pair

The Fort Hills is one of the most prominent physiographic features in the study area, mainly because it stands above, and is surrounded by, an otherwise featureless plain (Figure 2). The Fort Hills were initially interpreted as a glaciofluvial landform deposited by meltwater flowing directly in contact with an ice margin to form a positive, constructional feature referred to as a kame moraine or end moraine (Bayrock, 1971). McPherson and Kathol (1977) referred to the Fort Hills as a ‘kame delta’, formed along an ice margin. Subsequent melting of the ice margin caused the glaciofluvial sediments to collapse to form an irregular mound. A series of kame deltas developed along an ice margin would ultimately be linked to form a kame moraine. McPherson and Kathol (1977) identified three major kame moraines in the study area: the Fort Hills (Twp. 96–97, Rge. 9 and 10), a smaller moraine directly to the west (Twp. 97, Rge. 11) and a large complex east of the Fort Hills (Twp. 97, Rge. 5–7; Figure 7, unit 5). A minor northeast to southwest ridge near Kearl Lake is also interpreted to be part of the kame-moraine or end-moraine complex.

A more recent study (Savigny and Leboe, 1998) interpreted the Fort Hills as a thrust moraine, in which the arcuate, northward-closing forms of the high-relief landforms represent imbricate glacial thrust features. The authors of this report support this interpretation and suggest that the Fort Hills and McClelland Lake form a special type of glacially thrusted landscape referred to as a ‘hill-hole pair’. A ‘hill-hole pair’ landscape is created by glacial thrusting that quarries or excavates the unfrozen substrate beneath the glacier, creating the ‘hole’. Quarrying is believed to be triggered by the build-up of subglacial pore pressure, perhaps in a zone of sporadic permafrost where pressures in the groundwater cannot be dissipated fast enough, causing the substrate to fail instead of the overlying glacial ice (Moran et al., 1980). Buried channel aquifers are considered to be areas particularly susceptible to failure because of build-up of pore-water pressure by overriding ice. The quarried substrate is then frozen to the glacier bed and the entrained material is sheared upward (creating a ‘hole’) and transported in a down-ice direction, where it accretes to form a compositional landform, the ‘hill’. McClelland Lake is therefore interpreted

to be a hole created by the thrusting, while Fort Hills is considered to be the hill where the displaced material was accreted (Figure 30). Water-filled depressions with high mounds or hills located directly down-glacier are common in the Cold Lake area in east-central Alberta, where high-resolution seismic and core-hole data show the internal structure of the hills to be glacially contorted and folded beds of displaced older strata (Andriashek and Fenton, 1989).

If the arcuate, transverse form of the Fort Hills is indicative of glaciotectonism rather than glaciofluvial deposition in an ice-contact environment, then it is conceivable that the complex of high-relief mounds or ridges that extends east and west of Fort Hills was also formed by glaciotectonism. Subsequent glacial overriding of these hills remoulded the thrusted sediment to create streamlined landforms oriented subparallel to the direction of ice flow (Moran et al., 1980). On the basis of morphology alone, the northeast-trending ridge directly north and south of Kearl Lake may represent such a streamlined thrust-moraine feature (Figure 30).

8.1.2 Muskeg Mountain Tear-Fault Scarp

Glacially induced strike-shear and brittle-tear faults in the underlying substrate, particularly bedrock, are striking features in glaciotectonic landscapes. Tear-faulted landscapes are conspicuous by the angular, rectilinear form of headwall scarps that form on the up-ice edge of the quarry site, transverse to the direction of ice flow. The rectilinear pattern might reflect incipient planes of weakness within the substrate, such as regional joint patterns in bedrock, which, in Alberta, intersect orthogonally along northwest-southeast and southwest-northeast axes. These features contrast with the surrounding landforms, which have generally been smoothed and moulded by glacial overriding. In Alberta, glacial tear-fault features were first documented in landforms of the Cold Lake area, where older pre–Late Wisconsin tills were sheared and thrust during several ice advances in the region (Andriashek and Fenton, 1989). Later studies in the St. Paul area southwest of Cold Lake documented glacially induced tear-faulting and displaced blocks of intact sandstone of the underlying Belly River Formation (Brierley et al., 1993). In that study, the geomorphic expression of tear-fault processes (fault scarps) was supported by outcrop evidence of displaced blocks of bedrock.

On the basis of similarity in form, the authors propose that the angular to rectilinear, steep southern face of Muskeg Mountain represents a glacial tear-faulted quarry zone. Figure 31 is an oblique 3-D view of the DEM of the Muskeg Mountain area, showing well-defined rectilinear geometry along the south face of the mountain. The authors suggest that the south face has been glacially quarried and the debris transported down-ice, to the south. A possible zone of failure may be the contact between sandstone of the Grand Rapids Formation and weaker shale of the Clearwater Formation. Also visible in Figure 31 is an isolated high-relief knob, which is interpreted as a remnant block of quarried material. Although an aerial survey failed to identify any evidence of glacial thrusting, if this interpretation is correct, evidence of thrusted material, including bedrock, may be found in the stratigraphic record south of Muskeg Mountain. This may include some of the clayey sediments previously described in borehole logs within the Pemmican Valley and the eastern end of Clarke Channel.

8.2 Subsurface Evidence of Glacial Thrusting

8.2.1 Fort Hills Thrust Moraine

There is geomorphological evidence of glacial thrusting, but how well does the sedimentary record support that interpretation? This section discusses the subsurface evidence for widespread glaciotectonism in the northeastern half of the study area.

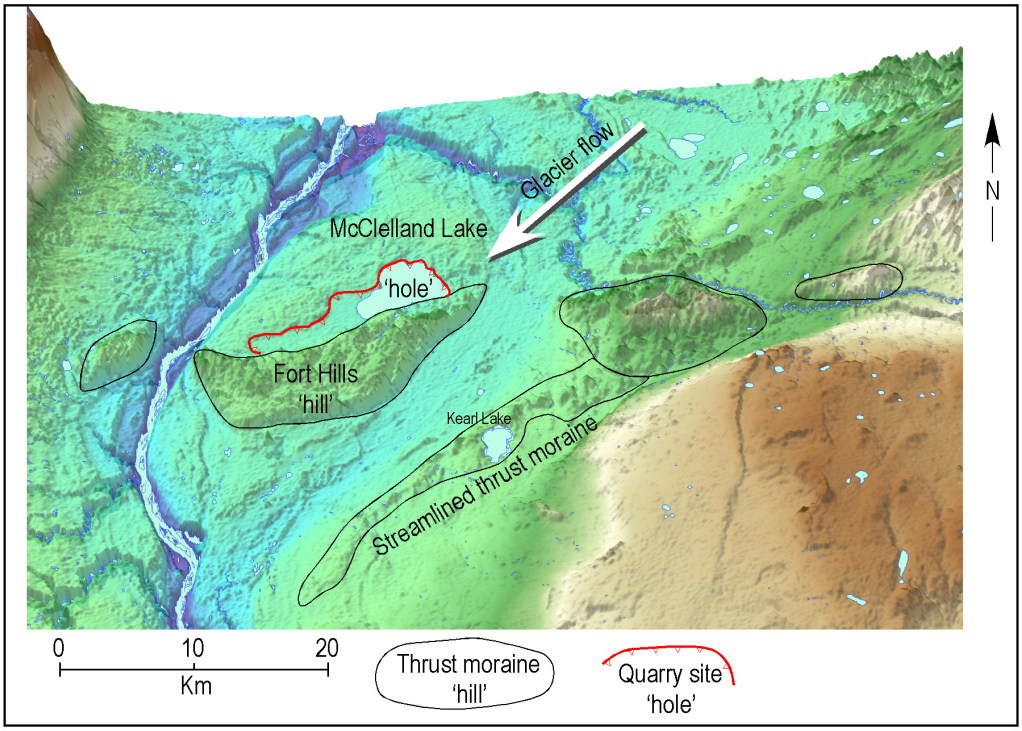


Figure 30. Three-dimensional view of the Fort Hills–McClelland Lake hill-hole thrust moraine complex, Fort McMurray region.

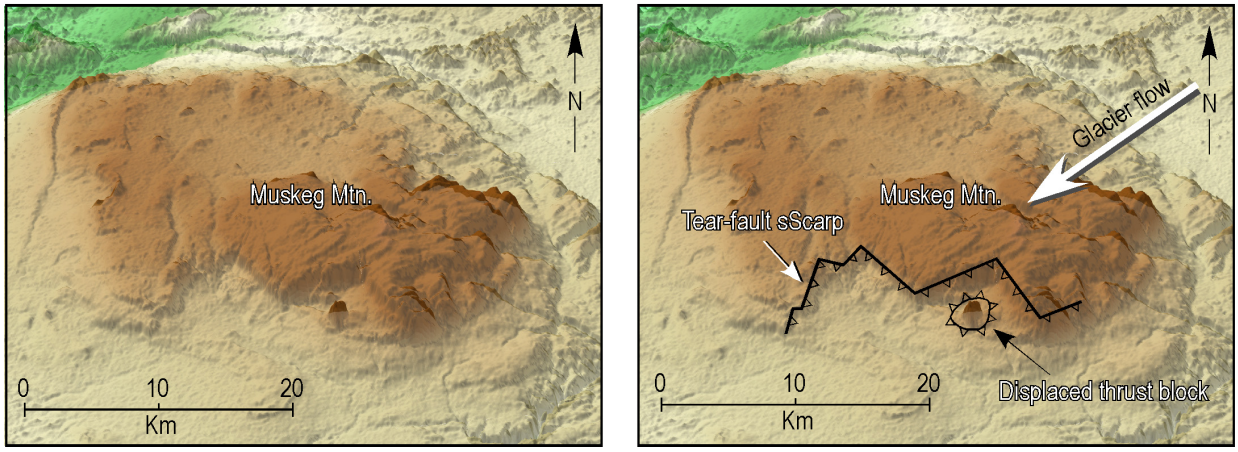


Figure 31. Glacial tear fault and quarrying on the south face of Muskeg Mountain, Fort McMurray region.

McPherson and Kathol (1977) described the material within the Fort Hills primarily as stratified silt and fine sand, which exhibited lateral and vertical compositional changes over short distances. Lenses or layers of till or clay are common, and they noted a high percentage of bitumen within the sand in the Fort Hills, which they interpreted as reworked McMurray Formation oil sand. Of special interest in the stratigraphic record is the presence of what is locally referred to as the 'pink clay', which consists of pink to dull red to grey clay of apparent glaciolacustrine origin. The pink clay is recorded at differing depths within neighbouring boreholes and, on the basis of stratigraphic position, does not appear to be correlative.

Savigny and Leboe (1998) argued for an entirely different origin of the sediments within the Fort Hills. They contended that much of the Fort Hills was glacially deformed, comprising reworked pre-existing material, including Quaternary glacial sediment as well as bedrock. They suggested that pre-existing sediments, including till and glaciolacustrine clay, were deformed or sheared by a readvance of the Late Wisconsinan glacier between 10.0 and 10.5 ka, and that the depth of shearing extended deep into shale of the Clearwater Formation, oil sands of the McMurray Formation and carbonate-rich sediments of the Methy and Waterways formations. Previously deposited glaciolacustrine 'pink clay' was reworked to produce intraclasts of angular fragments of clay embedded within glacial diamicts in the area. Presumably, these are the same pink and grey glaciolacustrine deposits encountered in the Firebag River outcrop (LA2005-08; Appendix 1, Figures 75–77) to the northeast, up-glacier of the Fort Hills. Geological cross-sections constructed by Savigny and Leboe (1998) depicted much of the sediment within the Fort Hills as McMurray Formation sandstone, which may explain the presence of oil sand in boreholes logged by McPherson and Kathol (1977). Recent borehole lithologs from the Fort Hills area, collected as part of this study, indicate that displaced bedrock is common in the lower parts of the drift sequence, supporting the interpretation of Savigny and Leboe (1998). While some of the sand within the Fort Hills may be derived from glacially quarried McMurray Formation sandstone, the authors suggest that much of the sand is derived from pre-existing outwash overlying the glaciolacustrine clay to the northeast. This clay may have been more susceptible to shearing, and it, along with the overlying sand, were transported southward and later stacked to form the Fort Hills. This might account for the varied depths of clay within boreholes in the Fort Hills.

Furthermore, recent observations of auger samples from boreholes spaced about 100 m apart along the south edge of the Fort Hills demonstrate that some boreholes contain up to 10 m of lacustrine clay, whereas clay thickness diminishes to 1 m or less in adjacent boreholes (A. Gaze, pers. comm., 2005). The significant variation in clay thickness over short distances is difficult to explain by sedimentation in a glacial lake, but is not uncommon in glacially thrust areas, where steeply tilted beds yield anomalous apparent thicknesses when drilled vertically from above.

8.2.2 Glacially Displaced Bedrock along the Athabasca River Lowland

Widespread subsurface information indicates that bedrock of the Clearwater and McMurray formations was glacially thrust and quarried up-ice of the Fort Hills. This material was transported southward along the Athabasca River lowland by an ice lobe that subsequently eroded portions of the Fort Hills thrust moraine. Figure 32 shows the locations of boreholes in the Fort Hills area in which displaced bedrock is recorded in the lithologs. A cross-section constructed along the axis of former ice flow directly south of Kearl Lake (Figure 32, cross-section A–A') reveals that displaced bedrock is found not only at the base of the till overlying the Kearl Channel aquifer, but also embedded within the underlying aquifer.

There are several ways to account for beds of bedrock within a glaciofluvial channel deposit. Horne and Seve (1991, p. 10) interpreted the displaced bedrock either as slump blocks resulting from slope failure

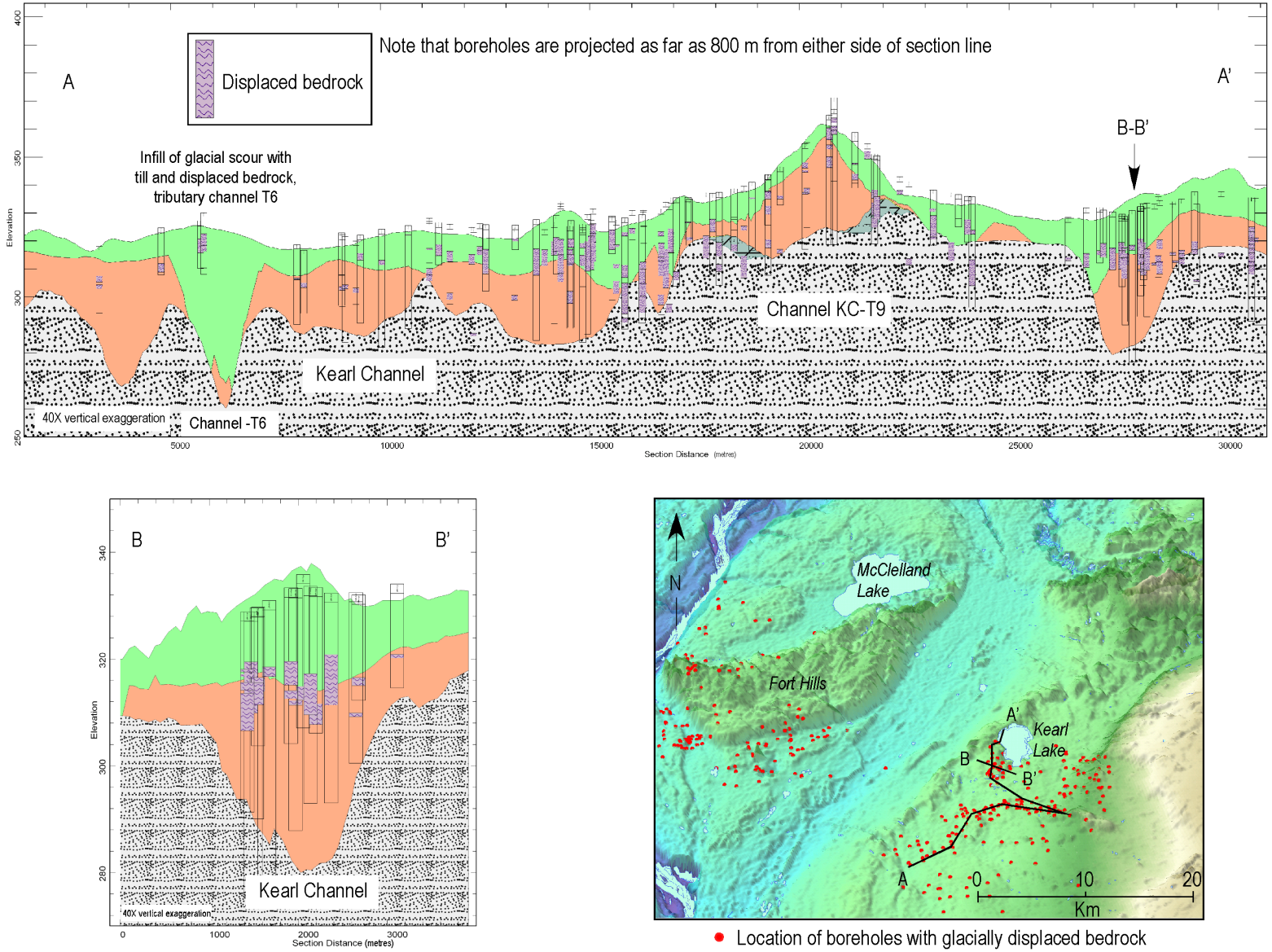


Figure 32. Glacially thrust bedrock embedded within the drift and channel aquifer above the Kearl Channel Fort McMurray region.

along steep-walled channels, or as "glacially plucked and ice-rafted material deposited within the channel during cyclical periods of advance and retreat." The authors agree with the latter interpretation and, as discussed previously, there is stratigraphic evidence to suggest that multiple ice advances affected the stratigraphy above the Kearl Channel. Due to the evidence of regional glaciotectonism, however, the occurrence of bedrock within the channel sand is thought to be the result of the erosion and subsequent emplacement of bedrock by an overriding ice lobe. Ice scour, and the subsequent infill with till and displaced bedrock, may also account for the absence of channel sand mapped at the junction of tributary channel T6 and the Kearl Channel (Figure 32, cross-section A–A'). Conceivably, the depression now filled by Kearl Lake may have been formed by glacial quarrying of the underlying bedrock, although lake bathymetry values are not available to confirm the depth and geometry of the lake floor.

Glacial thrusting and down-ice transport of displaced bedrock were not restricted to Kearl Lake. Borehole logs record deformed and displaced bedrock within the infill of the Clarke Channel, approximately 35 km south along the Athabasca River lowland. More detailed investigations in future industrial developments will likely provide evidence of widespread glacially disturbed or displaced substrate in the region.

8.2.3 Glacial Thrusting and the Genesis of Thick Drift on Muskeg Mountain

There is an abundance of gamma logs from closely spaced borehole logs that extend close to surface along the north flank of Muskeg Mountain. Nevertheless, the composition and internal structure of Muskeg Mountain are poorly understood, due to the lack of high-quality lithological information. The gamma logs record beds of thick (30–40 m) clay- and sand-rich sediment atop the Grand Rapids Formation that were initially interpreted as part of the Colorado Group (e.g., Joli Fou and Pelican formations) and later as part of the Quaternary succession.

Two geological cross-sections along the north flank of Muskeg Mountain illustrate the challenges in correlating units within the drift sequence above the bedrock surface (Figure 33). In both sections, the tops of clay-rich and sand-rich beds are marked by dark blue and orange correlation lines, respectively. The sections show two important features regarding correlation of the strata:

- The tops of the beds cannot be correlated meaningfully for more than 2–3 km, beyond which they appear to terminate or are truncated.
- The tops of correlative beds are all inclined to the north.

Recent geological interpretations, submitted as part of Environmental Impact Assessments for oil sand developments, similarly show abrupt and complex correlations of the sandy strata, which have also been interpreted as regional aquifers.

In the absence of lithological information, these inclined and truncated sediments are interpreted as glacially displaced pre-existing strata, including bedrock (possibly shale-rich beds from the Clearwater Formation and sand-rich beds from the McMurray Formation) or previously deposited glacial drift. These beds are believed to have been quarried from beneath the depressed landscape within the Firebag Plain physiographic unit (Figure 2), northeast of Muskeg Mountain, and thrust atop one another as a series of imbricate slabs along the north face of the highland (Figure 34). Abrupt truncations or overthickening of units are attributed to overturned or high-angle thrust beds, similar to those encountered in the subsurface of the drift in the Cold Lake region (Figure 35; Andriashek et al., 1999). Farther south, or down-ice, the quarried beds appear to have been reworked by glacial comminution, and the resulting units lack the sharp contrast in lithology. These southern beds are more flat lying and, although less distinct, can be correlated over larger distances.

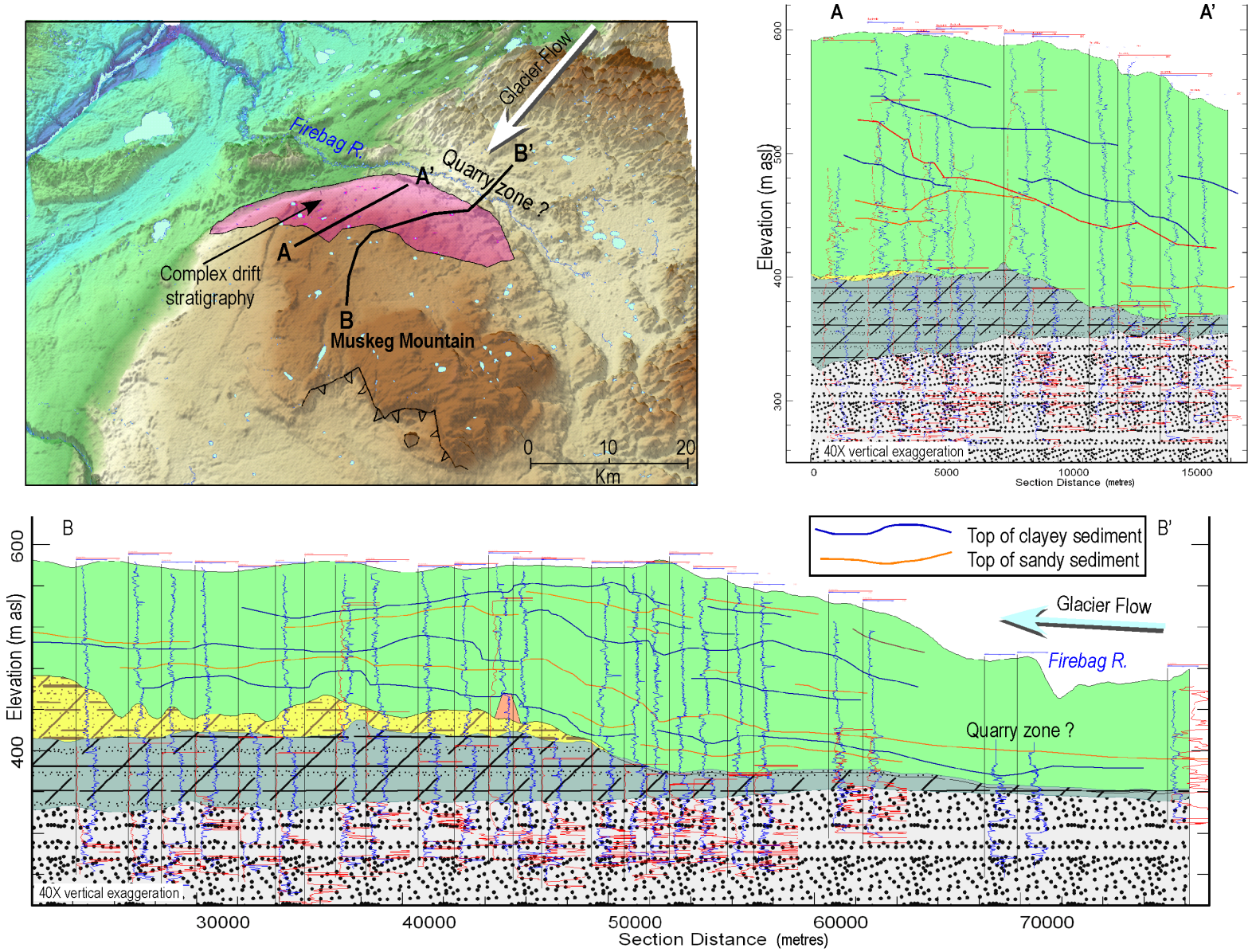
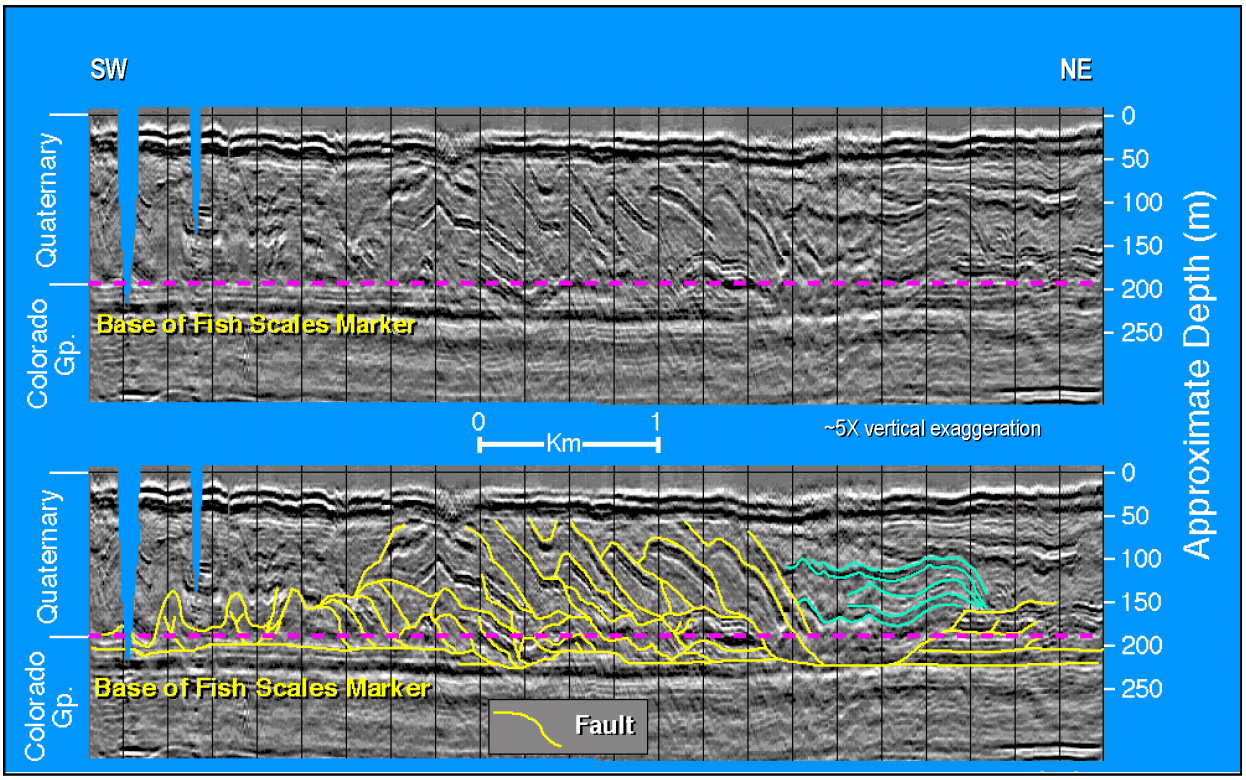


Figure 33. Complex drift stratigraphy on northern edge of Muskeg Mountain, Fort McMurray region.



(modified from Andriashek et al, 1999)

Figure 34. Glaciotectonic features of the Helina Channel, west of Marie Lake in the Cold Lake area, showing imbricate and folded beds of glacially thrusted Quaternary sediment.

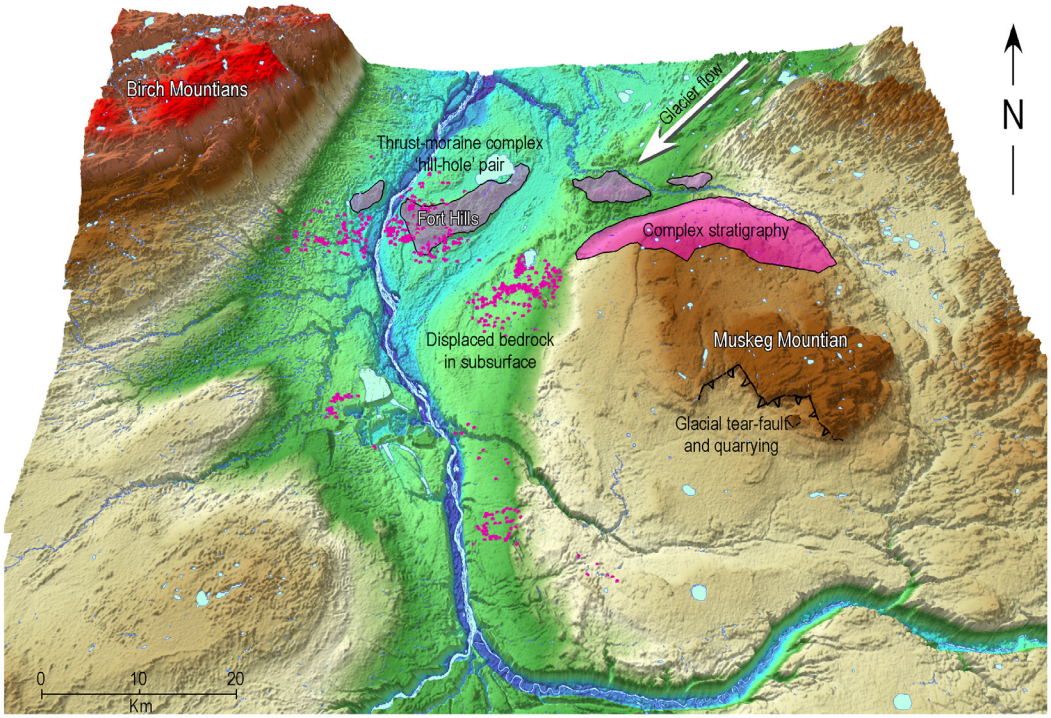


Figure 35. Regional extent of glaciotectonism in the Fort McMurray region.

To conclude, a glaciotectonic model accounts for two aspects of the geology of Muskeg Mountain: the unusually thick accumulation of drift above bedrock, and the hole-to-hole variability in drift lithology, as demonstrated by petrophysical logs. The authors infer that the regional continuity of aquifers has been severely disrupted by glacial thrusting along the northern part of Muskeg Mountain, and that the development of a hydrogeological model of the drift will be challenging.

8.3 Summary

Geomorphic and stratigraphic evidence provide strong support for regional glaciotectonism in the northern part of the study area (Figure 35). Construction of a hydrogeological model in these areas will be complicated by the internal complexity and composition of the sediments associated with glaciotectonized landscapes. More information, such as descriptions of drill cuttings or core, are required to properly characterize the sediments within the drift in Muskeg Mountain, but even then classifying the sediment may be difficult if the material consists of displaced or reworked bedrock derived from underlying in situ units. Mapping the strata in these landscapes, particularly the north face of Muskeg Mountain, may require more expensive methods, such as high-resolution seismic profiles, to acquire an accurate assessment of the geometry of the drift succession.

9 Interactions of Buried Channel Aquifers

One of the issues driving the mapping of the buried aquifers in the Ft. McMurray region is the potential for groundwater in buried channel aquifers to interact with surface water bodies or deeper bedrock aquifers, as well as the potential for buried aquifers to be affected by surface mining or SAGD recovery. It is beyond the scope of this report to provide an evaluation of industrial impacts on groundwater systems in the region, but some general statements can be made regarding the natural interactions of buried channel aquifers with other channel aquifers, with near-surface water bodies or unconfined surface aquifers, and with generic types of industrial infrastructure.

9.1 Interactions with Other Buried Channel Aquifers

The first type of aquifer interaction for consideration is the potential for interconnection of multiple drift aquifers within a single buried channel. From previous discussions, the stratigraphic record indicates that more than one aquifer may be present within at least the Clarke and Kearl channels, and the spatial extent of these multiple aquifers is likely superposed, giving the appearance of a single thick aquifer extending almost to surface. It has been shown that, in both channel systems, an upper aquifer appears to lap onto the bedrock and extend laterally for some distance. In the Clarke Channel, the aquifer may extend laterally for many kilometres from the thalweg and connect with the Lewis Channel aquifer (Figure 21). The significance of a stacked aquifer system is that, from place to place, any intervening till may behave as an aquitard separating the two aquifers. From the borehole data examined in this study, however, it seems more likely that the aquifers are not separated by a continuous aquitard, but are instead hydraulically connected.

The second interaction to be considered is the potential for an aquifer within a buried channel to connect with other buried channel aquifers. With the exception of the Clarke–Lewis aquifer complex, most of the channel aquifers reported in this study are confined to discrete channels and do extend above the channel margins and across adjacent interfluves. There does not appear to be a continuous buried aquifer system across the study area, as might be found in buried preglacial channels to the south (Andriashek, 2002). There is, however, connection between aquifers where they intersect, such as at the junctions along the Clarke and Kearl channels, as well as at the junction of the Birch Channel with the North Spruce Channel

along the east side of the MacKay River. At this location, however, the more significant interaction is between the MacKay River and the buried channel aquifers, rather than between the aquifers themselves.

9.2 Interactions of Buried Channel Aquifers with Bedrock Aquifers

Two bedrock aquifers are known to underlie the study area: the Grand Rapids Formation and the non-bitumen-saturated phase in the lower part of the McMurray Formation. There is no evidence that any of the buried channels have incised the bitumen into the water-saturated sand of the McMurray Formation. Consequently, the bitumen acts as an effective aquitard separating near-surface fresh water aquifers from saline groundwater in deeper bedrock aquifers.

Several bedrock valleys and channels, including the Pemmican, South Pemmican, Thickwood and Spruce valleys, and the Birch, Clarke and Lewis channels, are known to be either floored on, or incised through, the Grand Rapids Formation (Figure 13). With the exception of the Thickwood and Spruce valleys, where there is little information on aquifer distribution, aquifers within the other channels lie in contact with the Grand Rapids Formation and are presumed to be hydraulically connected. Information on the chemistry of the groundwater in these aquifers has not been collected to verify any interaction between channel groundwater and bedrock groundwater.

9.3 Interaction of Buried Channel Aquifers with Surface or Near-Surface Water

There are direct and indirect paths by which surface water can interact with groundwater in buried aquifers in the study area. The most direct path is by subaerial incision through the overlying drift and into the channel sediments, the locations of which are summarized in the following discussion.

Two buried channel aquifers, the Birch and North Spruce channels, are incised by the MacKay River and its tributaries. At its east end, the Birch Channel aquifer lies within a few metres of the surface and is incised by shallow streams that flow through a wetland to join with the MacKay River. Discharge is presumed to occur directly into the stream, and by evapotranspiration in the wetland. The west end of the Birch Channel lies outside the study area, but previous studies indicate that this may also be incised by the MacKay River (Andriashek, 2000) The North Spruce Channel aquifer outcrops along a meander face on the east bank of the MacKay River and is presumed to merge with the Birch Channel aquifer. Groundwater within the North Spruce aquifer likely discharges directly into the MacKay River.

The southern edge of the Willow Channel aquifer is incised by the Dover River, although the main part of the aquifer lies north of the river. There is insufficient information to comment on other stream incisions.

It is currently possible only to speculate on a possible connection between potential aquifers within the Fort Hill Channel and surface water bodies. If new information indicates the presence of a buried aquifer within the Fort Hill Channel and if bathymetric data show that McClelland Lake is sufficiently deep, then the lake may be fed by groundwater from a buried aquifer. More work is required to evaluate the existing information in this area.

The drift above the buried Kearl Channel aquifer thins to only a few metres along parts of the channel, particularly north of Kearl Lake, and it is probable that groundwater within the aquifer discharges to surface in these areas. Two possible sites of channel incision and groundwater–surface water interaction are proposed. The first site is at the intersection of the headwaters of the Muskeg River, where it crosses the buried aquifer north of Kearl Lake. The second site is beneath Kearl Lake, which may itself be the product of glacial quarrying that extended into the underlying channel aquifer. Lake bathymetry data would help assess this hypothesis.

Although there is sparse information on the Pemmican and South Pemmican valleys, thick drift above the buried aquifers in both valleys likely precludes any interaction between surface water and groundwater. Future work in the area will establish possible connections between the basal aquifer in both valleys, and potential aquifers higher up in the drift.

The aquifers in the Clarke and Lewis channels are both incised by present-day streams and rivers. The Lewis Channel aquifer is believed to be exposed along both sides of the Steepbank River, as well as at the junction of the North Steepbank and Steepbank rivers. The absence of visible groundwater discharge at the outcrops of the Lewis Channel aquifer indicates that discharge likely occurs at river level or deeper. The drift above parts of the Clarke Channel aquifer thins to <5 m, making the aquifer particularly vulnerable to incision by streams and rivers. In this regard, the Clarke aquifer complex is believed to have multiple sites of stream incision. These include 1) the aquifer within the northern arm, which links with the Lewis Channel aquifer and is incised by the Steepbank River; 2) the aquifer within the central part of the channel, which may be incised by the Clarke Creek; and 3) the aquifer at the western end of the channel, which is incised by the Athabasca River and its tributaries, such as McLean Creek and possibly Wood Creek.

Lastly, nothing is known about drift characteristics within the Inglis, Ruth and Stony valleys, which underlie an area of intense industrial development and are incised at their eastern ends by the Athabasca River. If buried aquifers are present within these valleys, it is highly likely they would discharge to the river.

In addition to direct communication of groundwater with surface water by stream incision, the authors consider the likelihood of surface water interacting with groundwater by way of porous media overlying the aquifers. Figure 36 depicts the results of a simple GIS exercise in which all surficial geological materials in Figure 7 were reclassified into one of two categories: 1) coarse-grained, sandy material (high intrinsic permeability), and 2) fine-grained, silty or clayey material, including bedrock (low intrinsic permeability). When reclassified into these categories, almost 60% of the surface material in the study area comprises coarse-grained material with a relatively high intrinsic permeability. When combined with the subsurface distribution of buried channel aquifers, Figure 36 highlights those parts of the study area that could experience enhanced surface water–groundwater interaction through porous media. In more than half of the area, there is a higher potential for enhanced aquifer recharge and, within this area, any surface disturbance, such as road construction, waste-disposal sites or locating of other types of facilities, will occur on materials that have a relatively high surface permeability.

9.4 Induced Interactions from Below

Glacial channels are known to have eroded into the oil sands in some SAGD oil-recovery areas where the drift and bedrock atop the McMurray Formation oil sands are thin. In these settings, the integrity of the protective cap rock above the SAGD steam chamber may be potentially compromised by channel incision, creating a zone through which steam and production fluid can migrate into the channel aquifers and upwards to surface (Figure 37). Not only is this a safety concern if hot steam were to erupt at surface, but the influx of production fluid can also compromise the quality of the water in the aquifer and significantly impact the effectiveness of the oil-recovery process. From an operator's point of view, the presence of a buried channel may require increased set-back distances of SAGD wellbores from channel margins, to ensure integrity of the recovery operation.

Buried aquifers most vulnerable to impact from steaming operations will be those located closest to the surface-mineable boundary, where the shale cap rock of the Clearwater Formation is thinnest and where

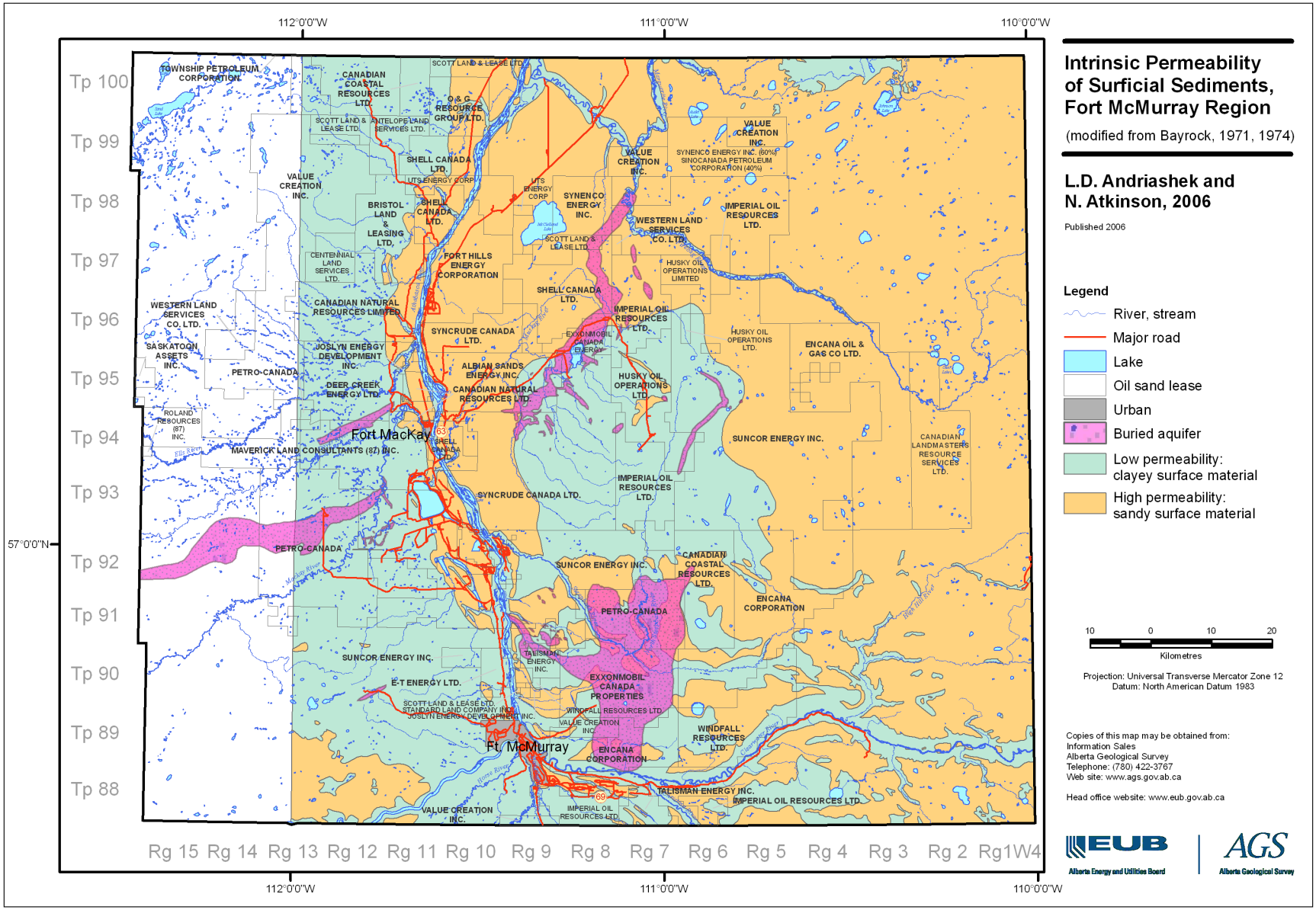


Figure 36. Intrinsic permeability of surficial sediment above buried aquifers, Fort McMurray region.

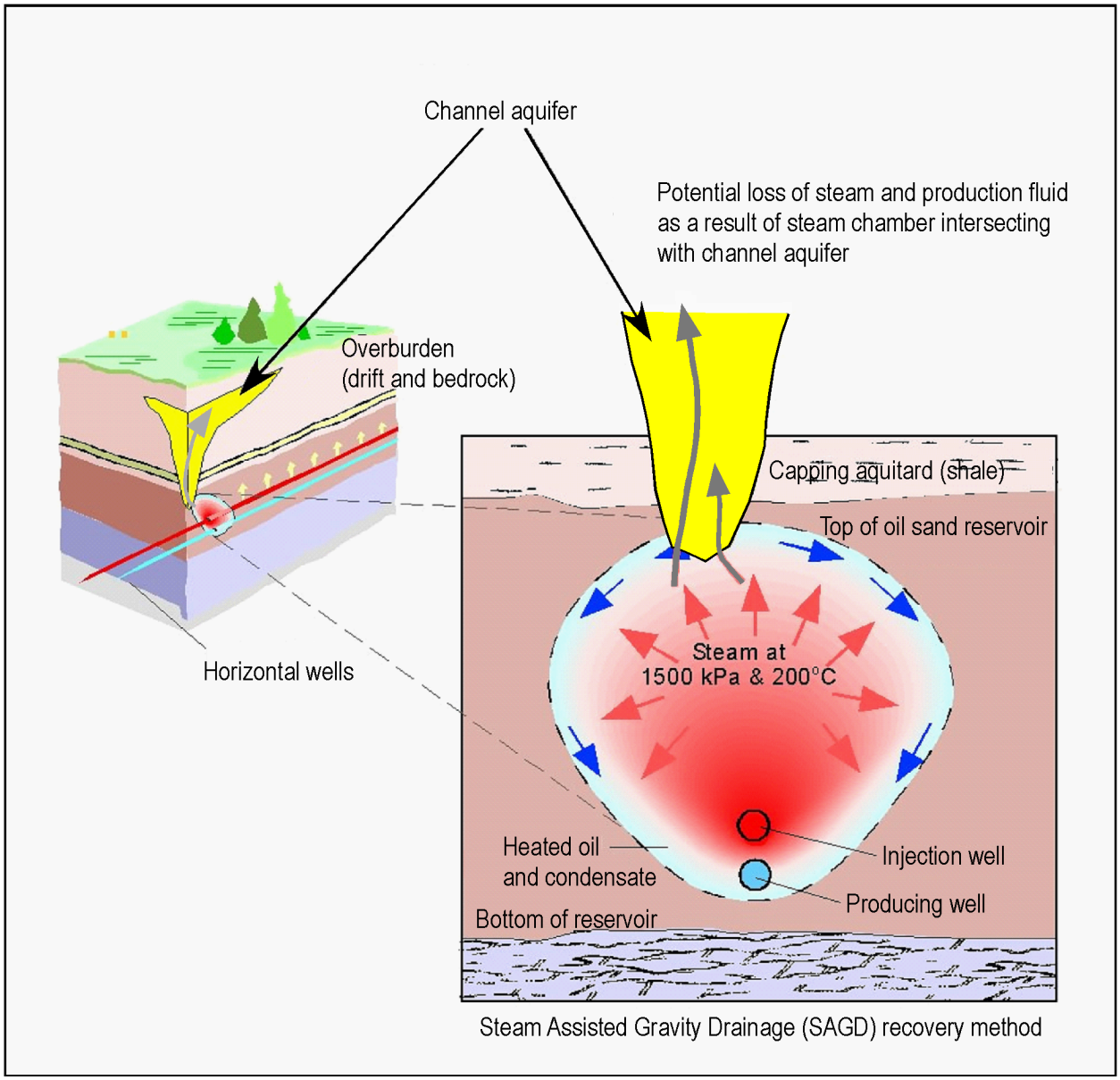


Figure 37. Buried channels and SAGD steam-chamber thief zones, Fort McMurray region.

channels may have incised into the McMurray Formation. Potentially vulnerable channels include the western segment of the Willow Channel, the western segment of the Clarke Channel, and the western segment of the Pine Valley, all of which lie within the SAGD recovery area and which are incised into, or close to, the top of the McMurray Formation.

9.5 Induced Interactions from Above

Buried channels can act as natural subsurface conduits, potentially connecting surface or near-surface groundwater with deeper or more extensive aquifers. Movement of near-surface groundwater and recharge to buried aquifers will be enhanced if the overlying surficial material is thin and highly permeable. In these settings, there is a high potential for fluids to leak from man-made structures, such as tailings ponds, and migrate rapidly offsite through the thin permeable substrate into the channel aquifer

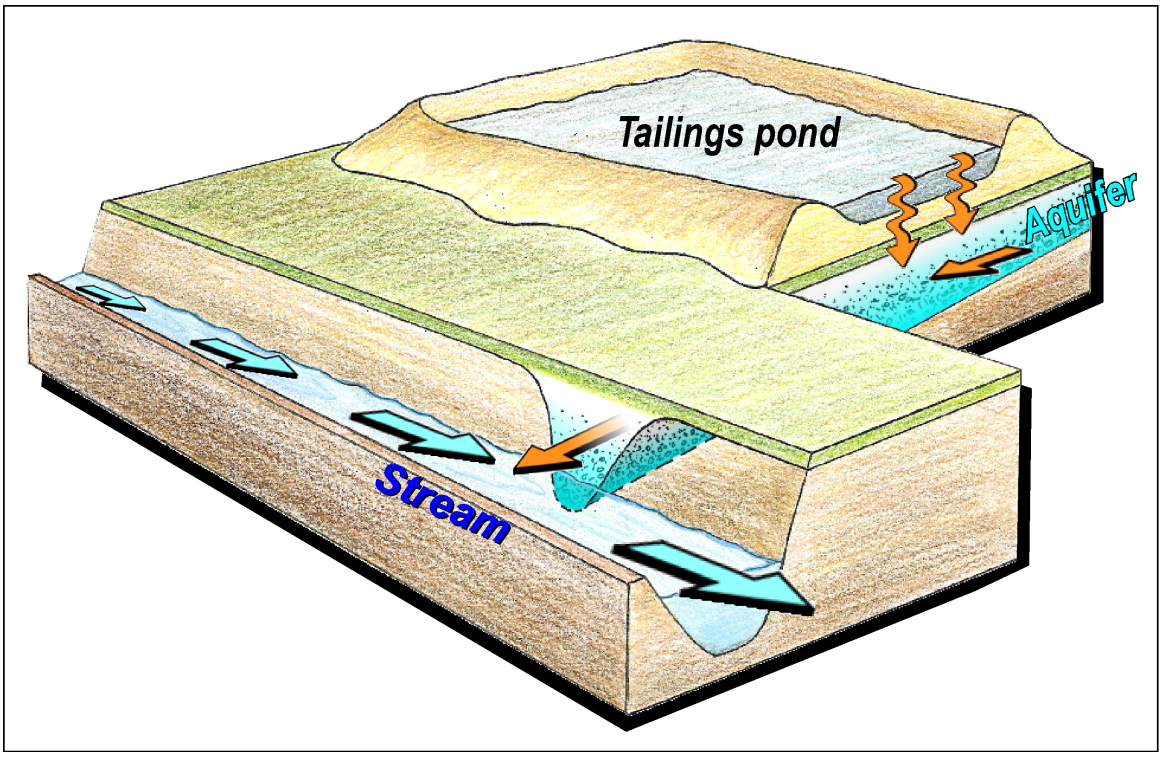


Figure 38. Conceptual flow of production fluids via buried aquifers, and potential link to surface water bodies, Fort McMurray region.

and discharge into intersecting surface water bodies, or excavations such as mines (Figure 38). These natural conditions prevail in many parts of the study area, particularly in the surface-mineable area within the Athabasca River lowland, where thin sandy drift overlies numerous buried channel and valley systems, some of which are incised by streams and rivers. Artificial barriers or liners are required to mitigate the effects of rapid seepage beneath tailings ponds.

Finally, perhaps the most dramatic impact of surface activities on buried channel aquifers is the excavation and complete removal of aquifers that overlie oil sands in the surface-mineable area. For example, most of the North and South Spruce channels were mined out shortly after AGS field visits in the summer of 2005. Even if all of the sand and gravel within a particular channel aquifer is not completely excavated, mine-scale dewatering renders the channel ineffective as an aquifer.

10 Conclusions and Recommendations

This study was designed as the first phase of an initiative to evaluate the groundwater resources in the surface-mineable and in situ–recoverable areas. The primary objective of this phase has been to update current knowledge of the subsurface distribution of buried aquifers that occupy valleys on the preglacial bedrock surface, or channels nested within the overlying glacial drift. The geological information presented in this study is intended to form the basis for a regional hydrogeological model in which the hydrology and geochemistry of groundwater within buried channel aquifers can be defined, and against which industrial activities can be evaluated. Based on the interpretation of the first-phase data, general remarks can be made regarding the current state of knowledge about the geological and hydrogeological framework of the region, and recommendations for the next phase of studies.

10.1 Current State of Geological Knowledge

A statistical plot of confidence in the geological interpretations of the drift distributed across the study area would show a bimodal distribution, with interpretations in the Athabasca River lowland having a high degree of confidence and those elsewhere a low degree of confidence. This is not surprising, since data density is not only an order of magnitude greater (and, in some cases, almost two orders greater) in the surface-mineable areas, but the information is also of a much higher quality. The disparity in data density and quality is so great that in some parts of the study area, such as in the northeast, meaningful interpretations of the geological framework could not be attempted.

The authors conclude that, with the exception of the northern fringe of the Athabasca River lowland, where data are sparse, it is unlikely that any major buried channel system remains to be discovered within the surface-mineable area. Nevertheless, small channels similar to the North and South Spruce channels may yet be discovered in the Athabasca River lowland. Furthermore, it is unlikely that the fluvial sediments associated with, and largely confined to, the bedrock channels form a regionally extensive aquifer system. Channel-to-channel hydraulic connections are therefore likely to be minor.

Current understanding of the geology outside the surface-mineable area (i.e., in situ–recoverable area), however, does not have the same degree of confidence. The following is a discussion of some issues that must be addressed before it will be possible to raise confidence in the understanding of the geological and, ultimately, hydrogeological framework in the in situ–recoverable area.

10.2 Requirements for Additional Geological Information

Although there is an abundance of boreholes in the study area, there is very little high-quality subsurface information for the upper bedrock and drift units outside the in situ–recoverable area. There is a need to calibrate geophysical logs with core from test holes drilled specifically to define the geology of the drift and uppermost bedrock strata within the in situ–recoverable area. Calibration test holes and core are required to

- define the uppermost bedrock geology and drift stratigraphy in the unmapped area north and east of Muskeg Mountain. Currently, boreholes in this area are too few and nondefinitive to permit any meaningful interpretation of the uppermost geological units. Point-specific borehole information indicates that thick sand or very sandy till overlies bedrock in this area; if mappable, this may constitute a major surficial aquifer.
- define the bedrock topography and uppermost bedrock geology units within Muskeg Mountain. The major challenge in the current interpretation of bedrock topography in Muskeg Mountain is differentiating sandy glacial sediment from Grand Rapids sandstone on geophysical logs, making the bedrock top and drift thickness difficult to establish. This differentiation becomes more critical if the Grand Rapids Formation is targeted as a supply of water for SAGD oil recovery.
- define the nature of the sediment and stratigraphy within the thick drift sequence above Muskeg Mountain, especially along the northern slopes, to validate a glaciotectonic origin for the landscape and deposits. Core samples are needed to differentiate glacially displaced sediments from in situ deposits of glacial origin, to enable meaningful hydrogeological correlations of buried aquifers. Thick sand units previously defined in other studies as regional aquifers may have limited areal extent in a glaciotectonic setting.
- define the nature of the sediments that occupy the Lewis and Clarke channels to determine their genesis and regional extent. Most of the current data regarding the geology within these channels is derived from geophysical logs recorded through casing. There is speculation regarding the presence

of glacially displaced sediment, notably bedrock, within the channel fill, and the role this sediment plays as an aquitard. Furthermore, as with Muskeg Mountain, there is a need to better define the bedrock contact in the areas adjacent to the channels where sandy glacial sediment (sandy till or glaciofluvial sand) is presumed to rest on the Grand Rapids Formation. This is particularly important for validating the interpretation in this report of a large, non channelled aquifer resting on bedrock adjacent to the channels.

- define the stratigraphy in the western segments of the Willow and Birch channels. The authors' current interpretation is based on high-quality information from a small number of boreholes located within the eastern segments of these channels. Little is known about the geology along the full extent of these channels.
- characterize the drift units within the Ruth, Inglis and Stony valleys. There is no subsurface information regarding the nature of the fill, yet these valleys lie in an area of intense industrial activity located adjacent to a major body of surface water.

10.3 Hydrogeological Information

The next phase of groundwater assessment of buried aquifers in the study area will involve the collection and interpretation of hydrogeological data. These data will provide information on the quality of groundwater within each of the aquifers, and the potential for hydraulic connection between other aquifers (drift and bedrock), as well as with surface water bodies. It is probable that data from monitoring wells in aquifers within the surface mineable area exist in private holdings, but are likely unavailable for much of the area slated for in situ development.

In addition to new coreholes to collect geological information, new groundwater-monitoring wells are required to provide information regarding water-table and hydraulic gradients within buried channels, as well as background chemistry values. Based on the geological findings in this study, groundwater information is needed to

- establish the degree of hydraulic communication between buried channel aquifers and bedrock aquifers, specifically where the underlying bedrock is Grand Rapids Formation sandstone. This potentially includes the Clarke, Lewis, Pemmican and South Pemmican aquifers in the east, and the Thickwood, Birch, and Willow aquifers in the west.
- establish the degree of hydraulic connectivity between thick sand units within the drift on Muskeg Mountain to determine regional stratigraphic correlations and aquifer continuity.
- validate with hydraulic data the stratigraphic interpretation of an extensive drift aquifer adjacent to the eastern segments of the Clarke and Lewis channel aquifers.
- establish the degree of connection between buried channel aquifers and surface water bodies, particularly where aquifers may contribute to wetlands. Potential target areas include 1) the north end of the Kearl Channel aquifer, which lies near the surface; 2) the Fort Hills Channel, which underlies wetlands adjacent to McClelland Lake; and 3) the Birch Channel, which likely discharges into wetlands west of the McKay River.
- investigate groundwater discharge into rivers, particularly from the Clarke and Lewis channels to the Steepbank and North Steepbank rivers.
- establish baseline groundwater chemistry values for all buried channel aquifers, particularly to determine background hydrocarbon values in those aquifers that are floored on McMurray Formation oil sand.

11 Summary

The acquisition of more than 35 000 new borehole logs from industry has significantly updated understanding of the bedrock topography, buried bedrock valleys and channels, drift thickness and glacial aquifers in the surface-mineable and in situ–recoverable oil sands north of Fort McMurray. Data are non uniformly distributed in the study area, ranging from highly clustered boreholes spaced as close as 75 m in the surface-mineable area to boreholes spaced 1–2 km or more in the in situ–recoverable area. The quality of the data follows a similar pattern, with the highest quality consisting of lithologs recorded in the surface-mineable area and the lowest quality consisting of petrophysical logs recorded through steel casing in the in situ–recoverable area. Interpretations of these new data enable the construction of a three-dimensional model of the bedrock topography and subcrop, as well as the major buried aquifers contained within buried valleys and channels. From this model, a series of maps and cross-sections has been generated depicting the subsurface distribution of previously known and newly discovered buried aquifers that underlie the oil sands operations in the region.

As many as 16 buried fluvial erosional features have been mapped on the bedrock surface in the study area, some with associated tributaries. These features are classified either as bedrock valleys, interpreted to have formed prior to the last glaciation, or as bedrock channels, formed by glacial meltwater. Names have been assigned to the major valleys and channels to facilitate common understanding and discussion between industry, government and research institutions. Many of the buried channels exhibit features indicative of erosion by subglacial meltwater under a significant hydraulic head. These channels, referred to as tunnel channels, are commonly narrow, deeply entrenched, discontinuous to anastomosing and unconstrained by the topography of the pre-glacial landscape. Subsequent deposition of glacial sediment has effectively masked any surface expression of the buried valleys and channels on the modern landscape. As a consequence, and given their narrow form and discontinuous nature, many channels fall between regional resource-evaluation boreholes and remain undetected following initial exploration drilling. Other methods, such as remote sensing technologies, may be required to locate and map buried channels lying beneath leases.

From the perspective of groundwater resources in the region, the most significant aspect of these valleys and channels is that most contain a thick infill of coarse fluvial sediment ranging from fine sand to metre-sized boulders. Episodic erosional and depositional events have produced a complex of stacked fluvial sequences, resulting in more than 90 m of sediment in some channels. In places, the tops of the aquifers lie within 5 m of the surface. Although hydrogeological data have not been evaluated, it is assumed that, when saturated, these channel deposits form aquifers capable of providing fresh groundwater for industrial and municipal use. Unlike continuous and extensive aquifers found in large, preglacial bedrock valleys south of the study area, buried glacial aquifers in the Fort McMurray area are confined to relatively narrow channels and valleys. In this regard, they do not form a continuous, well-connected network throughout the oil sands region. Nevertheless, buried glacial aquifers can function as natural pathways for the subsurface movement of water or other fluids at the local scale. If incised by streams and rivers, as is the case with some channels in the Athabasca River lowland, naturally occurring groundwater and other fluids can be transported along these natural buried pathways and potentially emerge and commingle with surface water bodies.

The geological interpretations presented in this study provide the basis for a hydrogeological characterization of the groundwater contained within buried glacial aquifers in the Fort McMurray region.

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Appendix 1 — Field Observations

LA 2005-01

UTM: E 495201 N6301122
Elevation from 50m SRTM grid: 436.43m
Outcrop on west side of North Steepbank River across from grassy floodplain.

Lithology intervals in metres.

From	To	Lithology	Description
0.0	0.6	Sand	Cobbly medium-grained sand, dense, wavy bed form, discontinuous over 10m horizontal distance; rounded cobbles quartzite; poorly stratified to massive
0.6	1.5	Diamict	Diamict and sand, cobble and boulder rich; contact with till below defined by boulder horizon. Looks like sandy debris flow. quartzite, quartz sandstone.
1.5	3.3	Sandy till	Till, buff coloured; forms vertical face; iron-staining along fractures and joints; columnar joint structure; massive; no reaction to 10% HCl; fissility starting to develop on outcrop face at contact; silty-sand till; sand est. > 60%, pebbles < 1%; very few in outcrop; quartzite, granite; clast-poor till; almost no coarse sand or granules – well sorted for a diamict.
3.3	4.3	Silty till	Till; silt rich; dominantly silt with minor coarse or medium sand; dense, stiff; clay content increase (clay-silt to silt loam); very few pebbles; very weak to no HCl reaction.
4.3	5.0	Silty till	Till; silt rich, very dense; blocky shard structure; becoming unoxidized, very dark grey brown to very dark grey.
5.0	6.0	Clayey silt till	Clay-silt till, very dark grey to black ; gypsum crystals along fracture surfaces.
6.0	11.0	Colluvium	Colluvium
11.0	12.5	Sandy till	Till; sandy numerous sand intrabeds (rip up? syngenetic?) horizontal to convex form at 0.5m scale. Very dark grey. Sample LA 2005-01-12m
12.5	13.5	Silty till	Silty till; very sandy, gritty; abundant iron-stained sand inclusions; deformed wavy bed to concave form, 0.5 cm to 7 cm thick sand lenses; est. >70% sand, much different than till at 6m; granite boulder.
13.5	13.8	Sand	Glacial sand
13.8	15.0	Till and sand	Till and sand; deformed sand lenses; sample of glacial sand at 14.5m LA 2005-01-14.5m. 15m grading to sand with diamict lenses, and beds; iron stained; granite pebbles; medium, soft, siderite cemented layers.
15.0	16.5	Unspecified	Not described
16.5	17.0	Sandy till	Sandy till; black, abundant gypsum crystals; numerous irregular sand inclusions; distorted wavy beds; Sample LA 2005-01-16.5m.
17.5	18.0	Sand	Sand; medium-coarse grained; glacial; black coal rich beds; strata defined by coal rich sand; appear to be steeply dipping to east. Bedding dip measured 8º S (inferred flow from north); Sample of coal rich sand at 18m LA 2005-01-18m.
19.0	20.0	Sand	Sand with diamict intrabeds 6-8 cm thick; bed dip 32-38º NNE to 12º NNW
21.0	22.0	Sand	Sand, dense, hard digging, fine-grained; numerous shiny flecks (muscovite flakes?); numerous non-calcareous, iron-oxide cemented beds; Sample LA-2001-22m; microfaulting on outcrops face makes it difficult to measure sedimentary structures; offset beds of iron-oxide rich sand; normal faulting.
22.0	24.0	Colluvium	Colluvium covered slope; at 24m dug through colluvium into black silty-sand till;

From	To	Lithology	Description
24.0	24.3	Silty till	Silty-sand till; black; 1-2% pebbles, few granules; massive to blocky; spalls off in shards with shovel; no HCl reaction; sample LA 2005-01-24m; breaks up easily when crushed by hand; numerous granite cobbles in exposed outcrop – more stony than till at 6m
24.3	28.0	Colluvium	Colluvium; tried to dig through colluvium but too thick; clayey-silt material at 24.3m; sticky; very moist; not sure what the genesis is but suspect colluvium; gneiss;

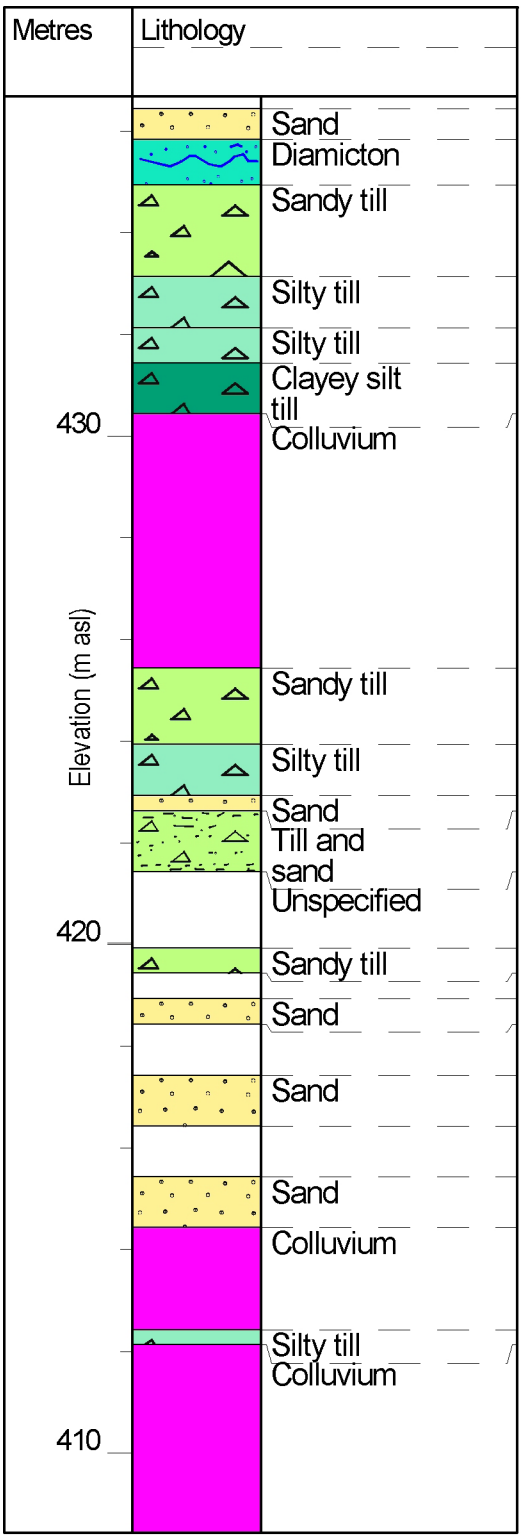


Figure 39. Schematic section of outcrop lithology at stop LA2005-01, near junction of North Steepbank and Steepbank rivers, south-central part of Fort McMurray region. See Figure 7 for location.

Figure 40. Site LA2005-1: diamict and sand, 1.5 m from surface. See Figure 7 for location.

Figure 41. Site LA2005-1: clayey silt till, 4.5 m from surface. See Figure 7 for location.

Figure 42. Site LA2005-1: till and sand, 14.5 m from surface. See Figure 7 for location.

Figure 43. Site LA2005-1: sand, coal-rich layers, 18 m from surface. See Figure 7 for location.

Figure 44. Site LA2005-1: micro-faults in sand, 22 m from surface. See Figure 7 for location.

LA 2005-02

UTM: E 493712 N 6300266
Elevation from 50m SRTM grid: 428.27 m
Outcrop on South bank of Steepbank River at Junction with N. Steepbank;
Hair-pin meander.

Lithology intervals in metres.

From	To	Lithology	Description
0.0	1.0	Sand	Dense massive fine sand with poorly developed, deformed to contorted beds; some high angle beds. 0.75m thick discontinuous cover of matrix supported boulder-cobble bed, sand matrix; dense, massive; 4m wide on section
1.0	2.0	Medium sand	Grades to medium grained sand; numerous black carbonaceous (coal?) blebs; iron stained, faulted beds; glacial provenance; Sample LA 2005-02-2m. Boulder lag at surface, discontinuous wavy black carbonaceous sand.
2.0	2.8	Medium sand	Medium sand black coal blebs along bedding planes;
2.8	3.5	Fine sand	Fine sand to silt, brown (silt ≈ .25m); fine sand from 3-3.15m; some apparent high angle beds; 3.15-3.4m Silt grading to fine sand at base; deformed bedding; wavy high angle.
3.5	4.5	Silt and fine sand	Silt and fine sand; mottled; oxidized and unoxidized rusty brown to grey; high angle deformed beds; mostly massive to contorted bedding
4.5	5.3	Medium sand	Medium sand; poor to moderate bedding; highly deformed beds in places; sub-horizontal bedding; Sample LA 2005-02-5m.
5.3	7.3	Till	Till, dense, stiff, blocky, spalls in shards when dug; si-sand loam; black unoxidized Fe staining along joint/fracture planes; very weak HCl reaction; limestone cobble, granite, carbonate pebble; gritty 2-3% pebbles; Sample LA 2005-02-5.5m; clay content increasing towards base of unit; sandy clay loam; platey-fissile structure near outcrop face;
7.3	7.8	Fine sand	Fine Sand, poorly bedded, wavy ripple beds; some sand rip-ups; wavy convoluted, minor cross-beds; medium sand shows bedding convoluted to slightly normal faulted minor coal blebs; contact with till highly deformed.
7.8	8.8	Fine sand	Sand, fine to medium; silty from 7.8-8.3; well sorted medium sand to 8.8m;
8.8	10.0	Medium sand	Sand; medium grained with 20 cm thick silty sand beds.
10.0	10.5	Sandy till	Till; Sample LA 2005-02-10.5m; sand till (>75% sand-some silt) a few very fine sand partings; very dark grey to black; fissile, friable, crushes in hand; cobbles, stones; 2%; granite; no HCl reaction; Athabasca Sandstone; rounded quartzite, high sand content and sand partings suggest water-laid diamict.
10.5	11.0	Diamicton	Diamict grades to silty fine sand, brown; bedding planes visible; discontinuous sub-horizontal;
11.0	11.3	Sand	White quartz rich sand; Sample LA 2005-02-11m
11.3	11.5	Silty fine sand	Massive silty fine sand; dense, visible, one or two granule/pebbles; sandy diamict (water-laid sediment? – almost till like).
11.5	21.5	Colluvium	Colluvium
21.5	23.0	Medium sand	Sand well sorted medium grained; well stratified, cross-bedded; abundant coal clasts along bedding; a few pebbles; Bed Dip 18º ENE.

From	To	Lithology	Description
23.0	24.0	Medium sand	Sand medium with granule rich layers; some coal rich beds; well bedded, soft; Bed Dip 13º West; Sample LA 2005-02-23.
24.0	24.4	Medium sand	Same medium sand, well sorted, cross-bedded; some pebble layers; Bed Dip 23º NNE, glacial clast composition.
24.4	25.0	Medium sand	Coarse pebbly glacial sand;
25.0	25.1	Medium sand	Same as above; medium sand with coal rich bedding planes; pebbly; Bed Dip 28º NE; Sample LA 2005-02-25m.
25.1	29.0	Colluvium	Colluvium to river edge.

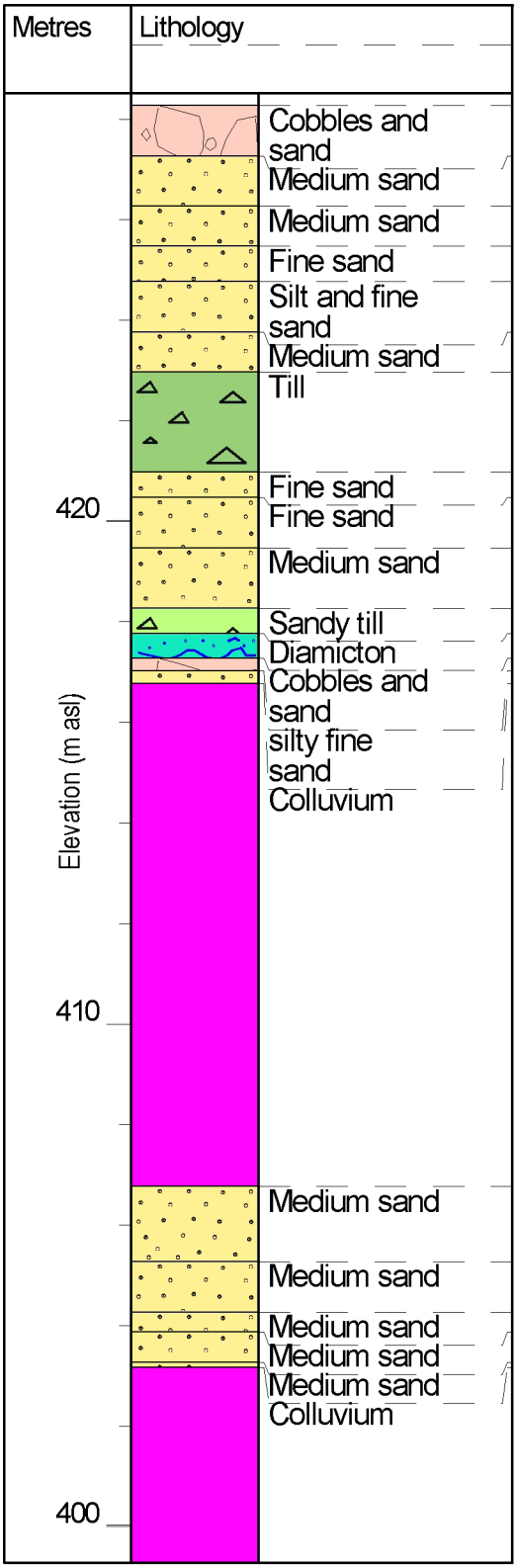


Figure 45. Schematic section of outcrop lithology at stop LA2005-02, near junction of North Steepbank and Steepbank rivers, south-central part of Fort McMurray region. See Figure 7 for location.

Figure 46. Site LA2005-02: deformed sand on sand, 2 m from surface. See Figure 7 for location.

Figure 47. Site LA2005-02: deformed and horizontal sand, 5 m from surface. See Figure 7 for location.

Figure 48. Site LA2005-02: till-sand contact, 7.3 m from surface. See Figure 7 for location.

Figure 49. Site LA2005-02: crossbedded coal-enriched sand, 21.5 m from surface. See Figure 7 for location.

Figure 50. Site LA2005-02: well-bedded coal-enriched sand, 23 m from surface. See Figure 7 for location.

LA 2005-03

UTM: E 491548 N 6302912
Elevation from 50m SRTM grid: 431.8 m
South facing slope on north bank of Steepbank River

Lithology intervals in metres.

From	To	Lithology	Description
0.0	0.8	Colluvium	Colluvium with stones and boulders at base of unit.
0.8	3.0	Sandy till	Till; Sample LA 2005-03-3m; dry hard, appears very sandy; gravel/coarse sand channel fill cut into till surface at section description, appears to be in place but could be rafted block in till.
3.0	4.5	Sandy diamict	Sandy diamict- massive pebbly to cobbly; dense; looks like glacially reworked sand; numerous boulders embedded in massive sand.
4.5	5.5	Medium sand	Sand, medium grained, well sorted, quartz rich.
5.5	7.5	Sandy diamict	Sand and diamict (“till”) Silty sand to medium sand; pebbles, cobbles; interbedded with sandy diamict with 3-5% granules, some cobbles; ice proximal depositional setting;
7.5	8.2	Fine sand	Fine sand; bedded, finely bedded (1mm beds); silty lacustrine appearance
8.2	9.0	Sandy diamict	Sandy diamict – till like; Sample LA 2005-03-8.5m
9.0	9.3	Sand	Sand
9.3	10.0	Sandy diamict	Diamict-stony, sandy; pebbles concentrated at upper contact between diamict and sand diamict; pebbles, cobbles, sand;
10.0	20.0	Colluvium	Colluvium

LA 2005-03a

UTM: E 491398 N 6302912
Elevation from 50m SRTM grid: 431.8 m
150 m west along section; interpreted to be subglacially deformed sediments and syngenetic gravel/sand discontinuously deposited on lodgment till.

Lithology intervals in metres.

From	To	Lithology	Description
0.0	2.0	Sandy diamict	Sandy diamict with boulders. 2-3m sized channel scour and gravel infill in middle of upper till unit. subglacial channelization?
2.0	2.6	Sandy till	Diamict-sandy till
2.6	3.0	Sand	Well bedded sand sub horizontal, wavy
3.0	3.5	Sandy till	Diamict-till
3.5	3.8	Sandy diamict	Deformed sandy diamict gravelly; massive to poorly bedded
3.8	4.1	Diamict	Diamict-till
4.1	4.5	Sand	Deformed sand grades to gravelly sand
4.5	6.5	Sandy diamict	Sandy diamict (till) with sandy lenses

From	To	Lithology	Description
6.5	7.0	Medium Sand	Medium sand; climbing ripples flow to west (280º).
7.0	7.7	Sandy diamict	Sandy diamict –pebbles
7.7	7.8	Sand	Sand
7.8	8.0	Diamict	Diamict

LA 2005-03b

UTM: E 491348 N 6302912
Elevation from 50m SRTM grid: 431.8 m
200 m west along section

Lithology intervals in metres.

From	To	Lithology	Description
0.0	2.0	Diamict	Massive diamict (till?) - weak stratification.
2.0	2.2	Sand	Sand

LA 2005-03c

UTM: E 491298 N 6302912
Elevation from 50m SRTM grid: 431.8 m
250 m west along section

Lithology intervals in metres.

From	To	Lithology	Description
0.0	4.0	Sandy diamict	Diamict and sand horizontally layer to bedded
4.0	4.5	Sandy clay till	Dense sandy-clay loam till, very dark grey; much more clay in matrix compared to diamict in east part of section; Sample LA 2005-3b-4.5m; No HCl reaction 2-3% pebbles.
4.5	5.5	Sand	Dirty sand

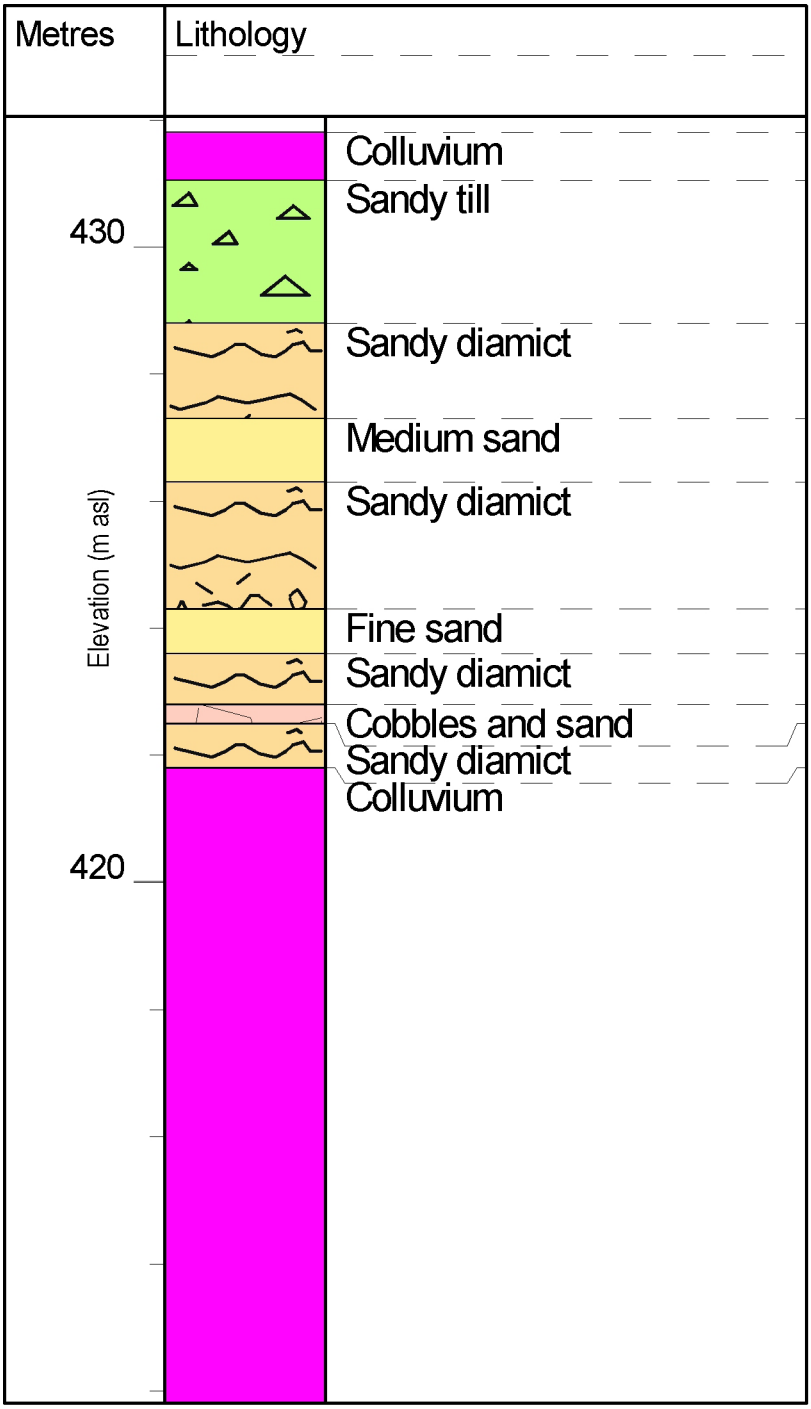


Figure 51. Schematic section of outcrop lithology at stop LA2005-03, near junction of North Steepbank and Steepbank rivers, south-central part of Fort McMurray region. See Figure 7 for location.

Figure 52. Site LA2005-03: till overlying sand, 2 m from surface. See Figure 7 for location.

Figure 53. Site LA2005-03: sandy diamict–reworked sand, 3–4.5 m from surface. See Figure 7 for location.

Figure 54. Site LA2005-03: climbing ripples, 7.6 m from surface. See Figure 7 for location.

LA 2005-04

UTM: E 454232 N 6328610
Elevation from 50m SRTM grid: 308.84
North Spruce Channel Outcrop

Lithology intervals in metres.

From	To	Lithology	Description
0.0	0.5	Colluvium	Colluvium
0.5	1.5	Lacustrine Diamict	Diamict; with 10 cm thick pink layers containing stones
1.5	4.0	Till	Till; gradational to poorly defined contact with diamict above; carbonates, Qtz sandstones; a few shield clasts; poorly defined layering (dark grey & brown) in till;
4.0	7.0	Sandstone	Sandstone with 50cm sized concretions (Clearwater?) olive grey, soft, easy to dig on outcrop; Photos of sandstone/till contact, could be Wabiskaw Formation. Boulder bed resting on sandstone about 50m west of site.

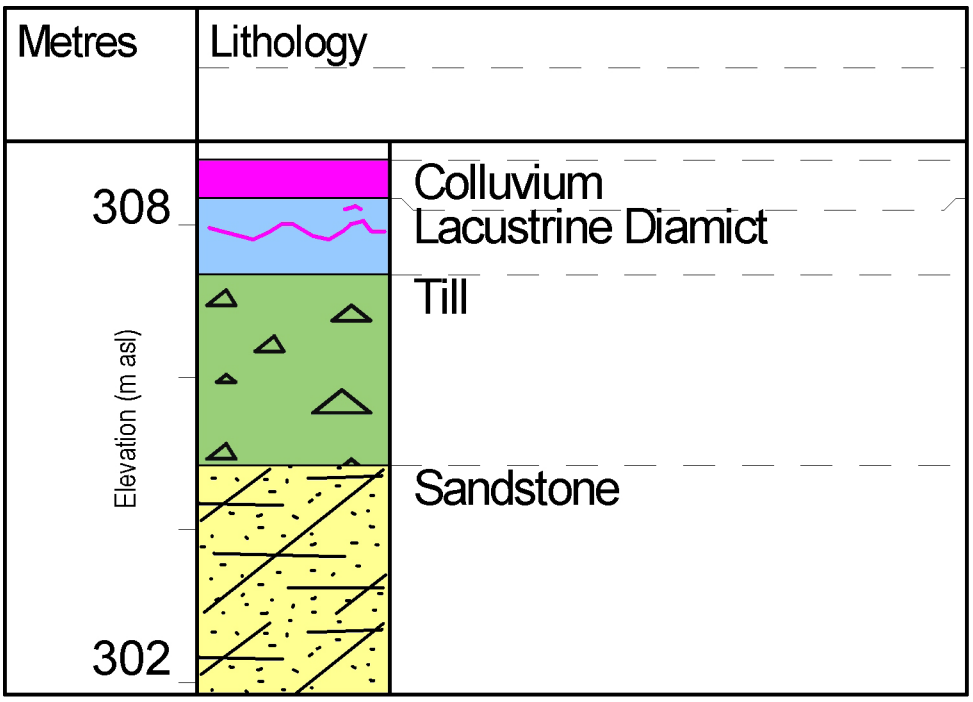


Figure 55. Schematic section of outcrop lithology at stop LA2005-04, McKay River, central part of Fort McMurray region. See Figure 7 for location.

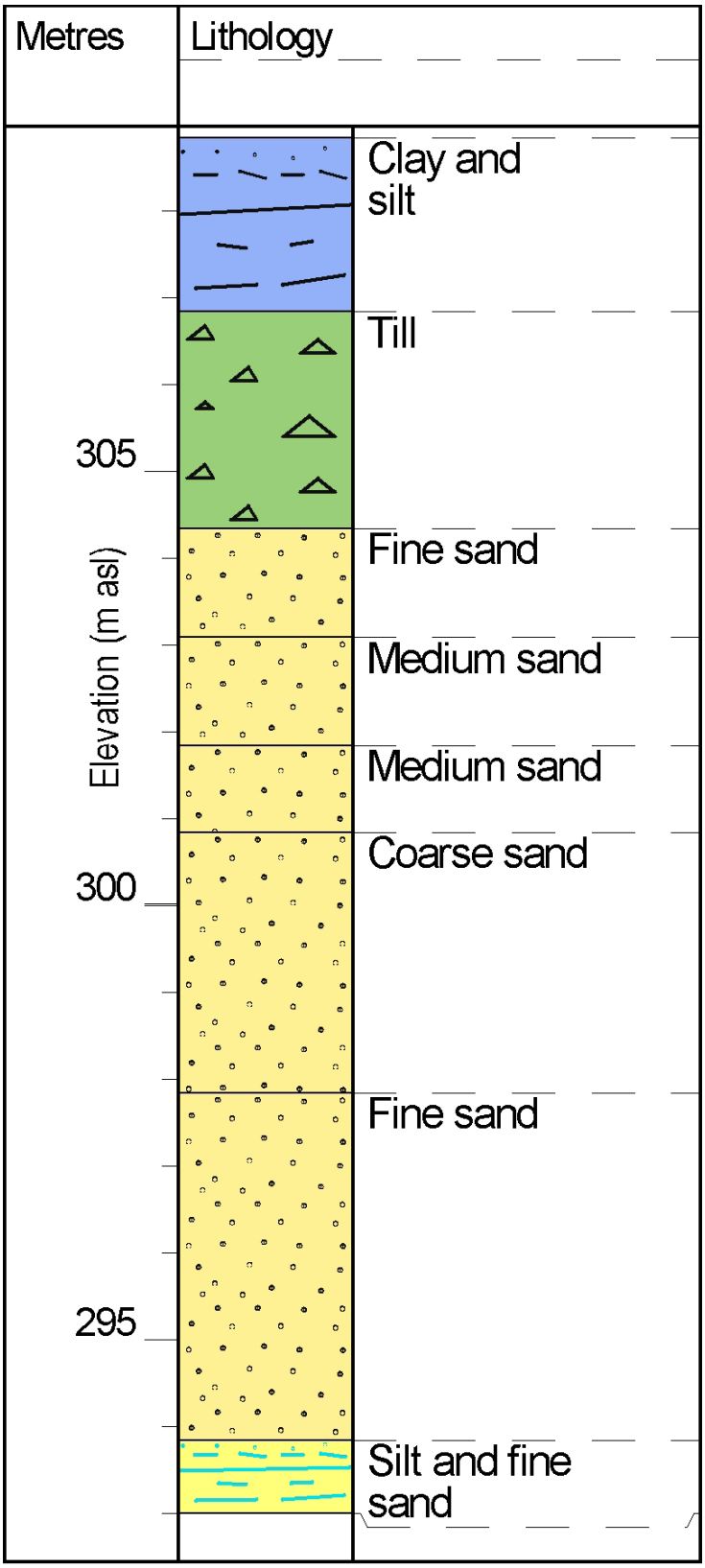


Figure 56. Schematic section of outcrop lithology at site LA2005-04a, McKay River, central part of Fort McMurray region. See Figure 7 for location.

Figure 57. Site LA2005-04a: outcrop of confluence between Birch and North Spruce channels, central part of Fort McMurray region. See Figure 7 for location.

Figure 58. Site LA2005-04: contact between pink lacustrine clay and till. See Figure 7 for location.

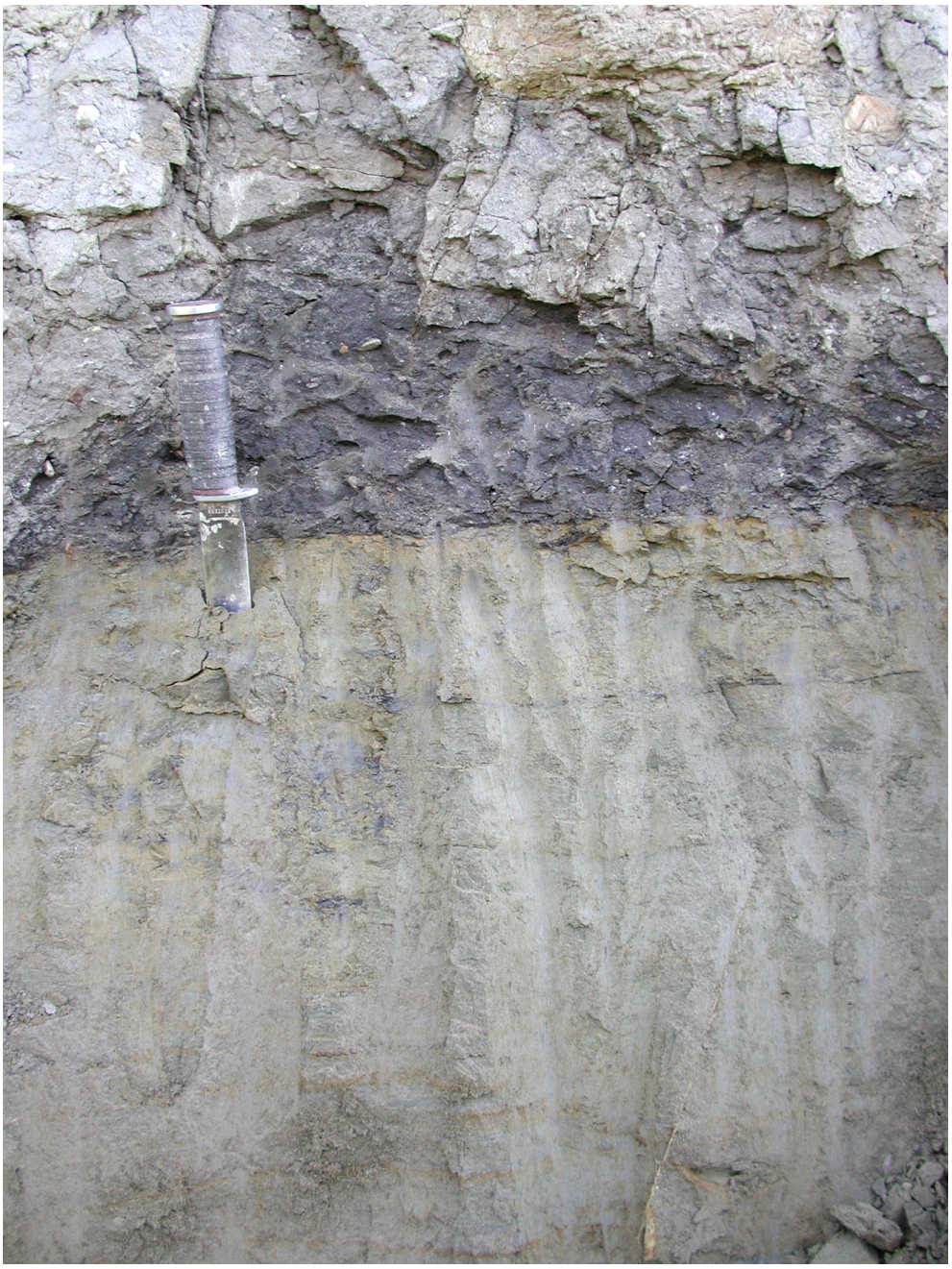


Figure 59. Site LA2005-04: till-sandstone contact, 4 m from surface. See Figure 7 for location.

Figure 60. Site LA2005-04: boulder bed in channel sediments. See Figure 7 for location.

Figure 61. Site LA2005-04: boulder bed in channel sediments. See Figure 7 for location.

Figure 62. Site LA2005-04a: silty sand, 5.5 m from surface. See Figure 7 for location.

LA 2005-04a

UTM: E 454232 N 6328610
Elevation from 50m SRTM grid: 308.84
North Spruce Channel Outcrop; 150m West along section, measuring flow directions in sand

Lithology intervals in metres.

From	To	Lithology	Description
0.0	2.0	Clay and silt	Glaciolacustrine clayey-silt, pink
2.0	4.5	Till	Till
4.5	5.8	Fine sand	Fine silty sand with 2cm thick black clay beds; finely laminated; Bed Dip 10° West; photo of finely bedded silty sand. At 5.5m Climbing ripple bedded sand, Bed Dip 30° SW.
5.8	7.0	Medium sand	Medium to coarse sand, finely laminated
7.0	8.0	Medium sand	Bed dip 20° SW
8.0	11.0	Coarse sand	Coarse sand - Channel crosscut bedding, well bedded. Bed dip 20° West.
11.0	15.0	Fine sand	Interbedded fine and med-coarse sand, 8cm thick med sand bed. Bed dip 20° SW
15.0	15.5	Sand and silt	Interbedded medium and fine san - silt with clayey silt beds. Bed dip 6° NW.

LA 2005-05

UTM: E 450329 N 6337824
Elevation from 50m SRTM grid: 301.14 m
Willow Channel Outcrop

Lithology intervals in metres.

From	To	Lithology	Description
0.0	3.0	Clay and silt	Clay and silt, pink; irregular wavy contact
3.0	6.0	Till	Till; Columnar joint face.
6.0	11.5	Sand	Sand, at 6.5m bed dip 25° WNW, at 7.5m medium to well sorted sand, some carbonaceous partings, bed dip 22° WNW; at 9m med sand, bed dip 15° NW; at 11m, silty, med grain sand with dark carbonaceous streaks, bed dip 25° WNW.
11.5	13.8	Gravel and boulders	Boulders and gravel
13.8	16.0	Fine sand	Fine sand; ripple beds; at 16m bed dip 22°-29° SW; climbing ripples; two photos plus two photos of river valley. Rippling sequence of fine sand and medium sand over 5-8m depth scale; 20cm thick med sand; 30-40cm fine sand, bed dip 30° WNW.
16.0	17.5	Medium sand	Medium sand, rippled; climbing ripples
17.5	18.0	Sand	Medium coarse sand

From	To	Lithology	Description
18.0	18.6	Medium sand	Medium sand, inclined beds; Flow measurements at 18.6m: bed dip 12°W, medium sand, well sorted; bedded; 18.0m: Bed Dip 10°NW, coarse sand with dark brown beds (carbonaceous?);
18.6	19.4	Medium sand	Medium sand; rusty brown; cross-bedded
19.4	19.7	Silt	Silt; well bedded; deformed wavy beds
19.7	20.5	Sand	Deformed grey sand; medium grained with 8 cm thick fine sand to silt layers; deformed, rusty sand bed dip 22°-29° WSW.
21.5	22.0	Medium sand	Sand; medium grained; high angle beds suggest slump movement
22.0	22.3	Ironstone	Ironstone concretion layer; discontinuous boulder lag on top of ironstone concretion layer.
22.3	28.0	Shale	Black shale - Colluvium covered shale

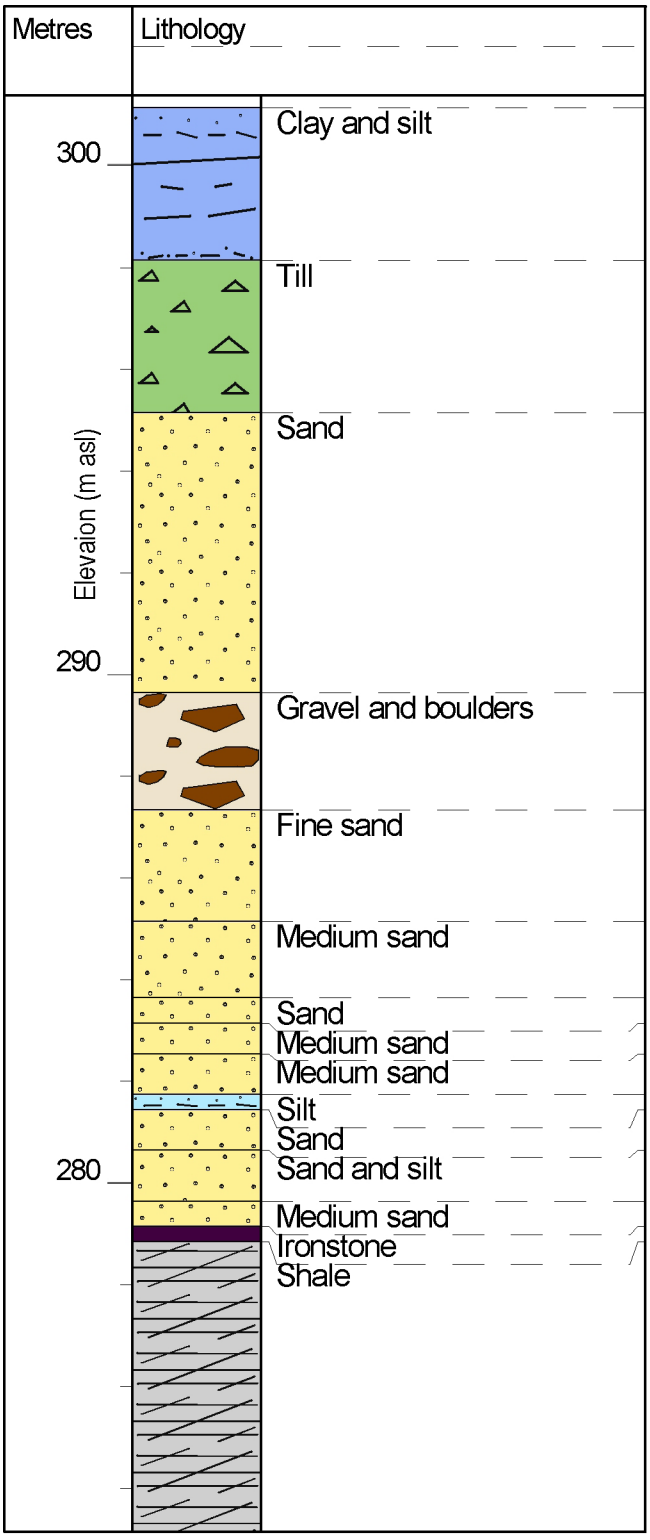


Figure 63. Schematic section of Willow Channel outcrop lithology at stop LA2005-05, Dover River, northwest part of Fort McMurray region. See Figure 7 for location.

Figure 64. Site LA2005-05: view of Dover River valley from site LA2005-05. See Figure 7 for location.

Figure 65. Site LA2005-05: Willow Channel outcrop. See Figure 7 for location.

Figure 66. Site LA2005-05: boulder bed, 11.5–13.8 m from surface. See Figure 7 for location.

Figure 67. Site LA2005-05: trough crossbeds, 18 m from surface. See Figure 7 for location.

LA 2005-06

UTM: E 493438 N 6349627
Elevation from 50m SRTM grid: 399.14 m
Twin Bridges Gravel Pit on Suncor Firebag road

Lithology intervals in metres.

From	To	Lithology	Description
0.0	22.84	Sand and gravel	Channel crossbedding at surface with deformed chevron fold, bed Dip 12° NE. 100m west along section, deformed wavy bedded poorly sorted silty sand with boulders; has diamict to till like appearance, very dark grey, but numerous 4-8cm thick sorted sand beds; abundant microfolds in sand laminae overlain by 10m of channel cross bedded sand and gravel. At 20m depth from surface; fresh exposure of gravel beds showing highly deformed, folded gravel beds. Interpreted as ice-floored channel collapse features or possibly deformation by loading of ice advance on top of gravels. Deformation appears to originate in the more finer-grained sediment; darker grey. 300m west along section glacially deformed and thrust dark brown sand; 20m east of thrust shear beds shows vertical beds of sand with pod of glacial diamict till deformed and folded. Outcrop provides evidence for glacially overridden and deformed outwash with injection/deposition of thin sandy diamict. About 3m of large boulders (.5 to .8m) at base of pit in some places. Comments: The gravel deposit appears to have been over-ridden by glacial ice from an easterly direction. Bottom 8m doesn't appear to be deformed, upper 12m highly deformed.
22.84	24.84	Silty till	Till massive, stiff, sandy silt, black bitumen odour; abundant coarse sand, pebbles 2%; angular clasts; granite; no HCL reaction; limestone clasts, quartzite; shiny black chert. Sample LA 2005-06-23m.

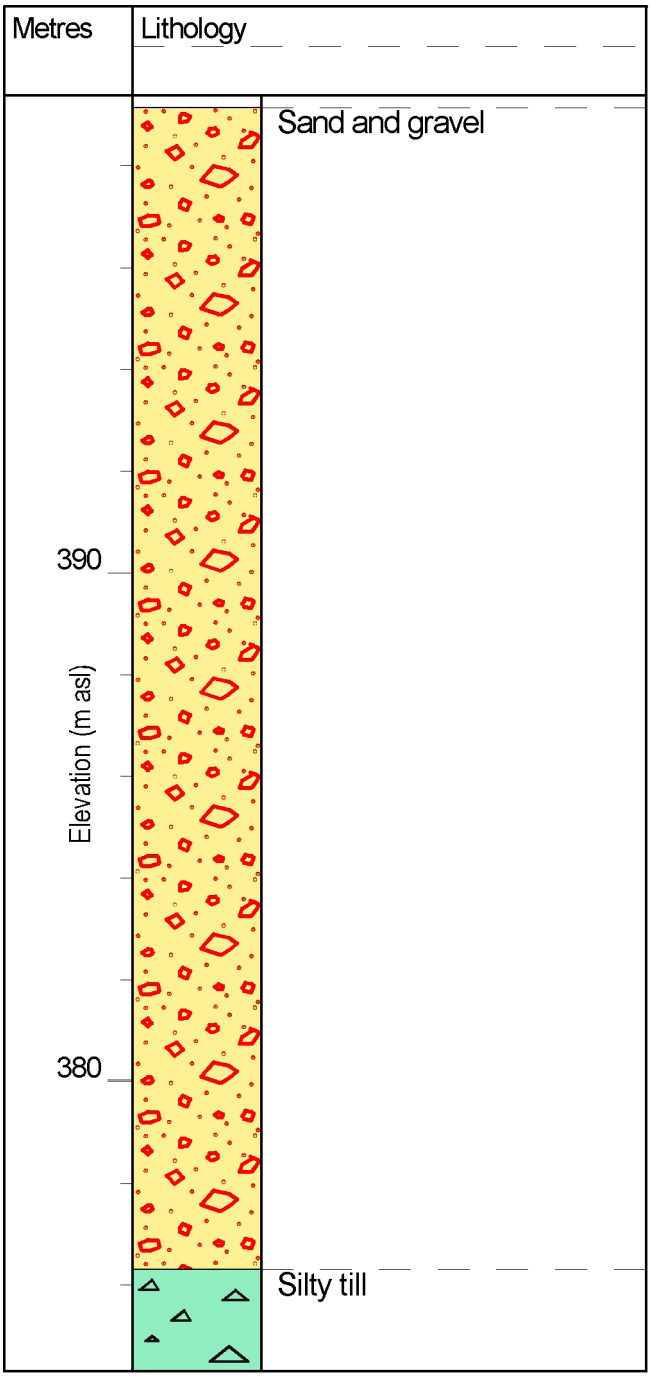


Figure 68. Schematic section of outcrop lithology at stop LA2005-06, gravel pit on northwest flank of Muskeg Mountain, central part of Fort McMurray region. See Figure 7 for location.

Figure 69. Site LA2005-06: Twin Bridges gravel pit. See Figure 7 for location.

Figure 70. Site LA2005-06: Twin Bridges gravel pit, view to northwest. See Figure 7 for location.

Figure 71. Site LA2005-06: folded diamict injected into sand and gravel. See Figure 7 for location.

Figure 72. Site LA2005-06: microfolds in finely bedded silty sand. See Figure 7 for location.

Figure 73. Site LA2005-06: folded and deformed gravel bed, 20 m from surface. See Figure 7 for location.

Figure 74. Site LA2005-06: boulder bed at base of pit. See Figure 7 for location.

LA 2005-07

UTM: E 498333 N 6341529
Elevation from 50m SRTM grid: 524.06 m
#3 Borrow Pit for Suncor Firebag construction

Lithology intervals in metres.

From	To	Lithology	Description
0.0	0.5	Silty sand	Poorly sorted glaciofluvial silty sand; modified by luvisolic processes; ashy grey white;
0.5	2.0	Till	Oxidized till; sandy silt loam; stiff blocky shard structure when excavated. Chert, limestone, Atha. Sst., Shield, Audible HCl reaction, no visible reaction; Sample LA 2005-07-1.5m
2.0	4.0	Till	Unoxidized till; well defined bitumen odour, numerous stones on surface; very dense; consolidated; si-sand loam; weak visible, audible reaction to HCl; overconsolidated; crushes in hands, excavates into shards, angular fragments; abundant Athabasca Sandstone boulders, some Shield clasts; some coarse sand in matrix; LA 2005-07-3.5m; Comment: Similar to till at bottom of pit on LA 2005-06.
4.0	8.0	Till	Unoxidized till exposed on eastern face; covered by 2m of discontinuous peat.

LA 2005-08

UTM: E 493017 N 6374751
Elevation from 50m SRTM grid: 280.2 m
10m Section on meander cut face along Firebag River

Lithology intervals in metres.

From	To	Lithology	Description
0.0	2.5	Medium sand	Medium sand; some fine sand to silty sand beds 1-4cm thick bedding planes at 1.5 m
2.5	3.5	Silt	Silt, dark grey brown
3.5	3.7	Clay and silt	Silty clay, plastic, moist
3.7	5.7	Coarse sand	Coarse sand with oil sand pebbles; some quartzites
5.7	6.2	Medium sand	Medium sand; subhorizontal bedding, Bed dip 5 º-7ºNE
6.2	8.6	Coarse sand	Coarse sand with some pebbles; cobbles; some black carbonaceous cemented cobbles (looks like coal-lignite, possibly oil sand)
8.6	8.7	Coarse sand	Iron-oxide rich coarse sand; abundant large cobbles, stones
8.7	9.4	Gravelly sand	Gravelly sand
9.4	11.0	Gravel	Black oil sand gravel; rip-up gravel facies with abundant coarse sand, fine gravel coarsens with depth; Sample LA 2005-08-10.5 m
11.0	12.0	Clay	Pink clay; laminae visible; dense; hard; groundwater discharge at gravel/clay contact. Sample LA 2005-08-11m; si-clay texture; brittle, not plastic; dark grey to pink; interbedded with dark grey si-clay; does not have till appearance

From	To	Lithology	Description
12.0	14.5	Silty clay	Dark grey silty clay, dense, plastic; poor site to sample, covered by colluvium; Comments: Inclusions and discontinuous beds of pink clay in the grey clay unit, and lenses of grey clay in the pink clay unit.
14.5	19.2	Colluvium	

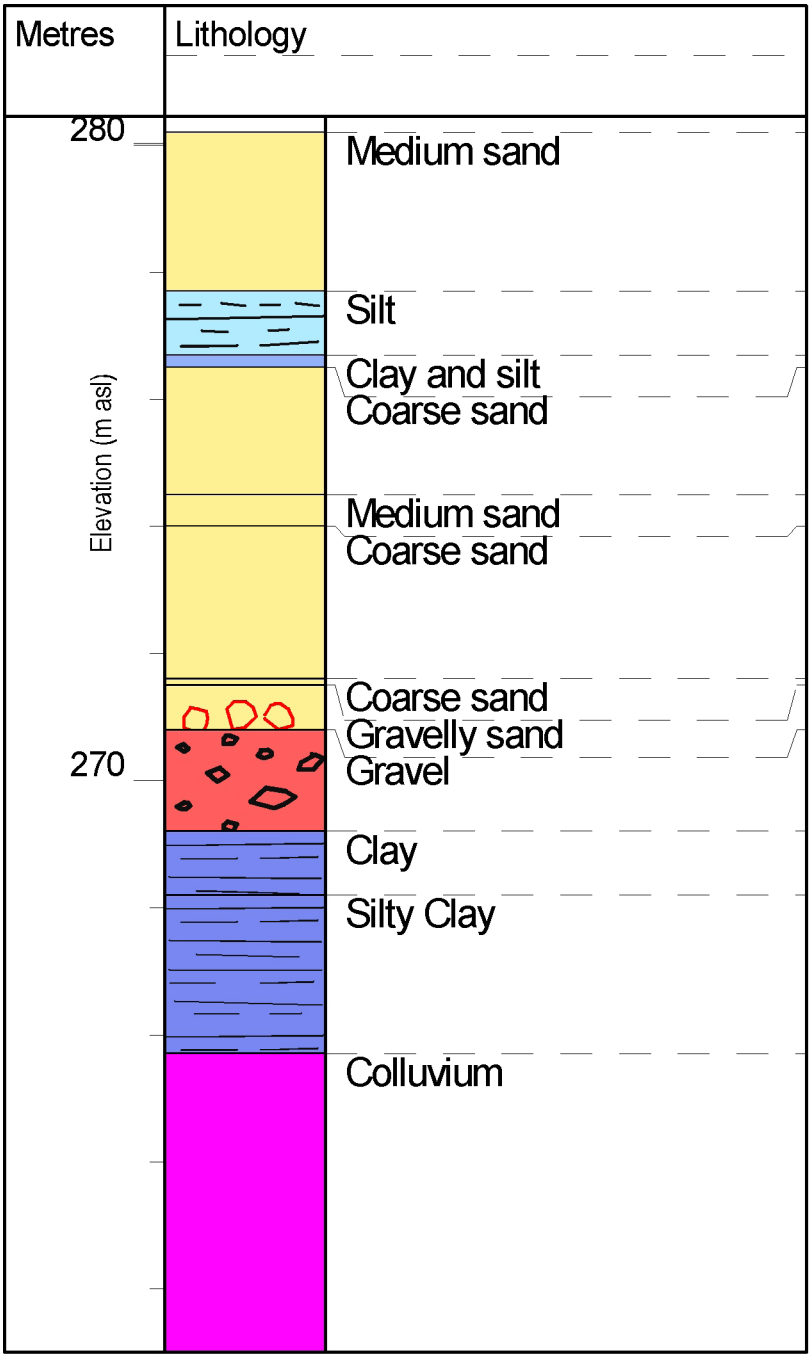


Figure 75. Schematic section of outcrop lithology at stop LA2005-08, southwestern bank of Firebag River, north-central part of Fort McMurray region. See Figure 7 for location.

Figure 76. Site LA2005-08: glaciofluvial sand on pink and grey clay. See Figure 7 for location.

Figure 77. Site LA2005-08: pink and grey glaciolacustrine silt and clay. See Figure 7 for location.

LA 2005-09

UTM: E 515134 N 6383409
Elevation from 50m SRTM grid: 353.0 m
Well pad site, black spruce, peat

Lithology intervals in metres.

From	To	Lithology	Description
0.0	0.6	Peat	Peat
0.6	0.8	Sand	Sand; gleyed, wet; medium-grained and silty fine sand (poorly sorted medium grained); a few small pebbles; sugary textured quartz, feldspar; Athabasca sandstone; earthy black blebs (Mn oxide?); Large Athabasca Sast. boulder (.4m) at edge of lease.

LA 2005-10

UTM: E 540318 N 6388777
Elevation from 50m SRTM grid: 425.18 m
Survey (DLS) clearing; hummocky moderate relief, jack pine, Caribou moss; sand exposed at surface

Lithology intervals in metres.

From	To	Lithology	Description
0.0	0.8	Sand	Sand; rusty brown; Sample LA 2005-10-.8m; medium grains, moderately well sorted, Feldspar grains, dominantly coarse; 1 large Athabasca Sast. boulder (25cm) - ventifact; wind eroded facets; looks like outwash deposit; no bedding visible.

Figure 78. Site LA2005-10: Ventifact boulder (Athabasca Sandstone, orthoquartzite) northeastern part of Fort McMurray region. See Figure 7 for location.

LA 2005-11

UTM: E 550519 N 6383194
Elevation from 50m SRTM grid: 550.54 m
Outcrop

Lithology intervals in metres.

From	To	Lithology	Description
0.0	4.0	Sand	General comments about area: Hummocky, high relief topography, between 60-70m relief, as much as 100m in places; Jack pines; sand exposed everywhere with lag cobbles and boulders on surface; At stop site: boulder and cobble lag on surface of sand; jack pine; horizontally bedded iron-oxide layers in sand may reflect primary bedding; if so, bedding shows micro s folds and wavy structures; Bed Dip 5-10°S; Sample LA 2005-11-4m (sand). Boulder lithology is 95% Athabasca Sandstone with les than 5% Shield clasts. More steeply inclined beds in upper 1.3 m may indicate reworking by glacial overriding; most lag boulders are rounded to subrounded.

Figure 79. Site LA2005-11, northeastern part of Fort McMurray region: cobble lag on sand. See Figure 7 for location.

Figure 80. Site LA2005-11: kame sand. See Figure 7 for location.

LA 2005-12

Esker Ridge
UTM: E 556419 N 6343621
Elevation from 50m SRTM grid: 538.71 m
Esker Ridge

Lithology intervals in metres.

From	To	Lithology	Description
0.0	0.6	Coarse sand	Coarse sand with cobble/boulder lag on surface; glaciofluvial ice contact; feldspathic, quartz rich; abundant ventifacts on surface; 2 conical-mound kames-like features 1 to 2 km west.

Figure 81. Site LA2005-12, north-eastern part of Fort McMurray region: esker ridge. See Figure 7 for location.

Figure 82. Site LA2005-12: ventifact cobble. See Figure 7 for location.

LA 2005-13

UTM: E 540236 N 6309451
Elevation from 50m SRTM grid: 476.36 m
Undulating sandy plain, 3 m local relief rolling, jack pine covered.

Lithology intervals in metres.

From	To	Lithology	Description
0.0	0.8	Sand	Sand, fine to medium, moderately well sorted; Sample LA 2005-13-.7 m; quartz dominantly; one or two cobbles on surface (ventifacts); Athabasca Sandstone in all cases. An apparent 40m high ridge approximately 2 km to the west.

LA 2005-14

UTM: E 535054 N 6304346
Elevation from 50 m SRTM grid: 436.17 m
Outcrop on erosional spur where two streams meet; 9 to 10 m high section; exposing lower half of outcrop sequence.

Lithology intervals in metres.

From	To	Lithology	Description
0.0	9.0	Shale	Interbedded shale and siltstone/mudstone with ironstone; very dark grey brown and rusty brown. A few ironstone lag stones on surface of erosional bench, likely Clearwater Formation Sample LA 2005-14_9m.

Figure 83. Site LA2005-14, southeastern part of Fort McMurray region: mudstone and siltstone, Clearwater Formation. See Figure 7 for location.

LA 2005-15

E 467185 N 6308747
Elevation from handheld GPS: 330 m
Gravel pit

Lithology intervals in metres.

From	To	Lithology	Description
0.0	2.0	Gravel and boulders	Glacial outwash boulders and gravel
2	3.5	Sand	Sand, unconformably overlain by gravel and boulders; gently inclined beds dipping 5 degrees to north-northwest
3.5	3.7	Till	Till; pavement of limestone boulders on surface.

LA 2005-16

E 463333 N 6332640
Elevation from handheld GPS: 239 m
Gravel pit on east side of Peter Lougheed Bridge.

Lithology intervals in metres.

From	To	Lithology	Description
0.0	6.0	Sand and gravel	A fluvially eroded scabland depositional setting with glacial meltwater scour into McMurray Formation sandstone; near vertical walls on erosional bedrock remnants, showing fluvial sculpting and eddy pools along floor and walls of scoured bedrock. Local relief on remnants approximately 4 to 6 m with about 50 m spacing between remnants. Axis of landforms about 340ºN. About 5 to 6 m of bouldery coarse gravel deposited on top of and within scabland landforms. Far travelled boulders from Shield are very well rounded melon to basketball size, local sourced rocks (carbonates, clastics) are angular. Boulder beds are planar with apparent dip to the west. 1-1.5 m sized boulders near floor of gravel pit appear to be nested in the hollows and whirlpool pits of the bedrock.
6	8	Sandstone	McMurray Formation sandstone

Figure 84. Site LA2005-16, central part of Fort McMurray region: fluvial scour on McMurray Formation sandstone. See Figure 7 for location.

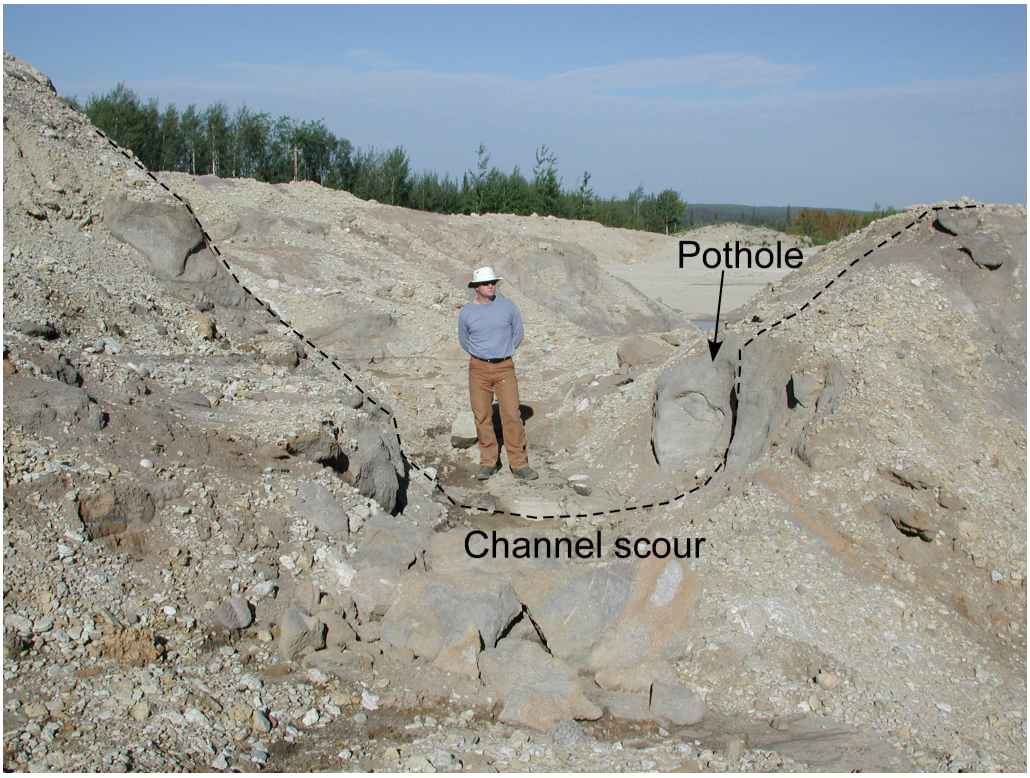


Figure 85. Site LA2005-16: fluvial scour and potholes. See Figure 7 for location.

Figure 86. Site LA2005-16: carbonate boulder lag on fluvial scoured bedrock surface. See Figure 7 for location.

LA 2005-17

E 455183 N 6321425
Elevation from handheld GPS: 342 m
Syncrude North Mine tour of buried glacial channel.

Lithology intervals in metres.

From	To	Lithology	Description
0.0	17.0	Gravelly sand	Gravelly sand with till inclusions and rafted shale and contorted till beds. 25-45 m incision of channel into Clearwater Fm. and then into McMurray Fm.; a 'two-channel' bifurcated system, main channel approximately 300 m wide; similar to the Birch Channel setting - may represent a secondary channel to the Birch Channel system. Eastward dipping imbricated boulders indicate flow to west, (orientation 272-278°). At south edge of outcrop boulder bed, and overlying sand and gravel are both scoured and infilled.

Figure 87. Site LA2005-17, west-central part of Fort McMurray region: exposure of fluvial sediments in South Spruce Channel, Syncrude lease. See Figure 7 for location.

Figure 88. Site LA2005-17: eastward imbricated boulders, South Spruce Channel. See Figure 7 for location.

Figure 89. Site LA2005-17: trough crossbeds, buried South Spruce Channel, Syncrude lease. See Figure 7 for location

Appendix 2 — Analytical Results

Matrix Carbonate Content (Chittick Method)

Sample number (depth)	Material	Weight percent of carbonates (%)			Calcite/dolomite ratio
		Calcite	Dolomite	Total carbonates	
LA2005-01 (2.5m)	Sandy till	1.0	0.7	1.7	1.39
LA2005-01 (4.3m)	Silty till	0.9	0.7	1.7	1.33
LA2005-01 (12.0m)	Sandy till	1.8	4.1	5.9	0.45
LA2005-01 (16.5m)	Sandy till	0.9	1.4	2.3	0.67
LA2005-01 (24.0m)	Silty till	1.3	0.9	2.2	1.50
LA2005-02 (5.5m)	Sandy till	1.9	1.9	3.8	0.98
LA2005-02 (10.5m)	Sandy till	1.2	0.8	2.0	1.60
LA2005-03 (3m)	Sandy till	1.2	3.3	4.5	0.36
LA2005-03 (8.5m)	Sandy diamict	1.0	0.4	1.3	2.61
LA2005-03b (4.5m)	Till	1.0	2.4	3.4	0.40
LA2005-06 (23.0m)	Silty till	1.1	3.7	4.8	0.31
LA2005-07 (1.5m)	Silty till	1.0	3.1	4.1	0.31
LA2005-07 (3.5m)	Sandy till	1.2	4.0	5.1	0.29
LA2005-08 (11m)	Lacustrine clay	1.0	2.1	3.0	0.46

Grain Size Analysis

Sample number (depth)	Material	Percentage						
		1–2 mm sand	Sand (>63 µm)	Silt (<63 µm)	Clay (<4 µm)	Sand (>50 µm)	Silt (<50 µm)	Clay (<2 µm)
LA2005-01 (2.5m)	Sandy till	0.14	16.10	71.60	12.30	23.00	69.20	7.80
LA2005-01 (4.3m)	Silty till	0.21	4.90	70.80	24.30	5.90	76.50	17.60
LA2005-01 (12.0m)	Sandy till	1.11	30.50	43.00	26.50	34.20	46.60	19.20
LA2005-01 (16.5m)	Sandy till	0.78	39.50	42.60	17.90	43.70	44.00	12.30
LA2005-01 (24.0m)	Silty till	0.68	45.20	38.50	16.30	49.20	39.10	11.70
LA2005-02 (5.5m)	Sandy till	0.92	42.40	36.20	21.40	45.20	38.50	16.30
LA2005-02 (10.5m)	Sandy till	3.43	46.40	47.10	6.50	51.10	44.30	4.60
LA2005-03 (3m)	Sandy till	2.21	40.30	39.50	20.20	44.60	40.90	14.50
LA2005-03 (8.5m)	Sandy diamict	1.11	50.10	41.40	8.50	54.30	39.70	6.00
LA2005-03b (4.5m)	Till	1.23	37.10	40.10	22.80	40.50	43.10	16.40
LA2005-06 (23.0m)	Silty till	0.88	46.60	49.90	3.50	49.70	48.20	2.10
LA2005-07 (1.5m)	Silty till	1.83	63.00	10.50	26.50	68.60	12.60	18.80
LA2005-07 (3.5m)	Sandy till	1.62	42.50	48.50	9.00	45.60	48.30	6.10
LA2005-08 (11m)	Lacustrine clay	0.68	6.70	71.20	22.10	7.50	75.80	16.70

Geochemical Analyses
Acme Analytical Laboratories Ltd.
Analysis: GROUP 4A
0.200 g sample by LiBO2 fusion, analysis by ICP-ES
LOI by Loss-on-Ignition; total C and S by LECO (not included in the sum)

Sample number-depth	Material	SiO2	Al2O3	Fe2O3	MgO	CaO	Na2O	K2O	TiO2	P2O5	MnO	Cr2O3	Ni	Sc	LOI	Ctotal	Stotal	SUM
		(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(ppm)	(ppm)	(%)	(%)	(%)	(%)
LA 2005-01 (2.5m)	Sandy till	77.09	9.34	3.95	0.79	0.73	0.76	1.84	0.83	0.17	0.05	0.008	21	8	4.3	0.39	0.05	99.86
LA 2005-01 (2.5m)	Sandy till	76.34	9.61	4.04	0.82	0.75	0.77	1.88	0.86	0.18	0.05	0.009	24	8	4.4	0.36	0.03	99.71
LA 2005-01 (4.3m)	Silty till	74.4	10.79	3.85	0.96	0.71	0.75	1.99	0.78	0.15	0.02	0.008	6	9	5.5	0.42	0.02	99.9
LA 2005-01 (12m)	Sandy till	68.99	10.99	3.98	1.65	2.65	0.71	1.98	0.73	0.14	0.05	0.009	24	9	8	1.59	0.58	99.87
LA 2005-01 (16.5m)	Sandy till	71.17	11.02	4.11	1.32	0.62	0.63	1.88	0.75	0.17	0.09	0.009	45	9	8.1	1.45	0.73	99.88
LA 2005-01 (24m)	Silty till	71.41	11.67	3.73	1.15	1.13	0.8	1.93	0.85	0.14	0.07	0.009	33	10	7	1.47	0.22	99.9
LA 2005-02 (5.5m)	Sandy till	69.92	11.43	4.41	1.41	1.64	0.71	2.04	0.75	0.15	0.04	0.009	30	10	7.4	1.35	0.09	99.91
LA 2005-02 (10.5m)	Sandy till	79.09	8.46	2.82	0.62	0.33	0.72	1.68	0.89	0.14	0.01	0.009	7	8	5.1	0.85	0.11	99.87
LA 2005-03 (3m)	Sandy till	67.16	11.76	5.22	1.73	2.22	0.63	1.95	0.77	0.16	0.17	0.009	21	10	8.1	0.94	0.03	99.88
LA 2005-03 (8.5m)	Sandy diamict	79.62	8.39	3.48	0.65	0.58	0.72	1.67	0.96	0.14	0.06	0.008	19	8	3.6	0.31	0.01	99.88
LA 2005-03b (4.5m)	Till	69.95	12.22	3.97	1.47	1.66	0.72	2.06	0.79	0.14	0.03	0.009	19	10	6.9	0.78	0.03	99.91
LA 2005-06 (23m)	Silty till	68.66	11.57	4.23	1.78	1.77	0.84	2.04	0.7	0.16	0.04	0.009	25	10	8.1	2.22	0.54	99.9
LA 2005-07 (1.5m)	Silty till	68.85	11.76	4.06	1.61	1.94	0.74	2.06	0.69	0.16	0.03	0.009	19	10	8	1.25	0.05	99.91
LA 2005-07 (3.5m)	Silty till	69.49	11.38	3.96	1.57	2.17	0.82	2.04	0.66	0.16	0.04	0.009	23	10	7.6	2.04	0.29	99.9

Analysis: Group 4B - REE
0.200 g by LiBO2 fusion, analysis by ICP-MS

Sample number-depth	Material	Ba	Be	Co	Cs	Ga	Hf	Nb	Rb	Sn	Sr	Ta	Th	U	V	W	Zr	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
		(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
LA 2005-01 (2.5m)	Sandy till	470.5	2	11.1	3.1	10.5	14.4	14.5	61.1	1	92.6	0.9	11.1	3.2	67	1.3	534.4	37.5	35	73.6	8.42	33.4	6.3	1.21	5.07	1.15	6.12	1.16	3.49	0.5	3.72	0.66
LA 2005-01 (2.5m)	Sandy till	487.8	1	10.8	3.2	10	13.9	13.9	60	1	96.3	1	9.7	3.1	72	1.1	516.1	38.6	37	78.2	8.55	34.2	6.3	1.19	5.53	1.07	5.83	1.22	3.28	0.58	3.58	0.63
LA 2005-01 (4.3m)	Silty till	524.3	2	7.3	3.8	13	9.1	14.7	72	3	94.6	1	10.6	3.1	85	1.3	330.7	34	37.1	72.7	8.7	32.3	6.6	1.18	4.73	0.94	5.1	1.08	2.98	0.53	3.12	0.57
LA 2005-01 (12m)	Sandy till	497.5	3	11.3	3.9	12.8	9	13.3	72.3	2	118.6	1	11.3	3.3	86	1.2	324.7	29.5	35	68.8	8.16	31.5	6.4	1.08	4.9	0.99	4.36	0.92	2.84	0.45	2.7	0.47
LA 2005-01 (16.5m)	Sandy till	520.3	2	14.6	4.7	12.7	11.7	14.5	73.7	1	112	1.2	10.4	4.2	111	1.7	403.7	42.8	37.1	79	9.4	37.4	7.5	1.68	6.53	1.15	6.44	1.35	3.96	0.57	3.44	0.64
LA 2005-01 (24m)	Silty till	457.5	2	12.5	3.8	13.6	14.3	14.3	68.7	1	113.8	1.1	10.5	3.6	88	1.5	493.9	36.5	38.9	82.7	9.42	35.7	6.9	1.48	5.51	1.12	5.76	1.26	3.81	0.67	3.33	0.57
LA 2005-02 (5.5m)	Sandy till	499.3	2	10.9	4.2	13.2	9.6	13.4	78.6	1	110	1.1	10.8	3	87	1	337.5	29.7	37.1	75.4	8.84	34.3	6.1	1.27	5.04	0.92	4.72	0.99	2.98	0.49	2.83	0.54
LA 2005-02 (10.5m)	Sandy till	394.3	1	4.4	2.4	8.6	16	13.8	51.2	1	70.9	1	11.1	4.3	62	1.1	572.5	30	31.5	65	7.43	29.7	5.3	0.99	4.25	0.85	4.38	1.03	2.91	0.45	3.25	0.58
LA 2005-03 (3m)	Sandy till	441.9	3	11.9	4.6	13.9	11.3	14.2	77.4	2	99.4	1.1	12.5	3.2	90	1.1	416.9	33.5	35.7	77	8.48	31.7	6.3	1.17	5.3	0.93	5.2	1.13	3.55	0.48	3.28	0.57
LA 2005-03 (8.5m)	Sandy diamict	429.2	2	9.3	2.3	8.8	15.7	14.9	53.1	1	83.5	1.1	10.1	3.5	60	1.2	569	37.6	34.2	74.8	8.38	32.6	6.4	1.19	5.35	1.05	5.88	1.2	3.71	0.53	3.23	0.6
LA 2005-03b (4.5m)	Till	453.3	1	8	4.2	14.7	9.7	14.5	84.1	1	107.6	1.2	11.4	2.4	94	1.6	364	30.3	37.5	77.3	8.91	33.4	6	1.16	4.89	0.92	4.65	0.98	2.91	0.48	2.73	0.41
LA 2005-06 (23m)	Silty till	504.3	2	10.8	3.9	13.3	9	11.7	75.2	1	115.4	0.9	9.6	2.7	95	1.1	326	26.2	30.2	63.5	7.35	28.2	5.6	1.08	4.35	0.8	4.43	0.88	2.6	0.38	2.96	0.42
LA 2005-07 (1.5m)	Silty till	541.6	3	7.8	4	13.6	10.3	12.8	80	1	115.4	1	12.9	3.1	102	1.3	338.8	27.3	34.7	68.6	7.94	31	6.2	1.18	4.47	0.83	4.25	0.92	2.7	0.39	2.64	0.42
LA 2005-07 (3.5m)	Silty till	627.3	1	9.9	4.2	14.6	9.8	12.7	81.5	1	143.2	0.9	11	3.1	102	1.7	364	29.5	36.7	78.4	8.29	31.5	5.9	1.14	4.78	0.8	4.23	0.94	2.84	0.44	2.65	0.45

Analysis: GROUP 1F1
1.00 g sample leached with 6 mL 2-2-2 HCl-HNO3-H2O at 95°C for 1 hour, diluted to 20 mL, analyzed by ICP-ES and -MS

Sample number-depth	Material	Mo	Cu	Pb	Zn	Ag	Ni	Co	Mn	Fe	As	U	Au	Th	Sr	Cd	Sb	Bi	V	Ca	P	La	Cr	Mg	Ba	Ti	B	Al	Na	K	W	Sc	Tl	S	Hg	Se	Te	Ga
		(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(%)	(ppm)	(ppm)	(ppb)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(%)	(%)	(ppm)	(ppm)	(%)	(ppm)	(%)	(ppm)	(%)	(%)	(%)	(ppm)	(ppm)	(ppm)	(%)	(ppb)	(ppm)	(ppm)	(ppm)
LA 2005-01 (2.5m)	Sandy till	1.28	16.86	12.62	76.9	89	21.3	11.3	390	1.99	7.4	1.2	2.3	6.9	23.7	0.28	0.22	0.17	20	0.36	0.06	26.3	13.2	0.25	94.3	0.01	7	0.81	0.008	0.13	<.1	2.6	0.2	0.01	24	0.3	0.04	2.6
LA 2005-01 (2.5m)	Sandy till	1.15	18.35	13.03	84.4	89	23.2	12.2	385	1.96	7.5	1.1	1.4	6.1	23	0.28	0.23	0.16	19	0.35	0.07	26.4	13.2	0.25	90.5	0.01	7	0.78	0.008	0.13	<.1	2.5	0.23	0.05	35	0.3	0.02	3
LA 2005-01 (4.3m)	Silty till	0.82	21.67	13.66	76.9	112	12.2	6.9	135	1.84	6.7	1.2	1.9	6.4	24.1	0.14	0.18	0.18	20	0.36	0.06	26.3	14.9	0.3	79.3	<.010	8	0.89	0.007	0.14	<.1	2.7	0.13	0.01	34	0.3	0.03	3.1
LA 2005-01 (12m)	Sandy till	0.83	19.21	13.03	72.2	81	22.2	10.9	391	1.93	6.6	1.6	0.7	5.8	42.2	0.21	0.21	0.23	24	1.67	0.05	19.3	17.4	0.71	108.2	0.01	9	0.96	0.011	0.19	<.1	3.1	0.16	0.59	30	0.6	0.02	3.6
LA 2005-01 (16.5m)	Sandy till	3	23.08	13.96	98.6	115	44.6	14.6	773	1.93	9.2	2.1	0.4	5.7	38.3	1.31	0.53	0.25	27	0.33	0.07	22.7	15.5	0.51	126	<.010	9	0.86	0.009	0.16	<.1	2.8	0.37	0.73	45	1.6	0.04	3.2
LA 2005-01 (24m)	Silty till	0.46	15.43	8.98	57.4	71	20	11.2	545	1.77	4.3	1.2	1	4.7	41.5	0.25	0.18	0.13	23	0.63	0.05	20.6	16.4	0.44	65.4	0.01	11	0.91	0.009	0.13	<.1	3	0.1	0.19	24	0.3	0.02	3.3
LA 2005-02 (5.5m)	Sandy till	0.85	17.64	11.22	63.1	77	22.2	9.7	255	2.14	5.9	1.2	1.1	6.3	27.2	0.26	0.21	0.19	27	0.92	0.05	21.7	18.9	0.54	104.3	0.01	7	1.04	0.008	0.19	<.1	3.2	0.16	0.03	31	0.5	0.02	3.7
LA 2005-02 (10.5m)	Sandy till	1.23	12.96	10.24	35.4	72	6.4	3.5	69	1.33	5.1	1.9	0.4	5	13.5	0.06	0.29	0.12	19	0.1	0.05	18.6	10	0.18	64.7	0.01	5	0.59	0.004	0.09	<.1	1.9	0.22	0.09	29	0.8	0.02	2.2
LA 2005-03 (3m)	Sandy till	1.01	18.57	12.02	69	70	19.4	11.5	1457	2.78	6.3	1.1	0.8	6.6	29.7	0.18	0.18	0.19	29	1.38	0.06	26.2	19.9	0.76	97.3	0.01	10	1.24	0.01	0.18	<.1	3.4	0.19	<.01	30	0.3	0.02	4.2
LA 2005-03 (8.5m)	Sandy diamict	0.99	13.19	9.59	52.6	58	15.1	9.6	468	1.81	5.2	1.2	0.6	5.1	20	0.22	0.26	0.11	19	0.27	0.05	25.7	11.1	0.21	87.8	0.01	6	0.66	0.006	0.1	<.1	2.1	0.16	<.01	29	0.3	0.02	2.1
LA 2005-03b (4.5m)	Till	0.4	19.14	11.32	58.1	63	14.3	7.4	201	2.05	4	0.9	0.9	7.3	26.8	0.08	0.15	0.19	32	1.02	0.06	29.1	27.8	0.62	87.7	0.01	11	1.27	0.01	0.24	<.1	4.4	0.15	<.01	27	0.3	<.02	4.7
LA 2005-06 (23m)	Silty till	0.68	20.32	11.03	68.7	88	24.1	11.1	306	2.17	7.7	1.1	0.5	5	31.3	0.14	0.23	0.16	27	1.09	0.07	17.9	20.6	0.78	90.2	<.010	9	1.03	0.013	0.18	<.1	3.9	0.11	0.49	43	0.5	0.03	3.7
LA 2005-07 (1.5m)	Silty till	0.98	20.89	11.71	66	86	18.4	7.8	203	2.13	6.2	1.4	1.2	7.6	31.5	0.14	0.26	0.2	36	1.17	0.07	24.9	26.5	0.68	142.9	0.01	7	1.24	0.008	0.2	<.1	4.3	0.17	0.01	34	0.3	0.03	4.5
LA 2005-07 (3.5m)	Silty till	0.96	19.25	10.58	59.8	78	22.1	9.4	351	1.95	5.5	1.4	1.2	6.1	35.7	0.25	0.24	0.18	31	1.27	0.06	20.4	23.3	0.65	143.3	0.01	8	1.12	0.009	0.19	<.1	3.5	0.16	0.25	30	0.5	0.03	3.9

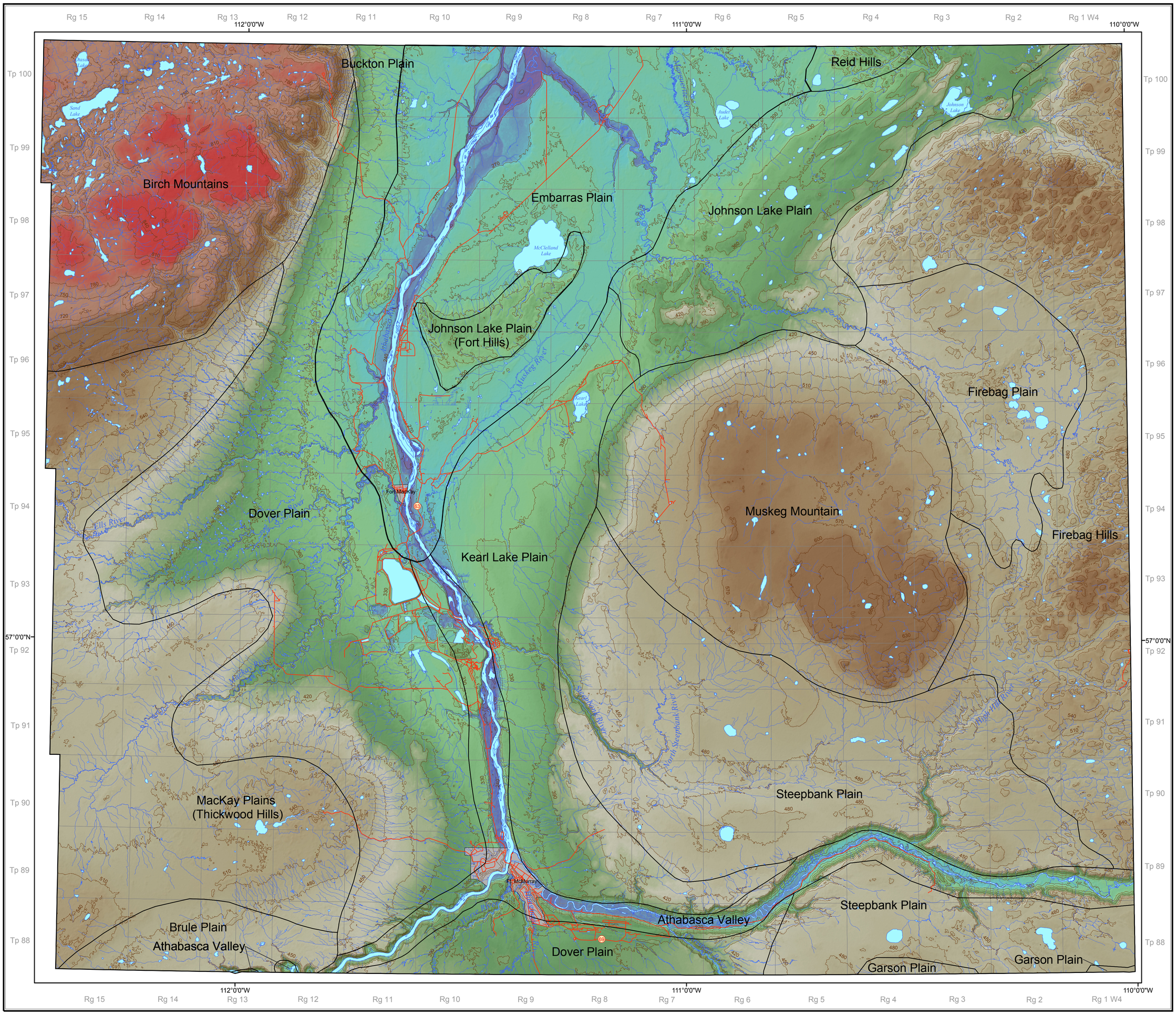
Appendix 3 — Map-Size Images of Key Figures (1:250 000 Scale)

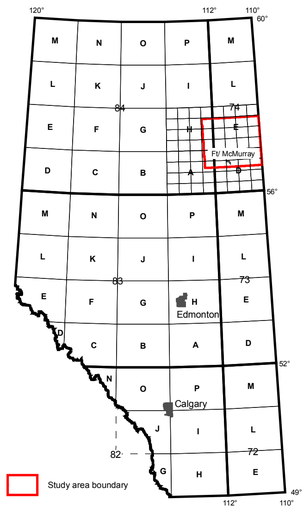
The following report figures (maps) have been generated at a 24" by 36" portrait format to enable printing and viewing at a scale of 1:250 000.

- Figure 2. Physiography and topography of the study area
- Figure 4. Locations of oil sand lease areas and distribution of borehole data (superposed on LANDSAT image)
- Figure 7. Summarized surficial geology map showing 2005 field season stops
- Figure 8. Bedrock topography, and buried channels and valleys
- Figure 14. Subcrop of bedrock geological units beneath glacial drift
- Figure 21. Point values of cumulative thickness of sand and gravel recorded in borehole logs
- Figure 22. Distribution and thickness of buried drift aquifers in the Fort McMurray Oil sands area
- Figure 36. Intrinsic permeability of surficial sediment above buried aquifers

The following report figures (cross-sections) have been generated at a 18" by 24" landscape format to enable printing and viewing at a larger scale.

- Figure 10. Regional cross-section R1-R1', illustrating the bedrock topography across the Athabasca Valley
- Figure 11. Regional cross-section R2-R2', illustrating the bedrock topography across the Athabasca Valley
- Figure 12. Regional cross-section R3-R3', illustrating the bedrock topography across Muskeg Mountain
- Figure 13. Regional cross-section R4-R43', illustrating the bedrock topography along the Athabasca Valley and into the Thickwood Hills
- Figure 16. Geological cross-section along the Pemmican Valley
- Figure 17. Geological cross-section along the South Pemmican Valley
- Figure 20. Geological cross-section along the Birch Channel
- Figure 23. Geological cross-section along the North Spruce Channel
- Figure 24. Geological cross-section along the South Spruce Channel
- Figure 25. Geological cross-section along the Willow Channel
- Figure 26. Geological cross-section along the Fort Hills Channel
- Figure 27. Geological cross-section along the Kearl Channel
- Figure 28. Geological cross-section along the Clarke Channel
- Figure 29. Geological cross-section along the Lewis Channel





Published 2006

Scale 1:250 000

5 0 5 10 15 20 Kilometres

5 0 5 10 15 20 Miles

Projection: Universal Transverse Mercator Zone 12
Datum: North American Datum 1983

Legend

- 30 m contours
- Major road
- River, stream
- Urban
- Lakes

Elevation (m asl)

860
450
220

50m Digital Elevation Model displayed as backdrop

Physiography of the Fort McMurray region (from W. Pettapiece 1986)

L.D. Andriashek and N. Atkinson, 2006

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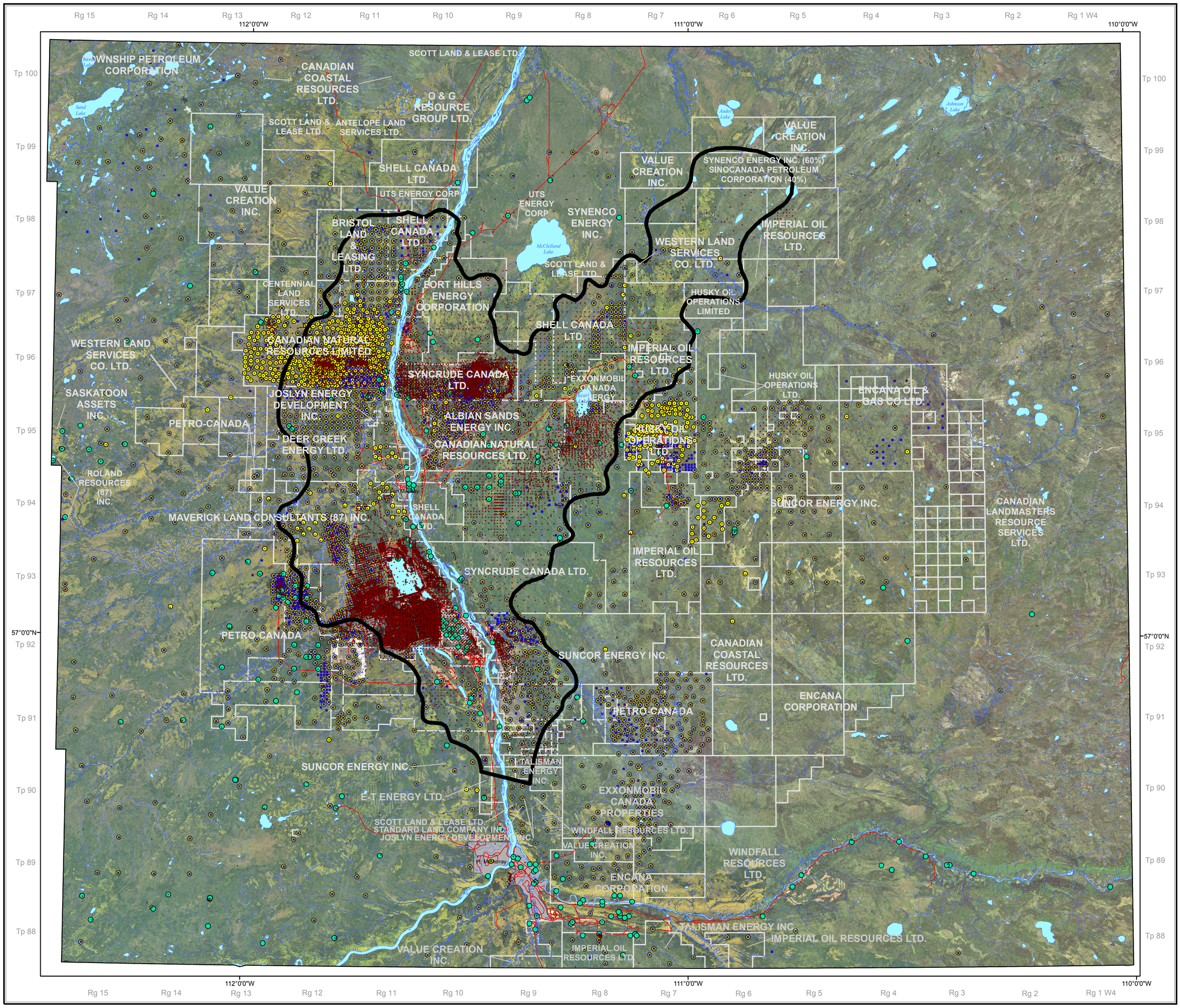
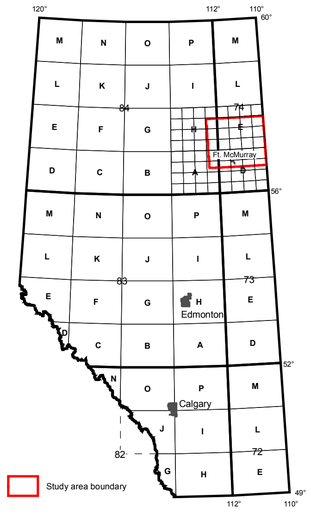
Figure 2. Physiography and topography of the study area.



Published 2006



Scale 1:250 000

5 0 5 10 15 20 Kilometres

5 0 5 10 15 20 Miles

Projection: Universal Transverse Mercator Zone 12
Datum: North American Datum 1983

- Borehole data location
- Water-well litholog
- Gamma log
- Resistivity log
- River, stream
- Major road
- Mineable oil sand boundary
- Oil sand lease
- Lake
- Urban

Coloured 2001 Landsat Image displayed as backdrop

Borehole Data Locations and Oil Sand Lease Areas: Fort McMurray Region, January 2006

L.D. Andriashek and N. Atkinson, 2006

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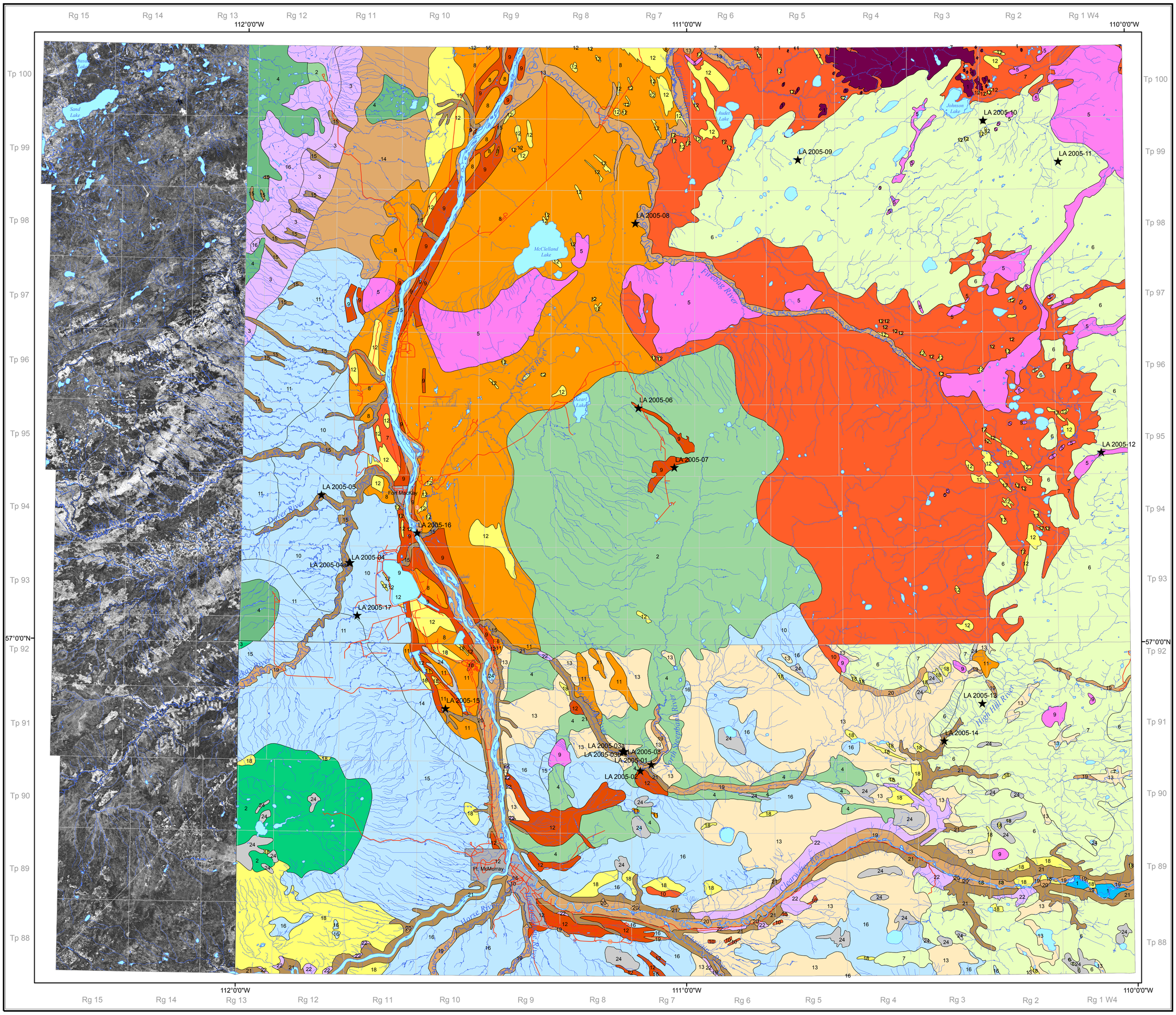
Figure 4. Locations of oil sand lease areas and distribution of borehole data (superposed on LANDSAT image).



Published 2006

Scale 1:250 000

5 0 5 10 15 20 Kilometres

5 0 5 10 15 20 Miles

Projection: Universal Transverse Mercator Zone 12
Datum: North American Datum 1983

Surficial Geology and 2005 Field Stops Fort McMurray Region (NTS 74D, E)

L.D. Andriashek and N. Atkinson, 2006

Legend

- ★ 2005 Field stop location
- Major road
- River, stream
- Lakes
- Urban
- Study area boundary

Grey-scale, 2001 Landsat Image displayed as backdrop

Surficial Geology NTS 74D

18	Eolian sand
20	Alluvial fan
16	Clay and silt (bedded)
15	Clay and silt (with pebbles)
6	Gipsy till - ground moraine
7	Gipsy till - hummocky moraine
21	Gully, creek valley
2	Horse River till - ground moraine
3	Horse River till - hummocky moraine
9	Kame, kame moraine
4	Kinosis till - ground moraine
12	Meltwater-channel outwash
1	Methy Formation
24	Organic
11	Outwash sand
10	Outwash sand and gravel
13	Sand and silt
14	Silt
22	Slump
19	Stream alluvium

Surficial Geology NTS 74E

12	Eolian sand, dunes
14	Alluvial fan
3	Colluviated ground moraine
1	Granite, gneiss and metasedimentary rocks
2	Ground moraine
15	Gully creek valley
4	Hummocky moraine
5	Ice-contact deposits
9	Meltwater-channel sediment
11	Mixed
8	Outwash sand
7	Outwash sand and gravel
6	Outwash sand and gravel overridden by glacier
10	Silt and clay
16	Slump
13	Stream alluvium

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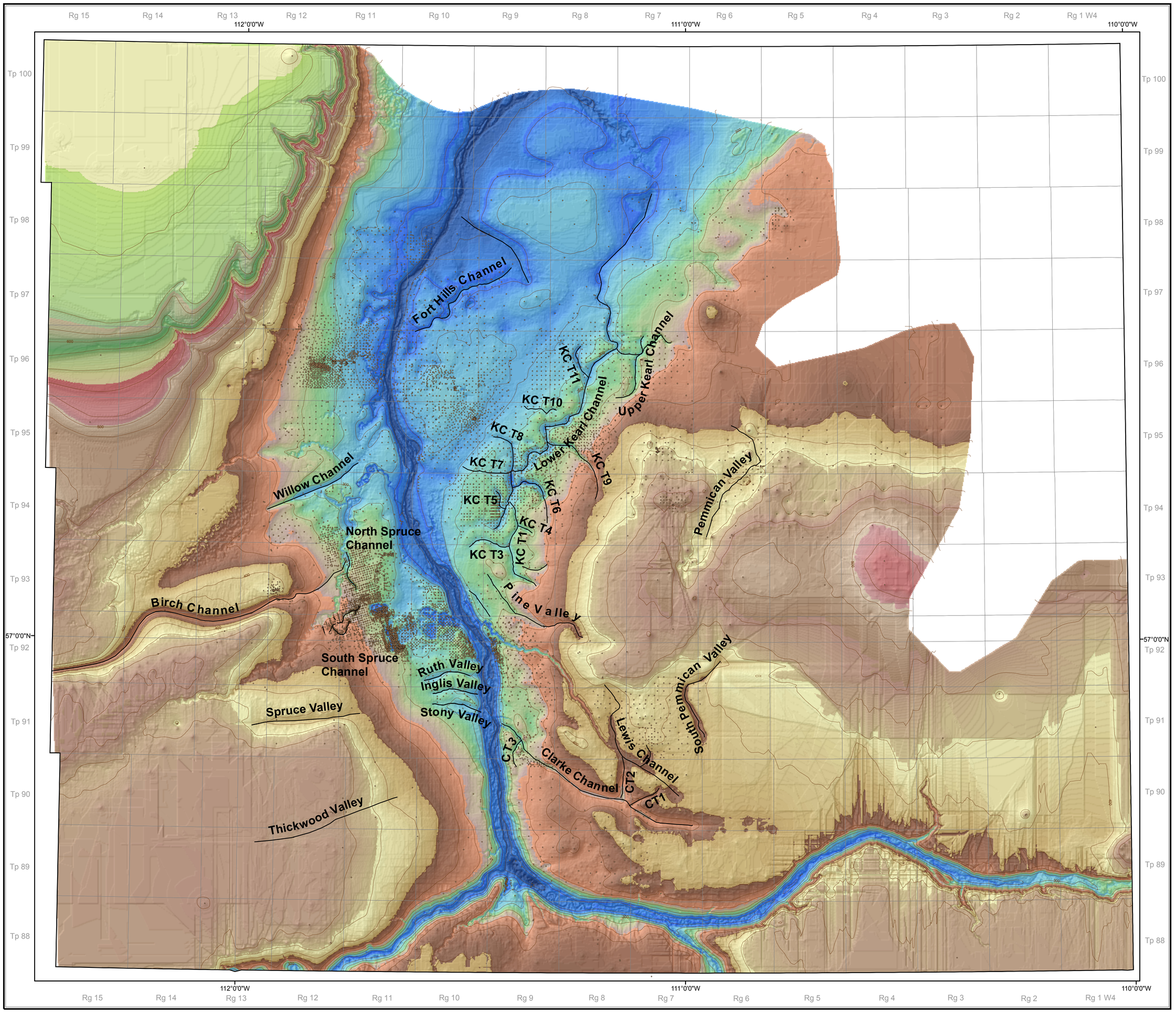
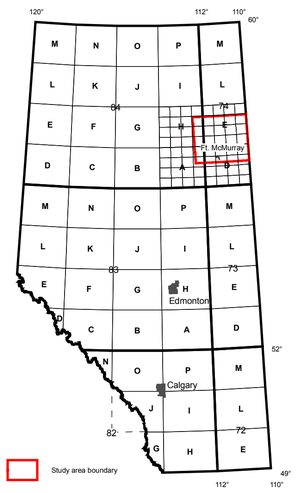
Figure 7. Summarized surficial geology map showing 2005 field season stops.





Scale 1:250 000

5 0 5 10 15 20 Kilometres

5 0 5 10 15 20 Miles

Projection: Universal Transverse Mercator Zone 12
Datum: North American Datum 1983

Legend

- Bedrock top data point
- Channel thalweg
- Bedrock contour (20 m)

Bedrock elevation (m asl)

720
450
210

Bedrock Topography and Buried Channels and Valleys, Fort McMurray Region

L.D. Andriashek and N. Atkinson, 2006

Published 2006

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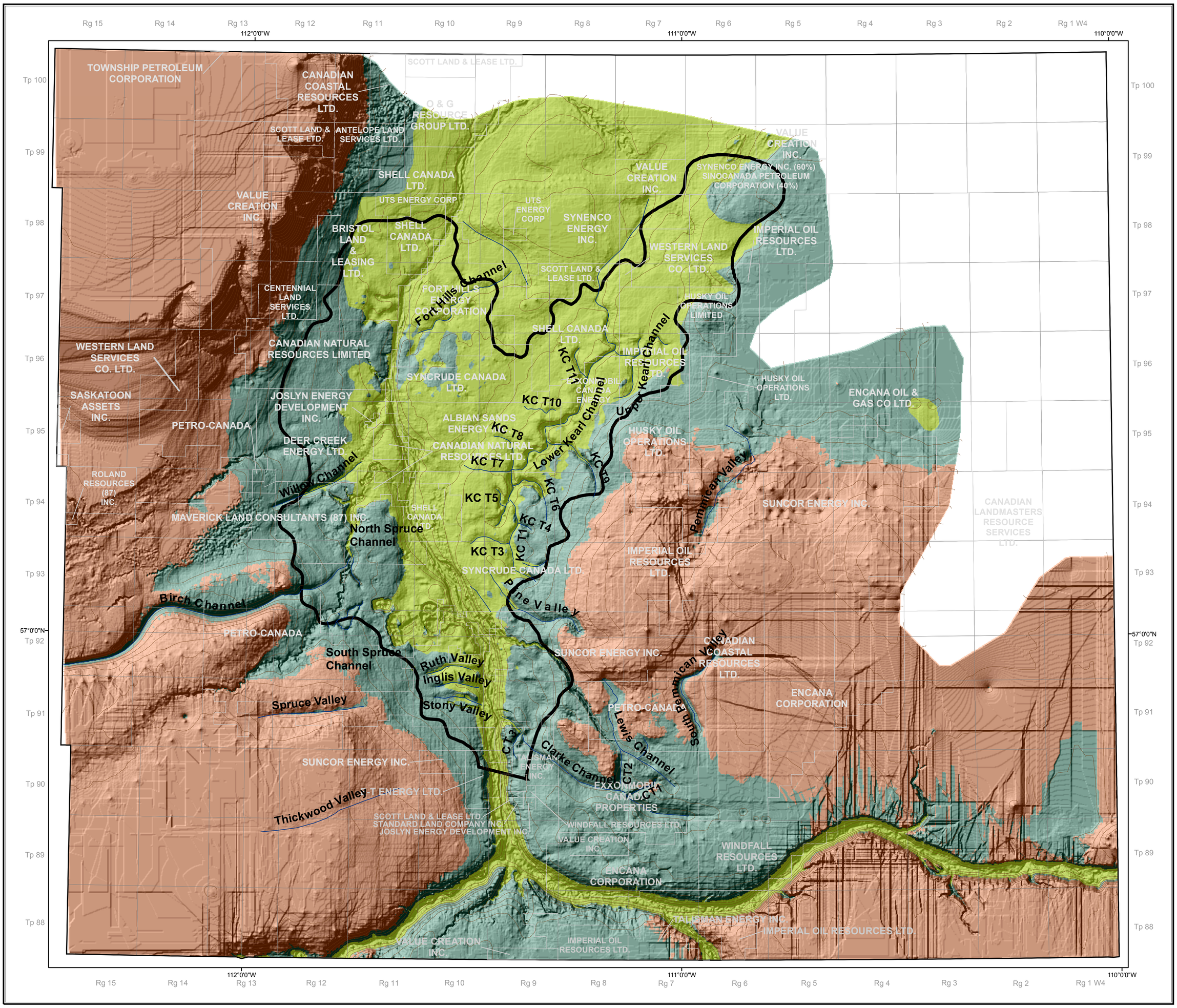
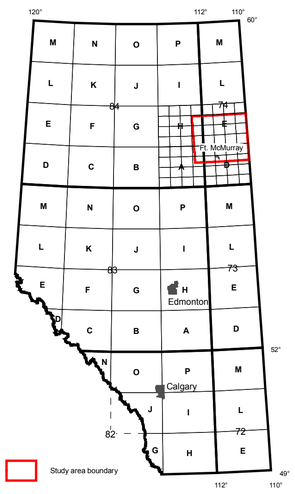
Figure 8. Bedrock topography, and buried channels and valleys.





Scale 1:250 000

5 0 5 10 15 20 Kilometres

5 0 5 10 15 20 Miles

Projection: Universal Transverse Mercator Zone 12
Datum: North American Datum 1983

Legend

- Channel and valley talwegs
- Bedrock Contours (20m)
- Oil Sands lease boundary
- Outline of Mineable Oil Sands
- Units above Clearwater Formation
- Clearwater Formation
- McMurray Formation
- Bedrock Surface Hillshade shown as backdrop

Published 2006

Subcrop of Bedrock Formations, Fort McMurray Region

L.D. Andriashek and N. Atkinson, 2006

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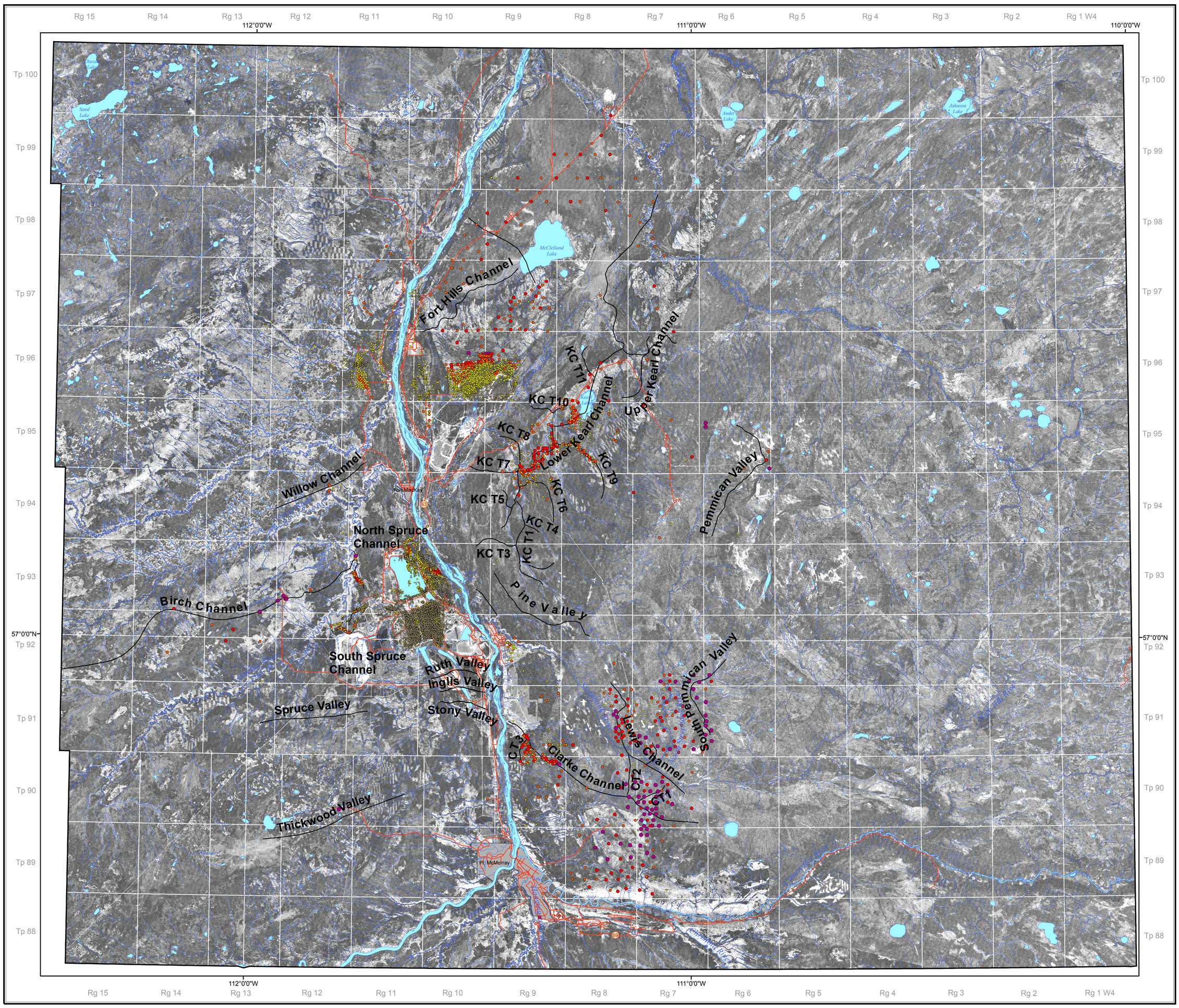
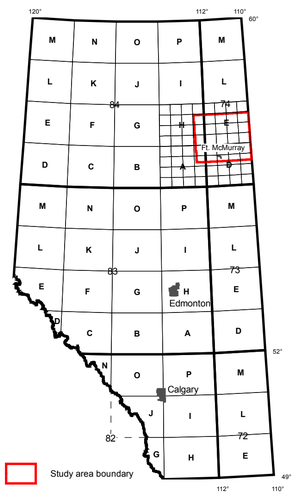
Figure 14. Subcrop of bedrock geological units beneath glacial drift.



Published 2006



Scale 1:250 000

5 0 5 10 15 20 Kilometres

5 0 5 10 15 20 Miles

Projection: Universal Transverse Mercator Zone 12
Datum: North American Datum 1983

Thickness (m)

- 0 - 3
- 4 - 10
- 11 - 21
- 22 - 43
- 44 - 96

- Channel thalweg
- Major road
- River, stream
- Lake
- Urban

Grey-scale, 2001 Landsat image displayed as backdrop

Cumulative Thickness of Sand and Gravel in Boreholes, Fort McMurray Region

L.D. Andriashek and N. Atkinson, 2006

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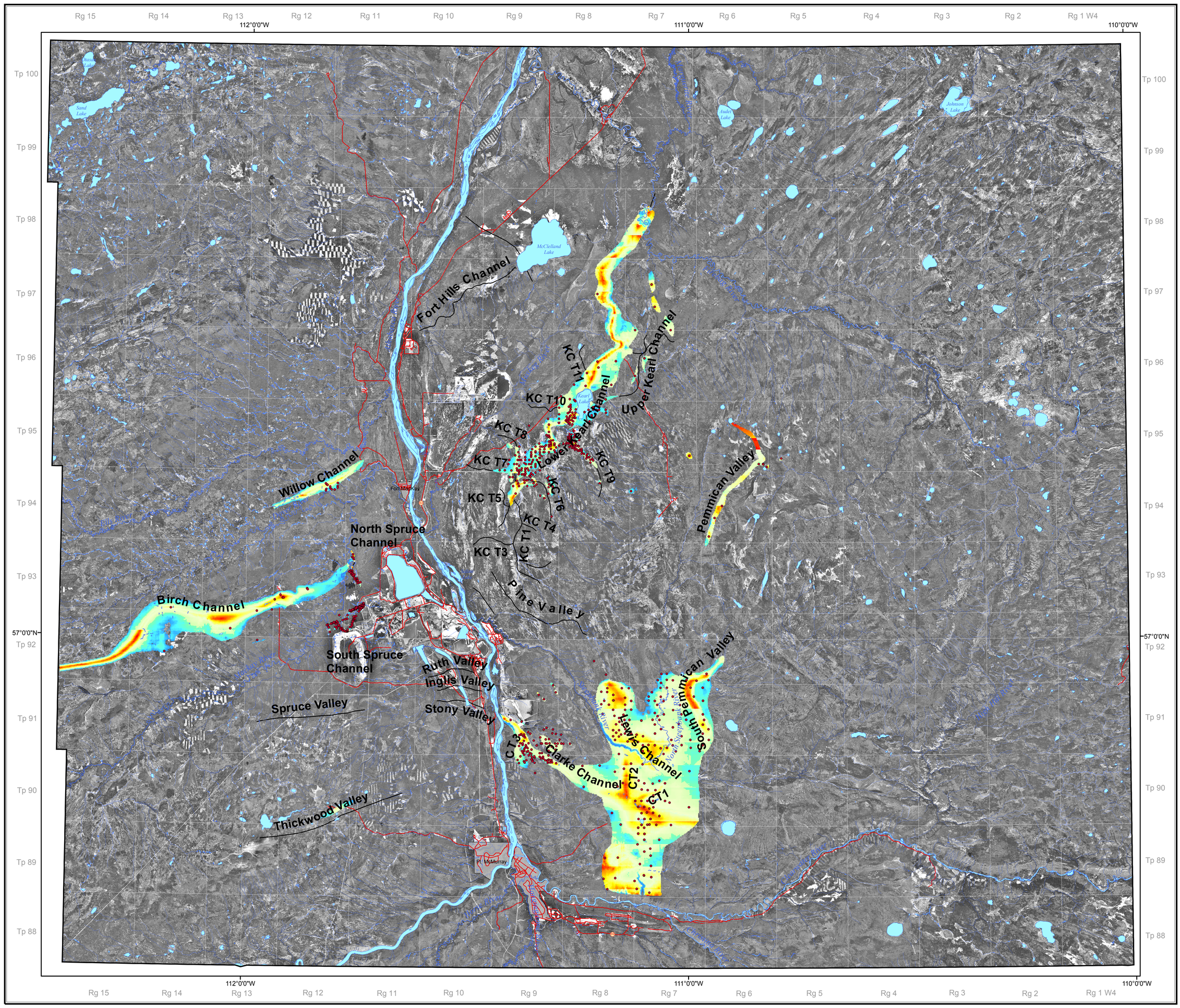
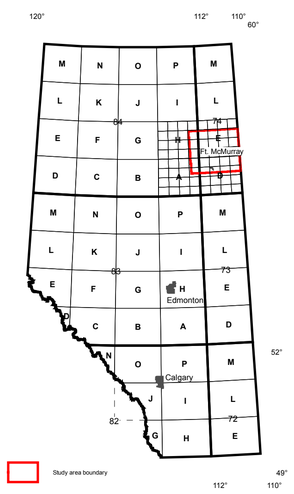
Figure 21. Point values of cumulative thickness of sand and gravel recorded in borehole logs.



Published 2006



Scale 1:250 000

5 0 5 10 15 20 Kilometres

5 0 5 10 15 20 Miles

Projection: Universal Transverse Mercator Zone 12
Datum: North American Datum 1983

Legend

- Data location
- Channel thalweg
- Major road
- River, stream
- Lake
- Urban

Thickness (m)
Value
115
60
1

Grey-scale, IRS image displayed as backdrop

Thickness of Buried Drift Aquifers in the Fort McMurray Region

L.D. Andriashek and N. Atkinson, 2006

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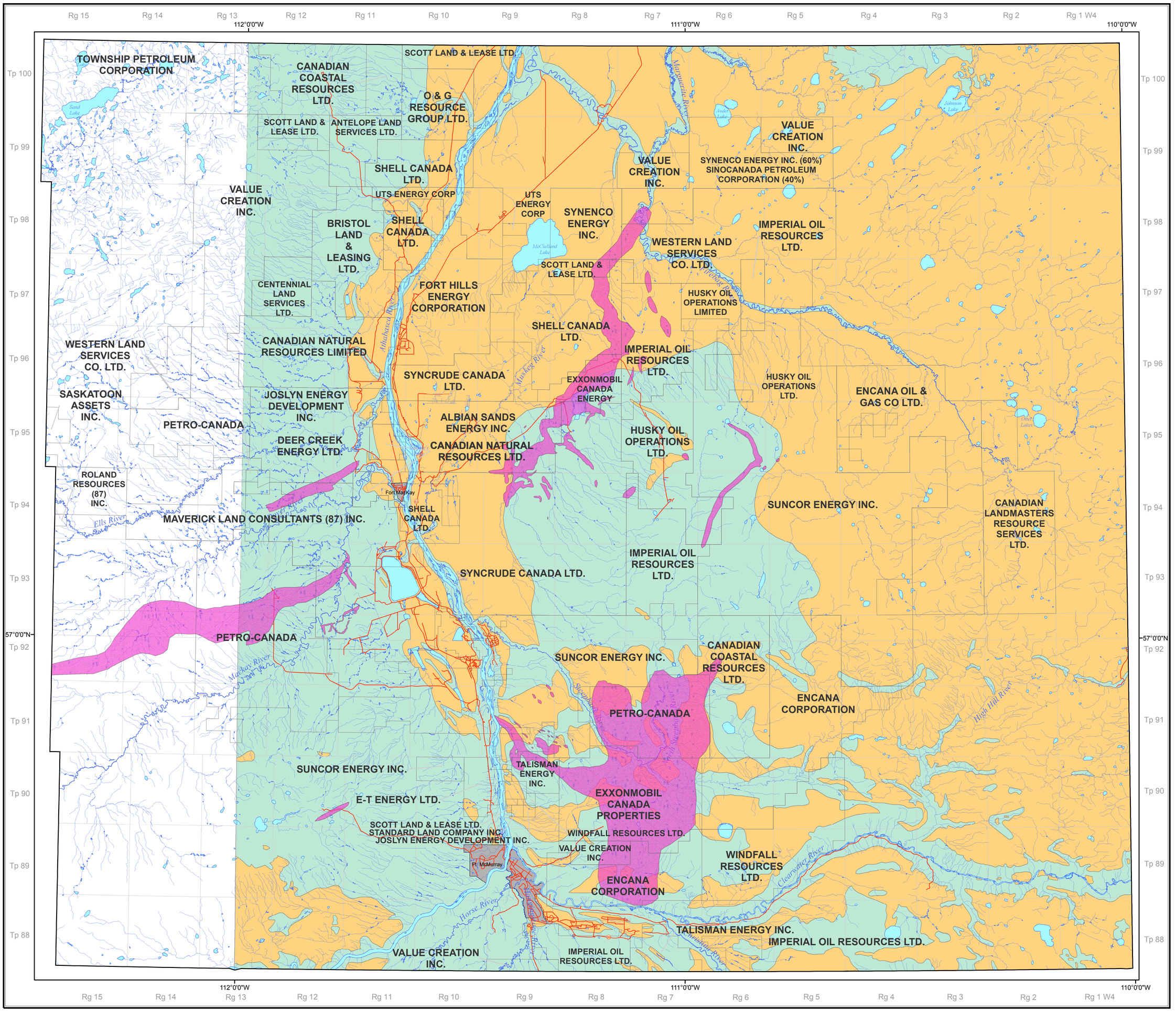
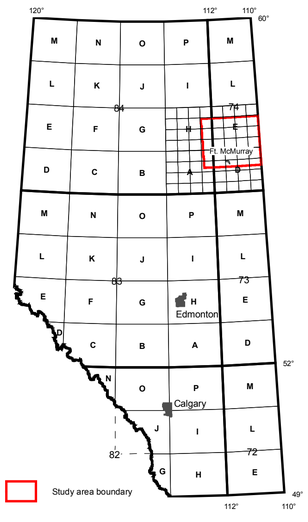
Figure 22. Distribution and thickness of buried drift aquifers in the Fort McMurray Oil sands area.





Published 2006

Scale 1:250 000

5 0 5 10 15 20 Kilometres

5 0 5 10 15 20 Miles

Projection: Universal Transverse Mercator Zone 12
Datum: North American Datum 1983

Legend

- Major road
- River, stream
- Lake
- Urban
- Oil sand lease
- Buried Aquifer
- Low permeability: clayey surface material
- High permeability: sandy surface material

Grey-scale, 2001 Landsat Image displayed as backdrop

Intrinsic Permeability of Surficial Sediments, Fort McMurray Region

(modified from Bayrock, 1971, 1974)

L.D. Andriashek and N. Atkinson, 2006

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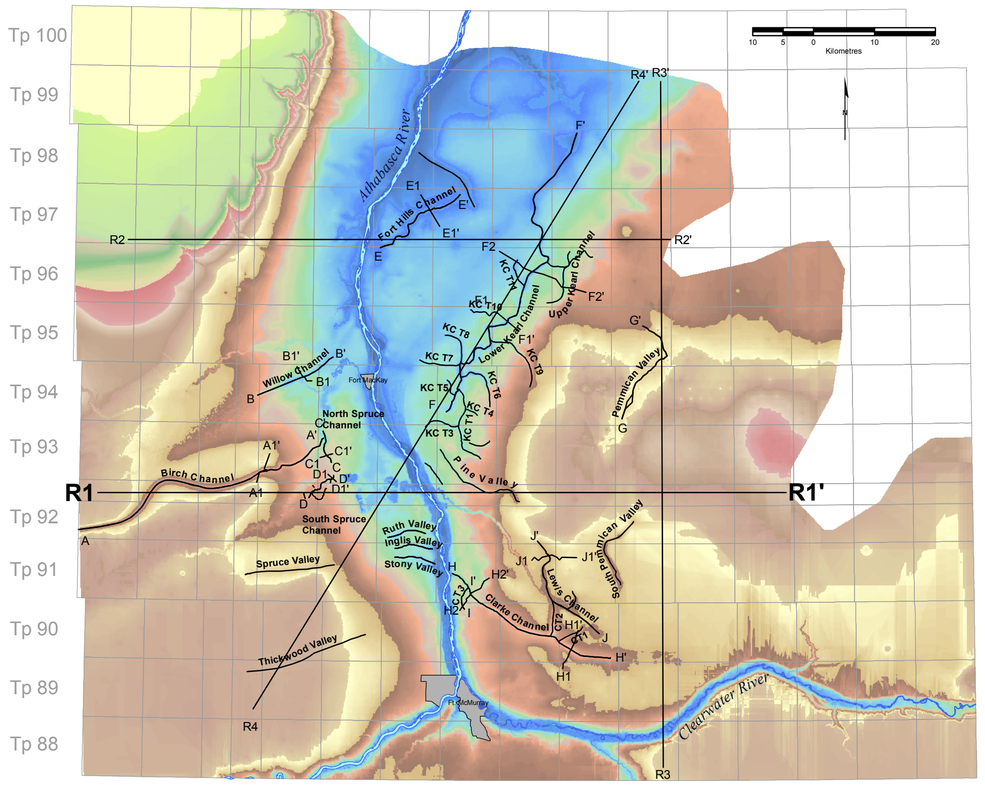
Figure 36. Intrinsic permeability of surficial sediment above buried aquifers.

R1-R1' Regional Cross-section

Legend

- Undifferentiated glacial sediment
- Sand, sand and gravel (aquifer)
- Grand Rapids Formation: sandstone, siltstone, shale (Note - In Birch Mountains area, this includes formations above the Grand Rapids Formation.)
- Clearwater Formation: shale, siltstone, sandstone
- McMurray Formation: sandstone, oilsand

Location of cross-section displayed on the bedrock surface



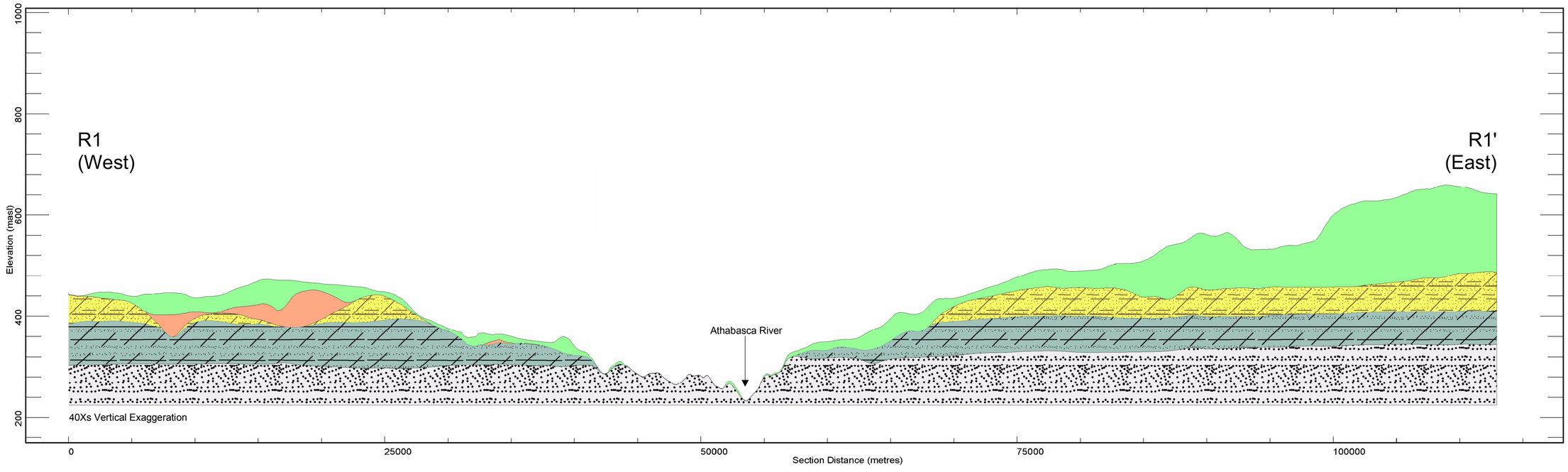


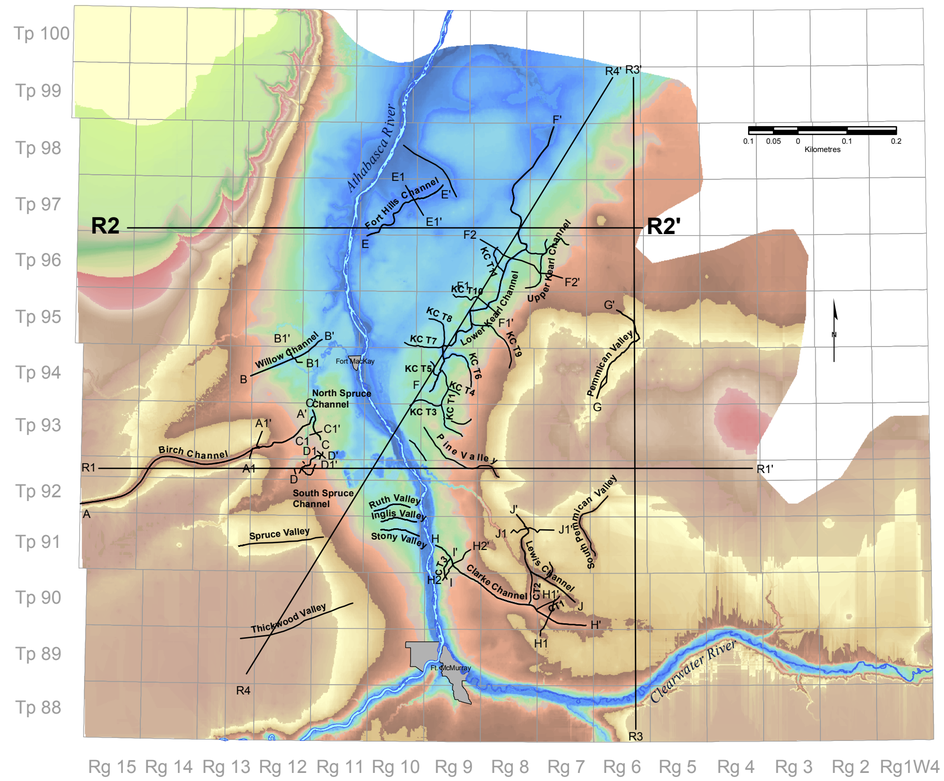
Figure 10. Regional cross-section R1-R1', illustrating the bedrock topography across the Athabasca Valley.

R2-R2' Regional Cross-section

Legend

- Undifferentiated glacial sediment
- Sand, sand and gravel (aquifer)
- Grand Rapids Formation: sandstone, siltstone, shale (Note - In Birch Mountains area, this includes formations above the Grand Rapids Formation.)
- Clearwater Formation: shale, siltstone, sandstone
- McMurray Formation: sandstone, oilsand

Location of cross-section displayed on the bedrock surface



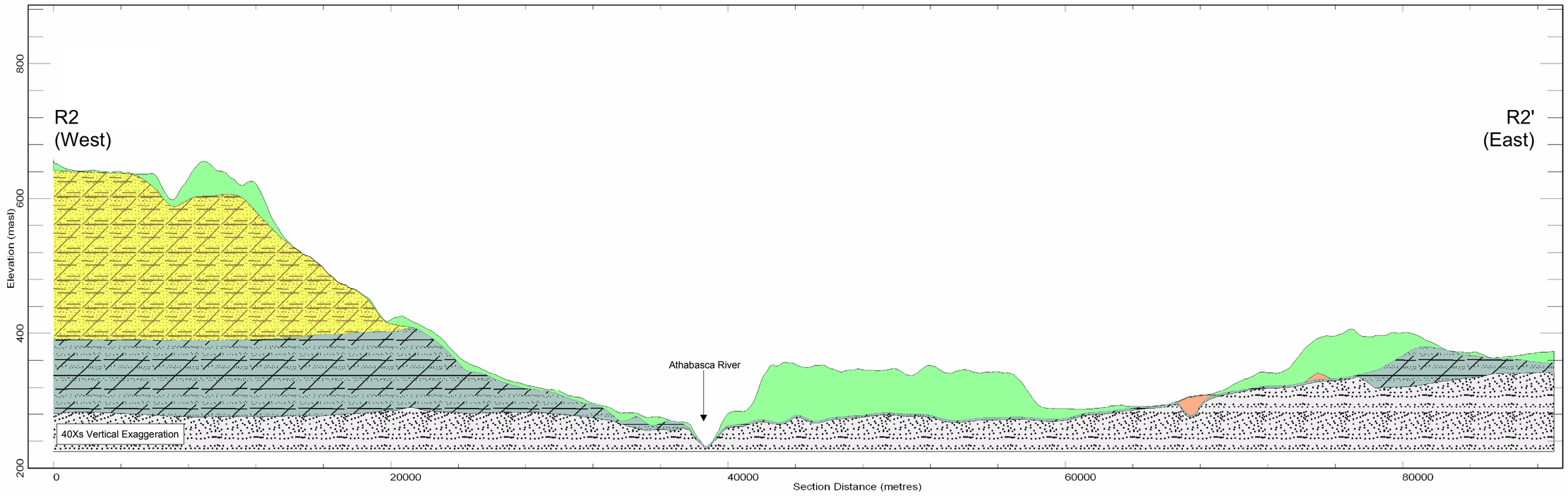


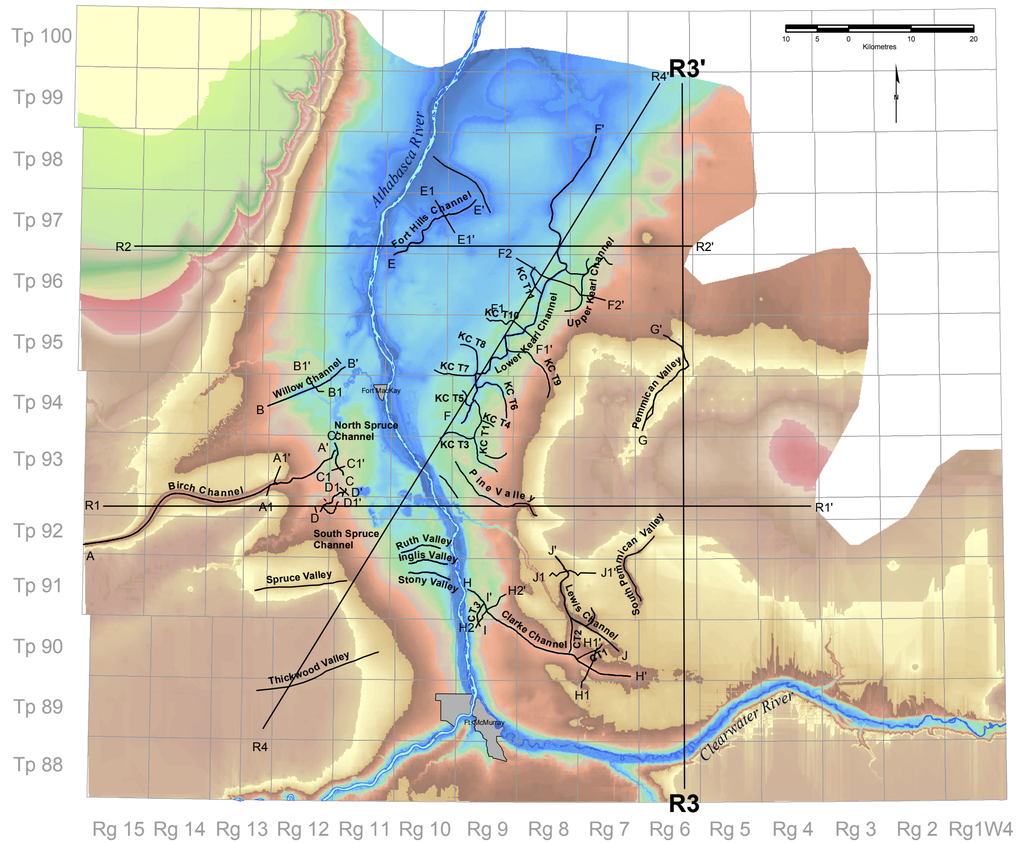
Figure 11. Regional cross-section R2-R2', illustrating the bedrock topography across the Athabasca Valley..

R3-R3' Regional Cross-section

Legend

- Undifferentiated glacial sediment
- Sand, sand and gravel (aquifer)
- Grand Rapids Formation: sandstone, siltstone, shale (Note - In Birch Mountains area, this includes formations above the Grand Rapids Formation.)
- Clearwater Formation: shale, siltstone, sandstone
- McMurray Formation: sandstone, oilsand

Location of cross-section displayed on the bedrock surface



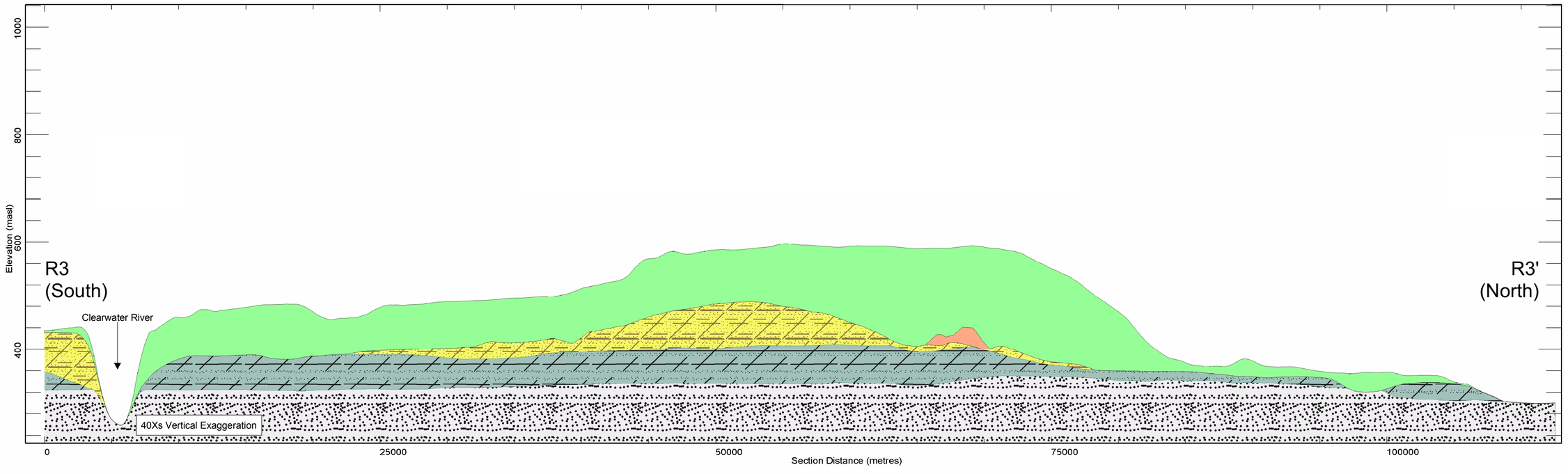


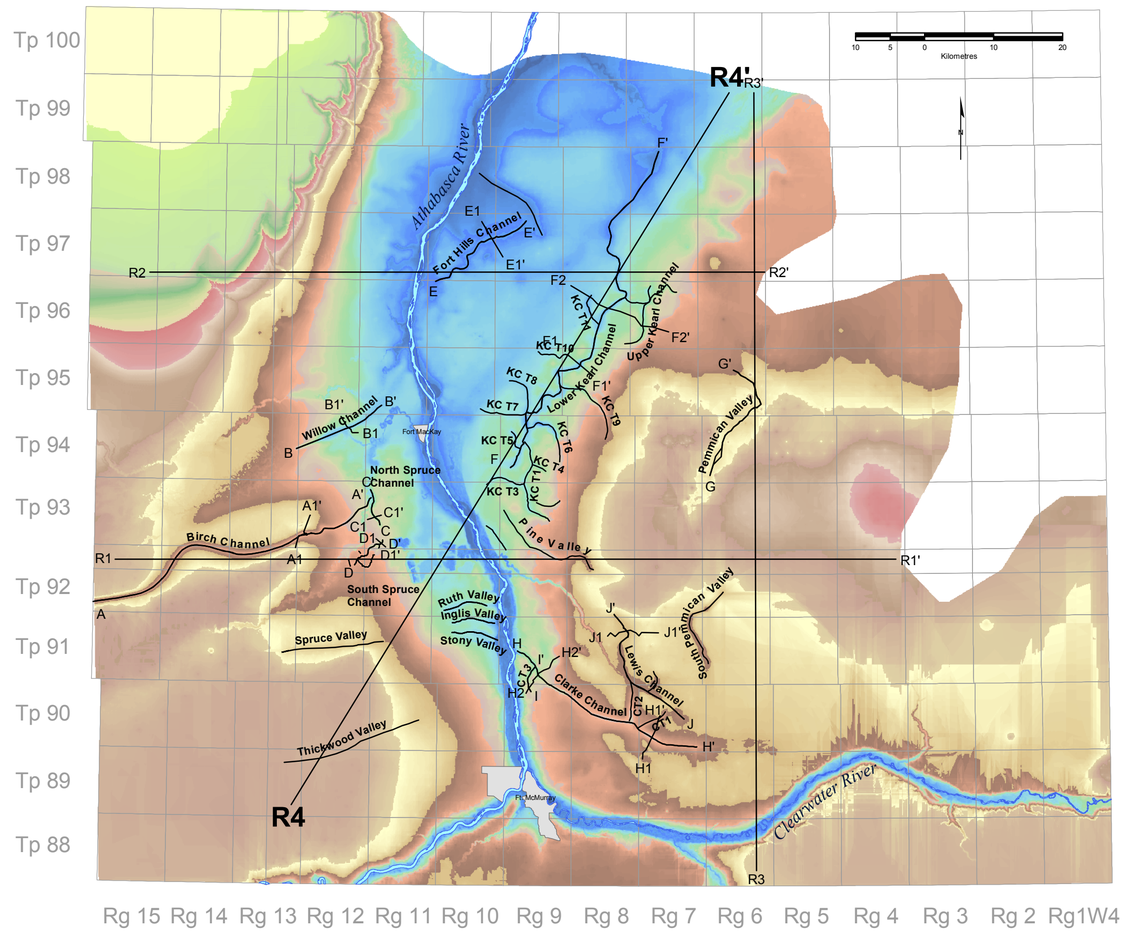
Figure 12. Regional cross-section R3-R3’, illustrating the bedrock topography across Muskeg Mountain..

R4-R4' Regional Cross-section

Legend

- Undifferentiated glacial sediment
- Sand, sand and gravel (aquifer)
- Grand Rapids Formation: sandstone, siltstone, shale (Note - In Birch Mountains area, this includes formations above the Grand Rapids Formation.)
- Clearwater Formation: shale, siltstone, sandstone
- McMurray Formation: sandstone, oilsand

Location of cross-section displayed on the bedrock surface



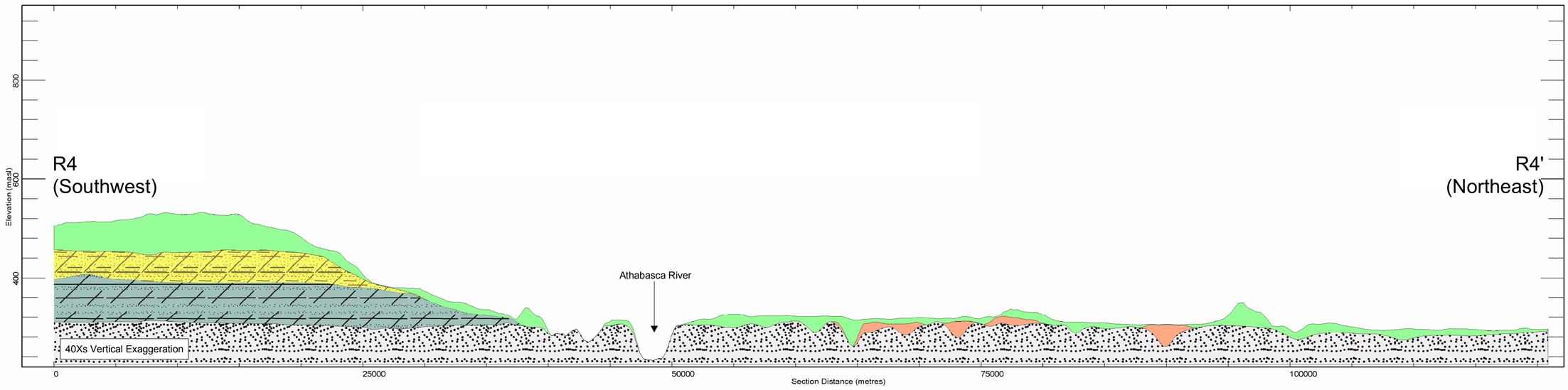


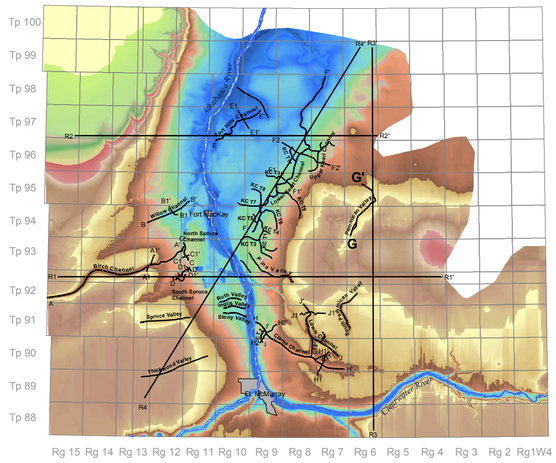
Figure 13. Regional cross-section R4-R43', illustrating the bedrock topography along the Athabasca Valley and into the Thickwood Hills.

Cross-section G-G' along the Pemmican Valley

Legend

- Undifferentiated glacial sediment
- Sand, sand and gravel (aquifer)
- Grand Rapids Formation: Sandstone, siltstone, shale
  (Note - In Birch Mountains area this includes formations above the Grand Rapids Fm.)
- Clearwater Formation: shale, siltstone, sandstone
- McMurray Formation: sandstone, oilsand

Gamma Log



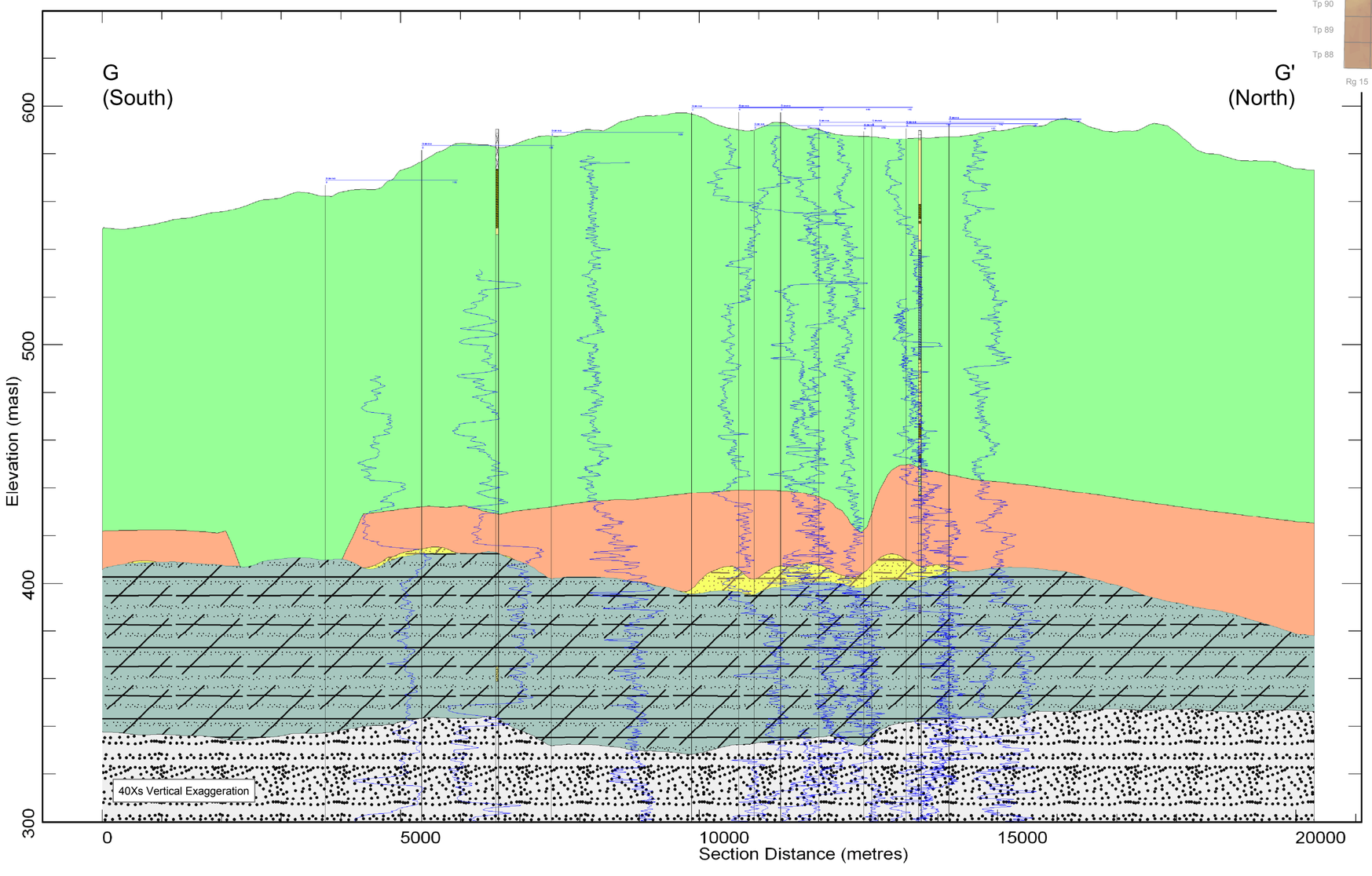


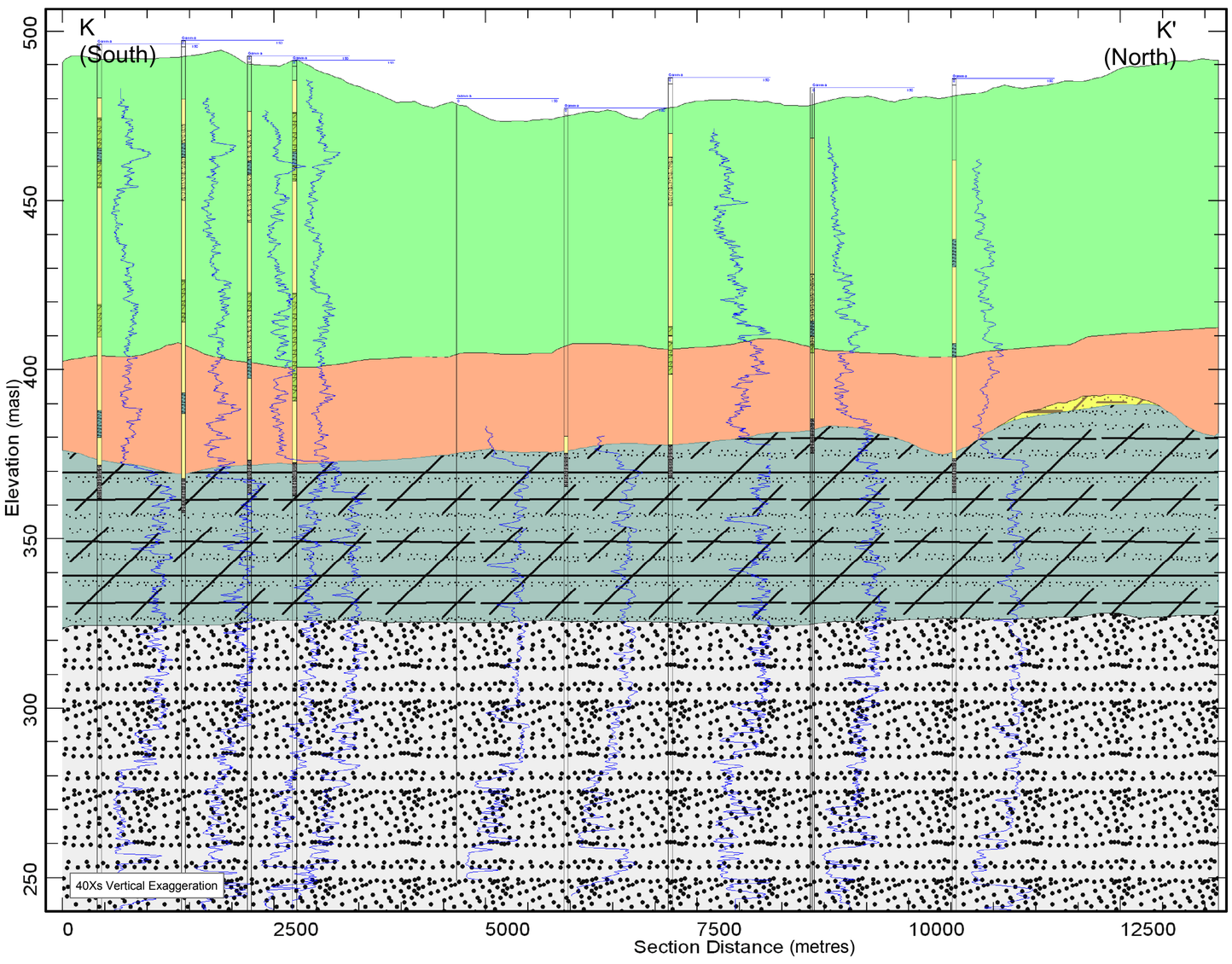
Figure 16. Geological cross-section along the Pemmican Valley..

Cross-section K-K' along the South Pemmican Valley

Legend

- Undifferentiated glacial sediment
- Sand, sand and gravel (aquifer)
- Grand Rapids Formation: Sandstone, siltstone, shale
  (Note - In Birch Mountains area this includes formations above the Grand Rapids Fm.)
- Clearwater Formation: shale, siltstone, sandstone
- McMurray Formation: sandstone, oilsand

Gamma Log



Location of channel cross-sections on the bedrock surface

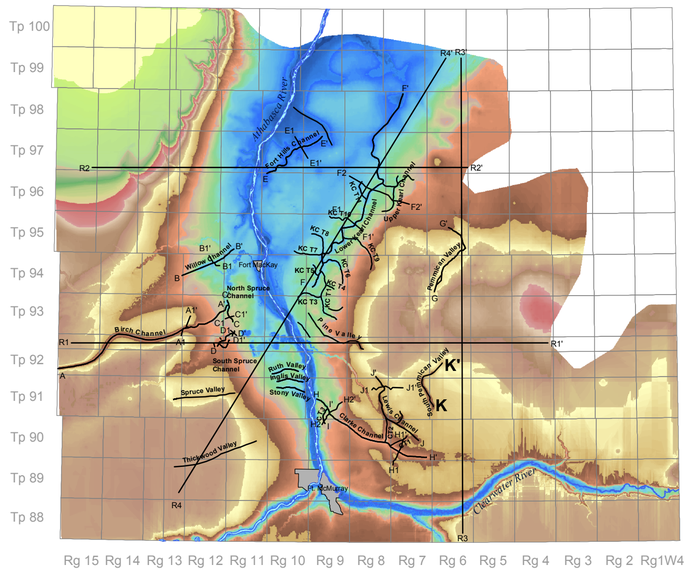
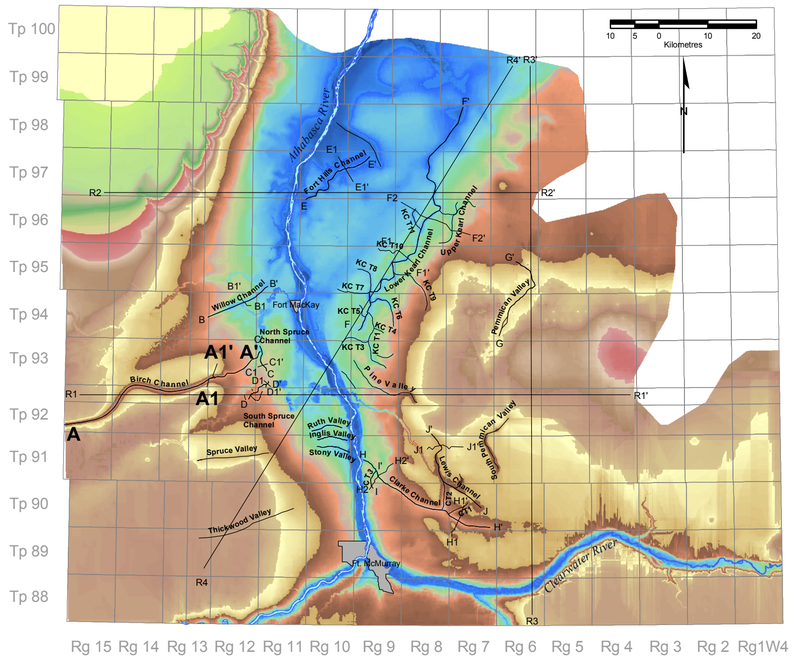


Figure 17. Geological cross-section along the South Pemmican Valley..

Cross-section A-A' along the Birch Channel

Location of channel cross-sections on the bedrock surface

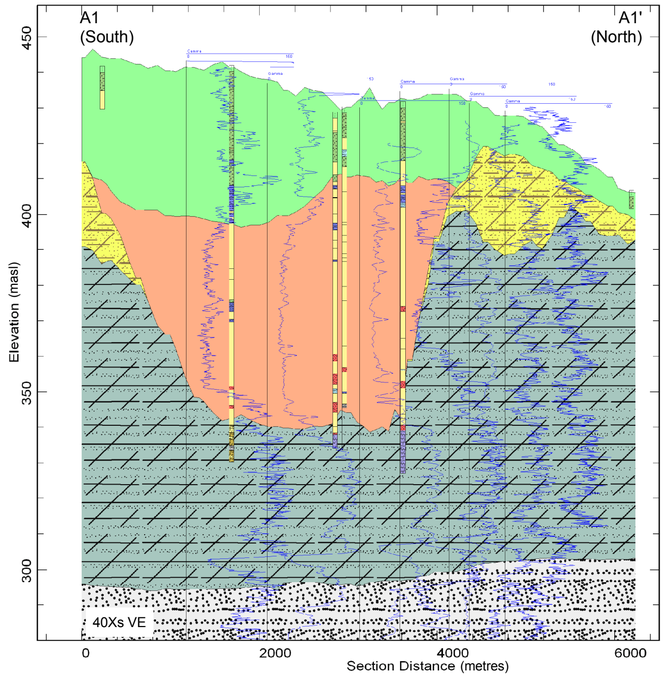


Legend

- Undifferentiated glacial sediment
- Sand, sand and gravel (aquifer)
- Grand Rapids Formation: Sandstone, siltstone, shale (Note - In Birch Mountains area this includes formations above the Grand Rapids Fm.)
- Clearwater Formation: shale, siltstone, sandstone
- McMurray Formation: sandstone, oilsand

Gamma Log

Cross-section across the Birch Channel



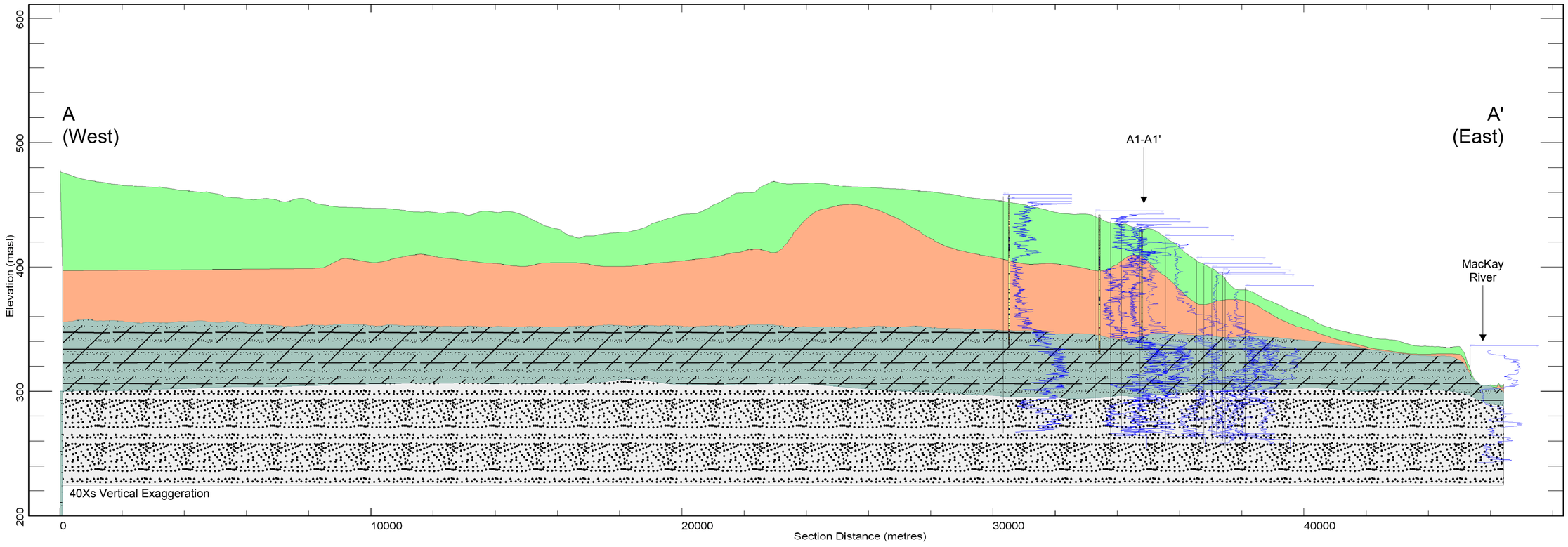
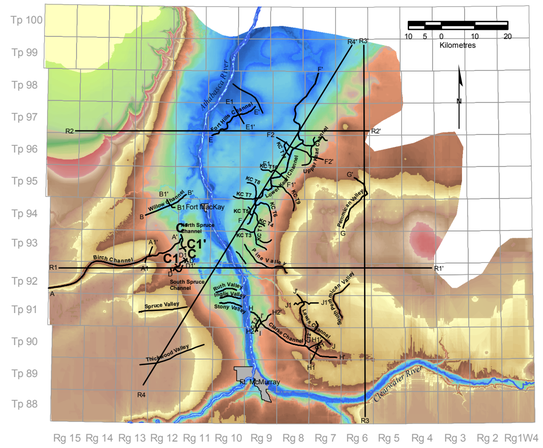


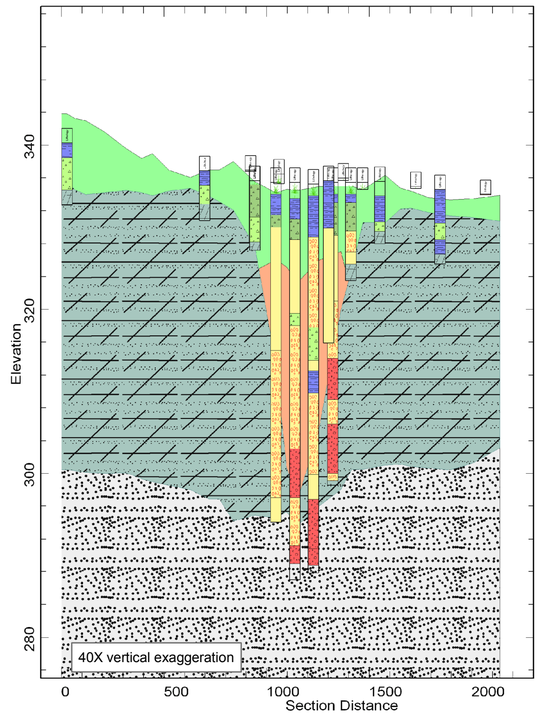
Figure 20. Geological cross-section along the Birch Channel..

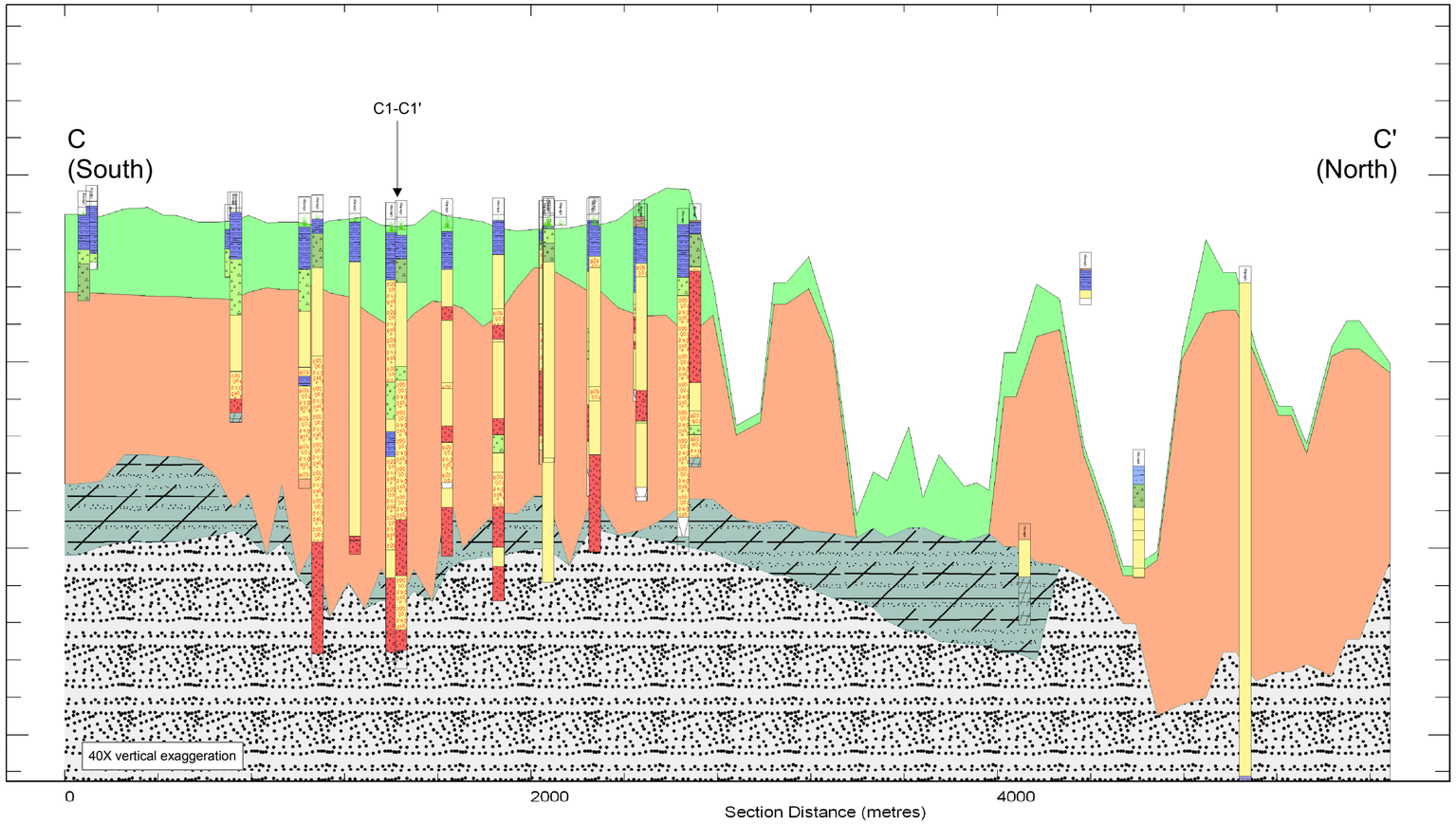
Cross-section C-C' along the North Spruce Channel

Location of channel cross-sections on the bedrock surface



Cross-section across North Spruce Channel





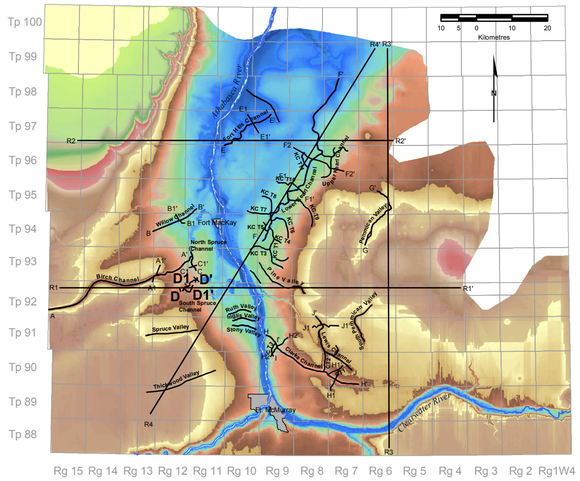
Legend

- Undifferentiated glacial sediment
- Sand, sand and gravel (aquifer)
- Clearwater Formation: shale, siltstone, sandstone
- McMurray Formation: sandstone, oil sand

Figure 23. Geological cross-section along the North Spruce Channel.

Cross-section D-D' along the South Spruce Channel

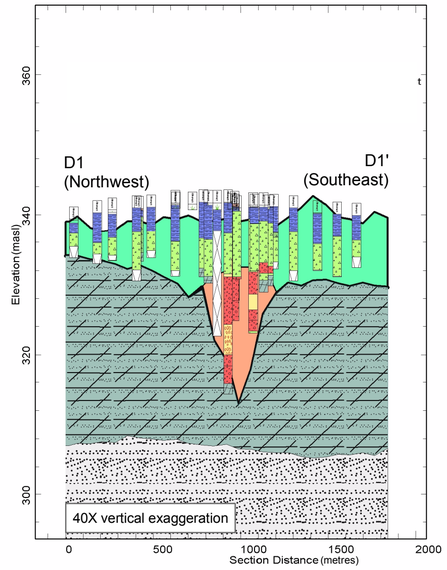
Location of channel cross-sections on the bedrock surface



Legend

- Undifferentiated glacial sediment
- Sand, sand and gravel (aquifer)
- Clearwater Formation: shale, siltstone, sandstone
- McMurray Formation: sandstone, oil sand

Cross-section across the South Spruce Channel



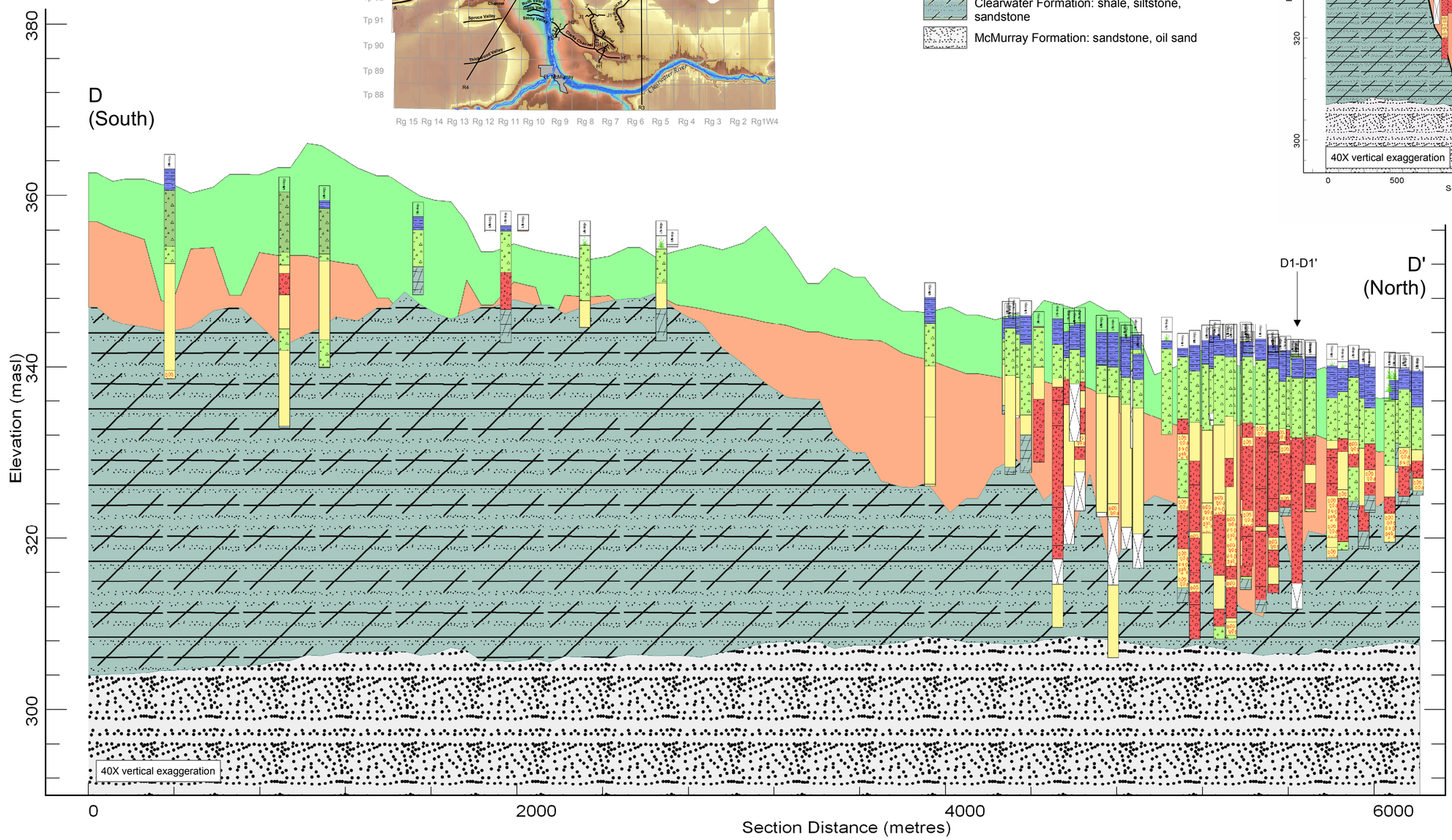
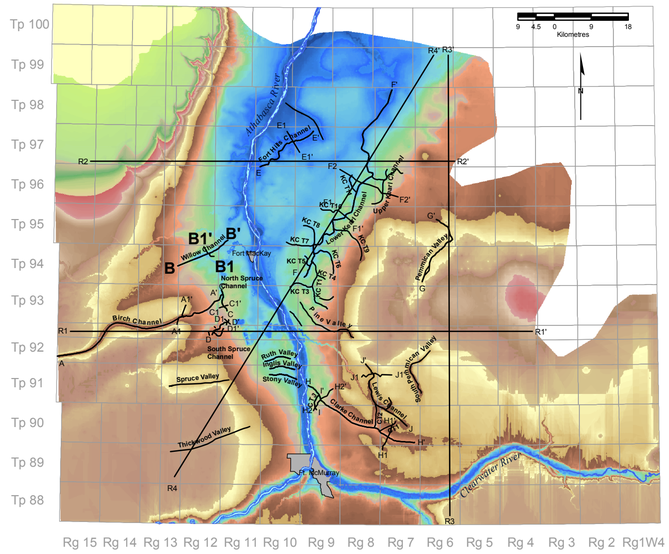


Figure 24. Geological cross-section along the South Spruce Channel.

Cross-section B-B' along the Willow Channel

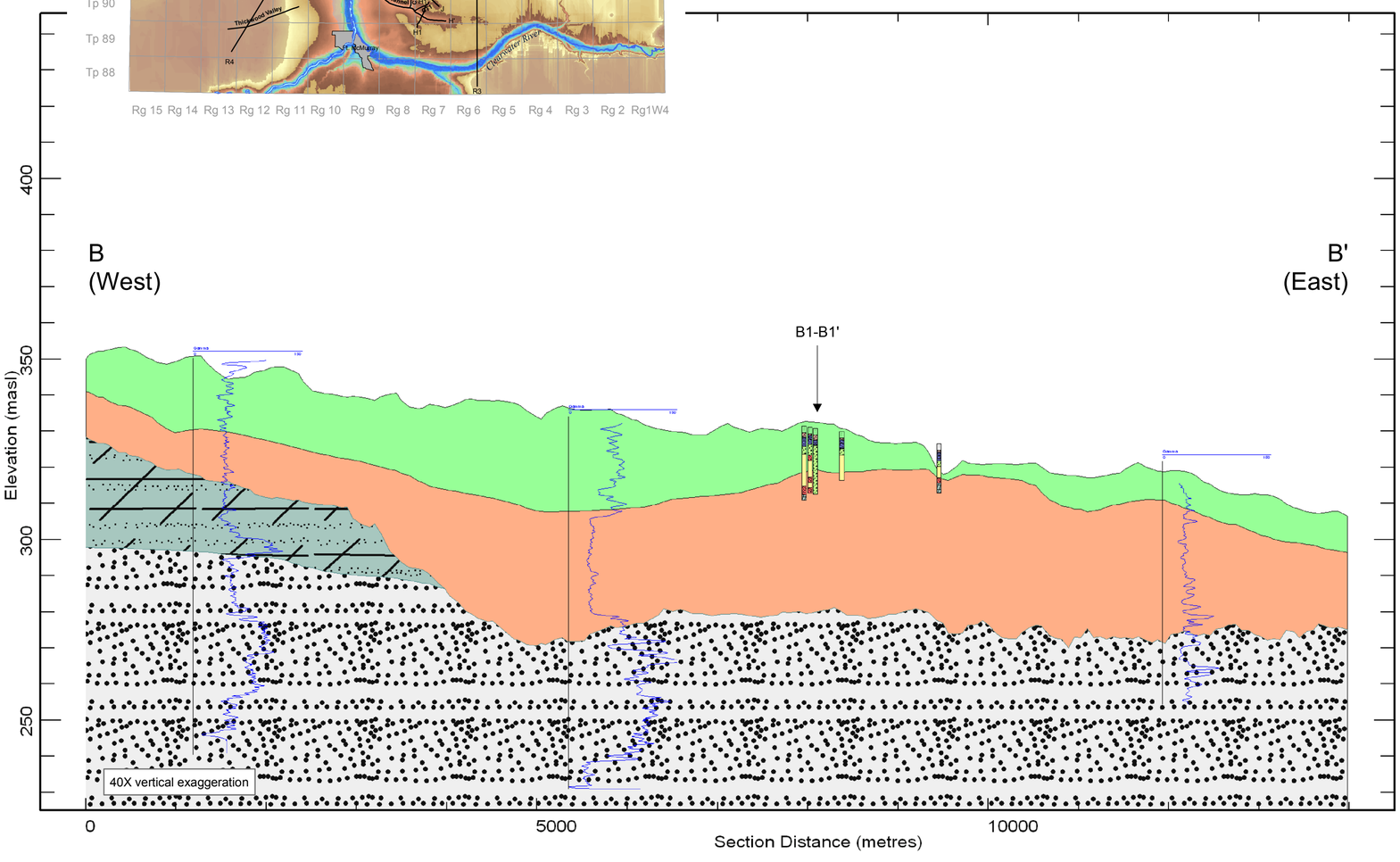
Location of channel cross-sections on the bedrock surface



Legend

- Undifferentiated glacial sediment
- Sand, sand and gravel (aquifer)
- Clearwater Formation: shale, siltstone, sandstone
- McMurray Formation: sandstone, oil sand

Gamma Log



Cross-section across the Willow Channel

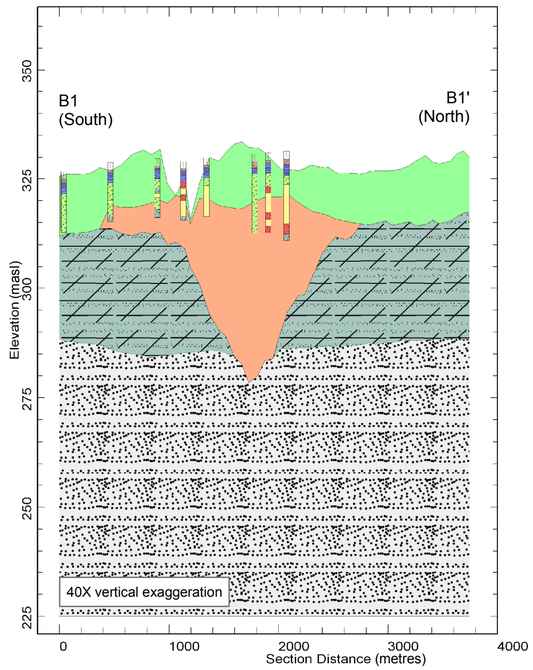


Figure 25. Geological cross-section along the Willow Channel.

Cross-section E-E' along the Fort Hills Channel

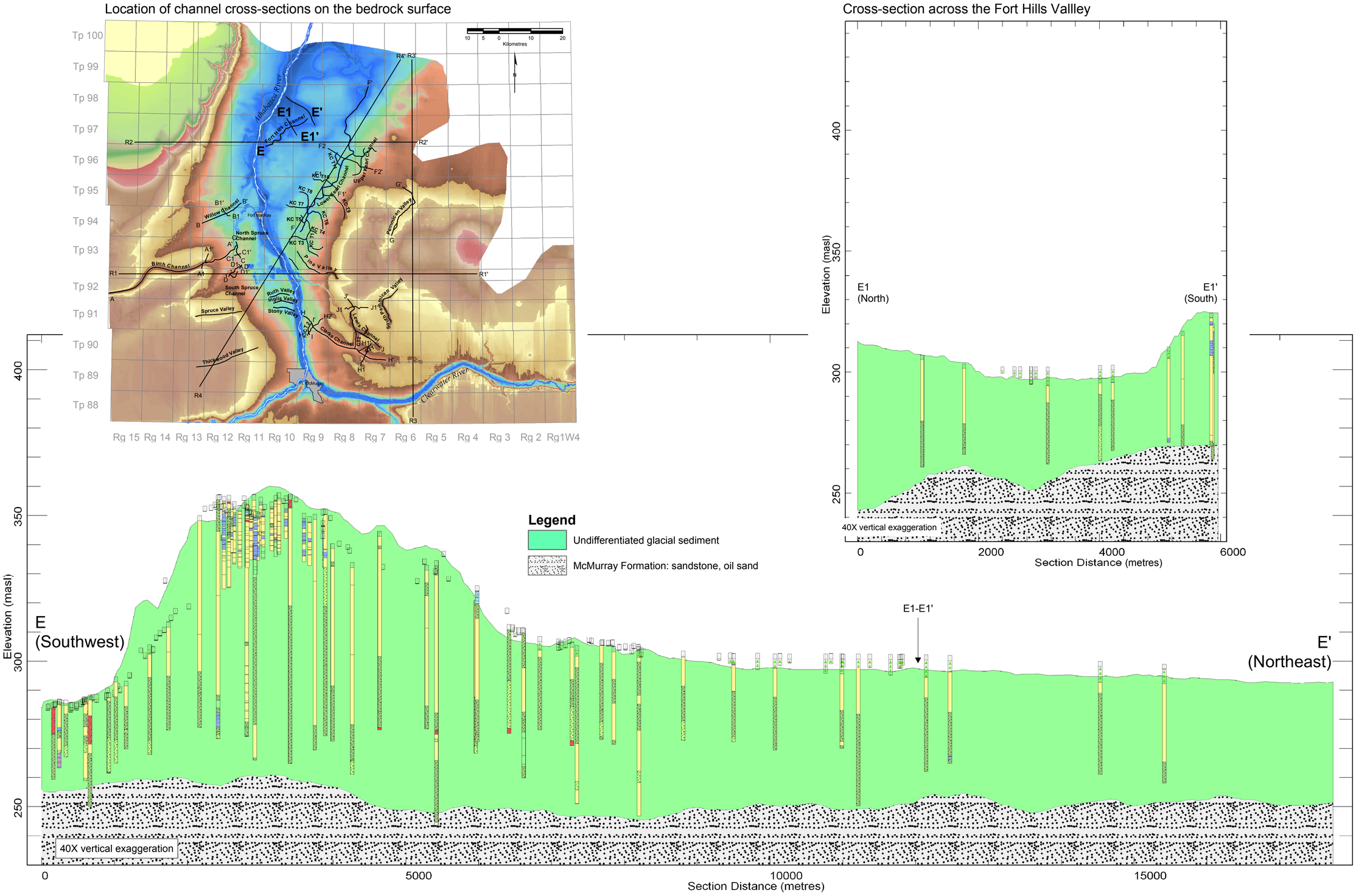
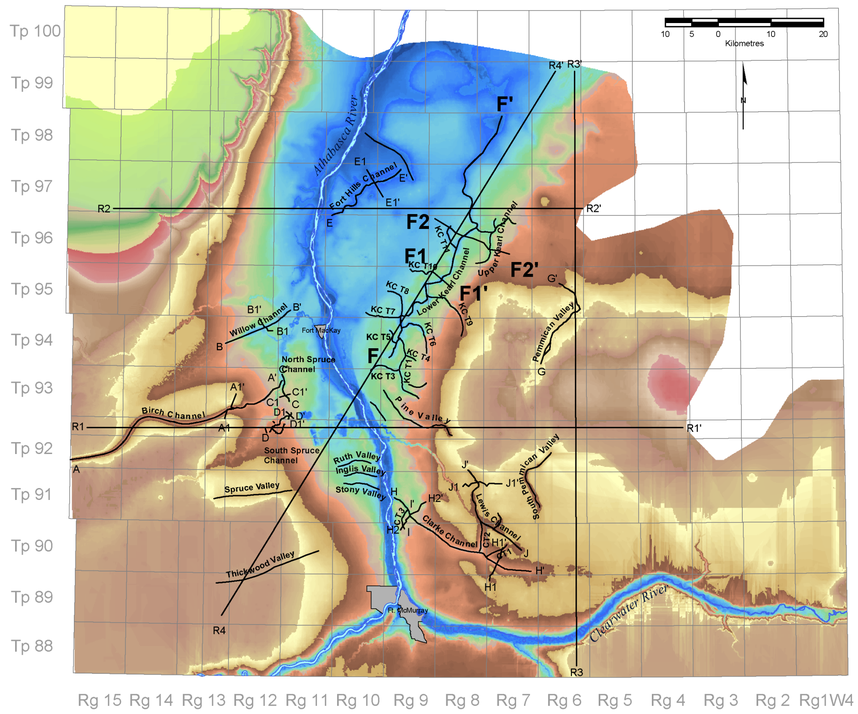


Figure 26. Geological cross-section along the Fort Hills Channel.

Cross-section F-F' along the Kearl Channel

Location of channel cross-sections on the bedrock surface

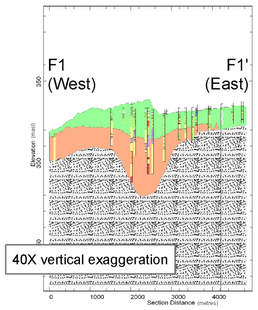


Legend

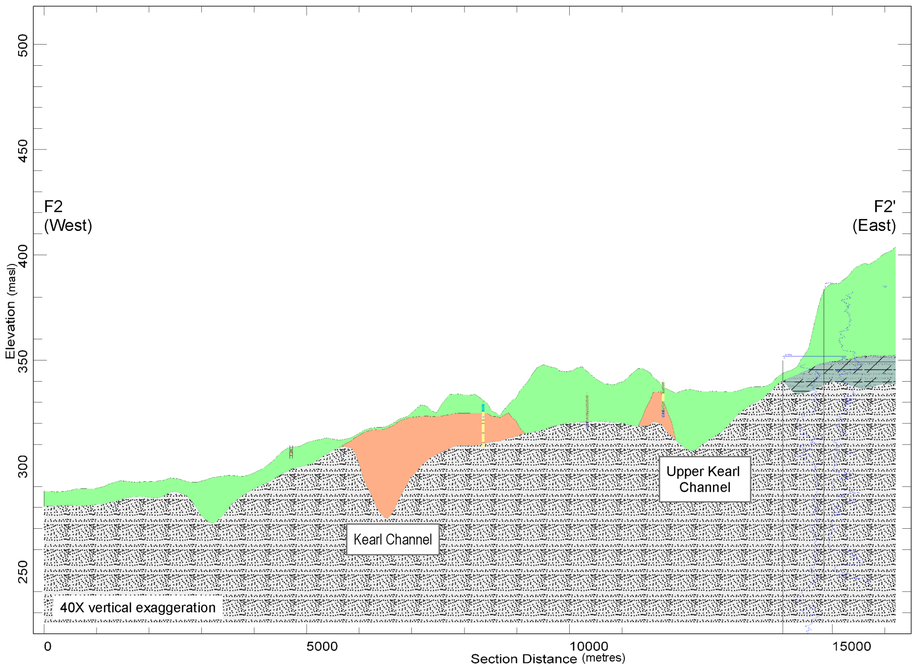
- Undifferentiated glacial sediment
- Sand, sand and gravel (aquifer)
- Clearwater Formation: shale, siltstone, sandstone
- McMurray Formation: sandstone, oil sand

Gamma Log

Cross-section F1-F1' across the Lower Kearl Channel



Cross-section F2-F2' across the Lower Kearl Channel



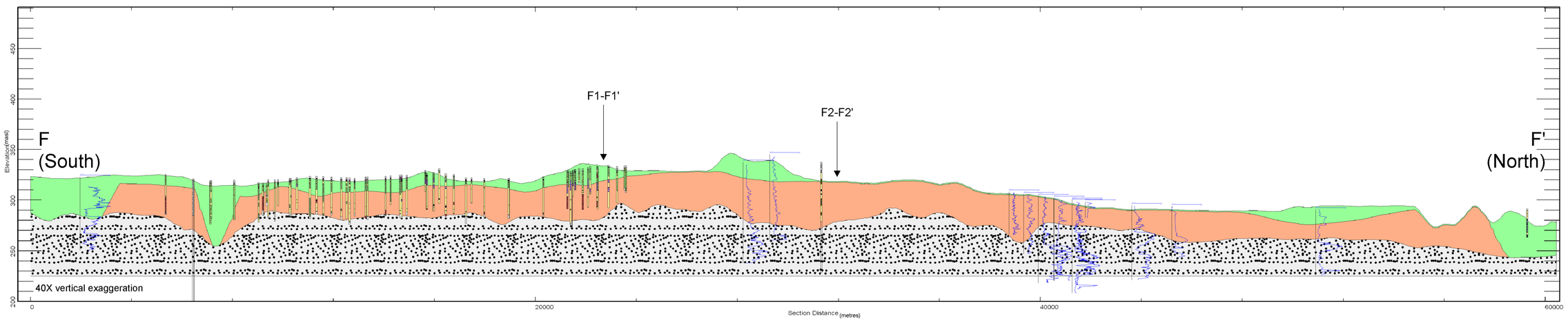
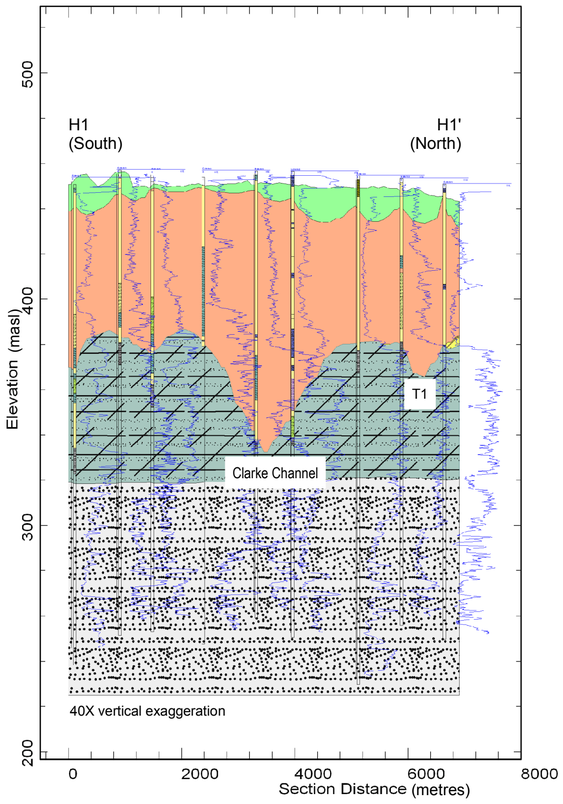


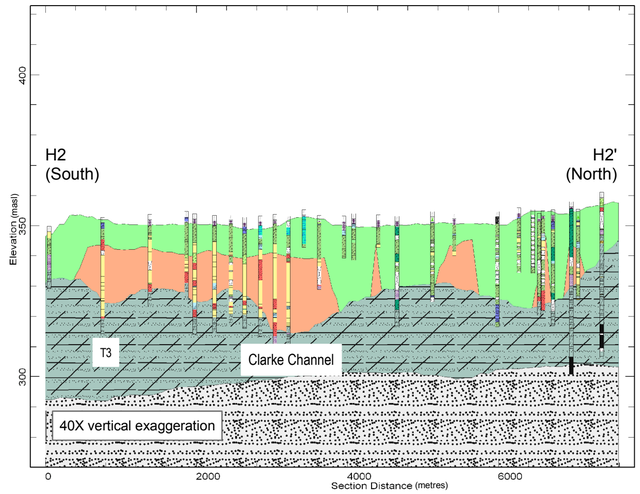
Figure 27. Geological cross-section along the Kearl Channel.

Cross-section H-H' along the Clarke Channel

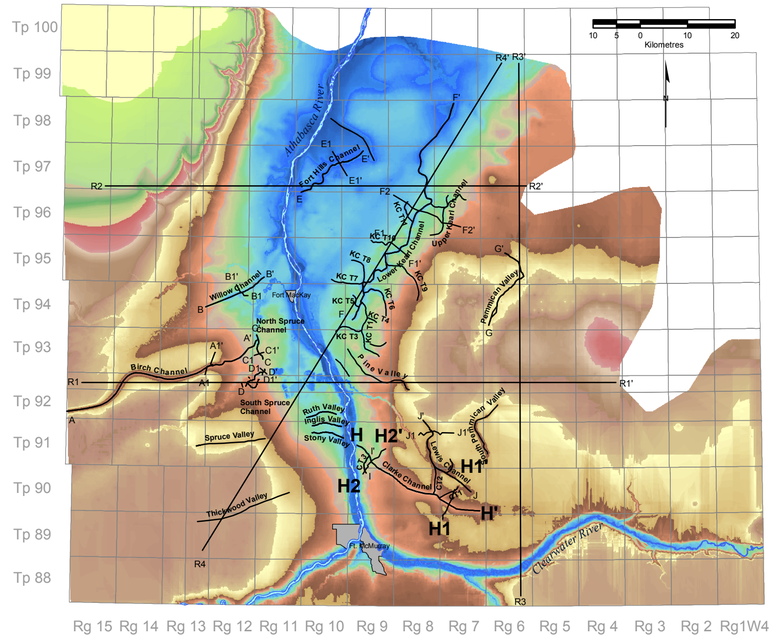
Cross-section H1-H1' across the Clarke Channel



Cross-section H2-H2' across the Clarke Channel



Location of channel cross-sections on the bedrock surface



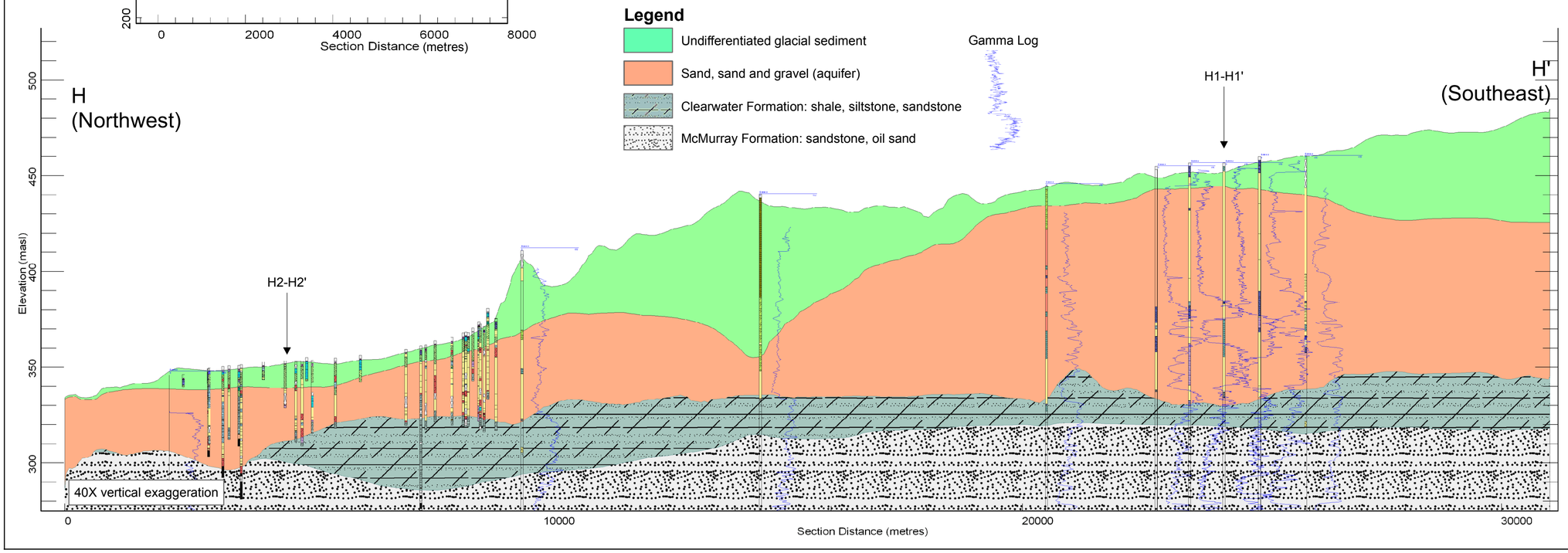
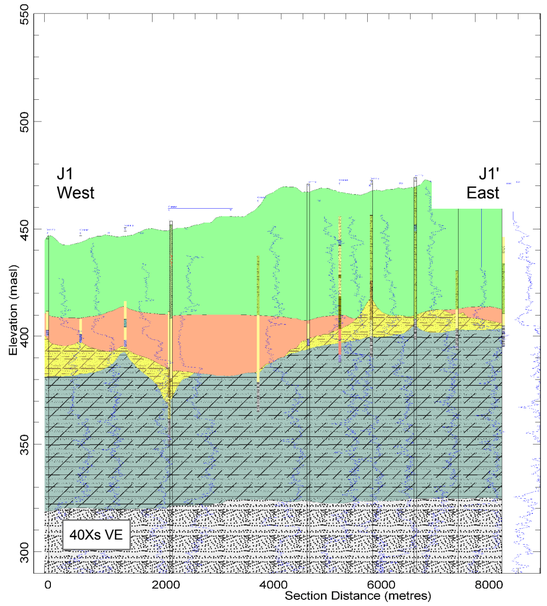


Figure 28. Geological cross-section along the Clarke Channel.

Cross-section J-J' along the Lewis Channel

Cross-section across the Lewis Channel

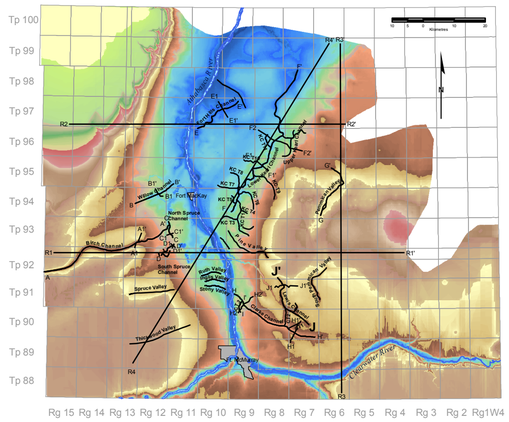


Legend

- Undifferentiated glacial sediment
- Sand, sand and gravel (aquifer)
- Grand Rapids Formation: Sandstone, siltstone, shale
  Note - In Birch Mountains area, this includes formations above the Grand Rapids Fm.
- Clearwater Formation: shale, siltstone, sandstone
- McMurray Formation: sandstone, oilsand

Gamma Log

Location of channel cross-sections on the bedrock surface



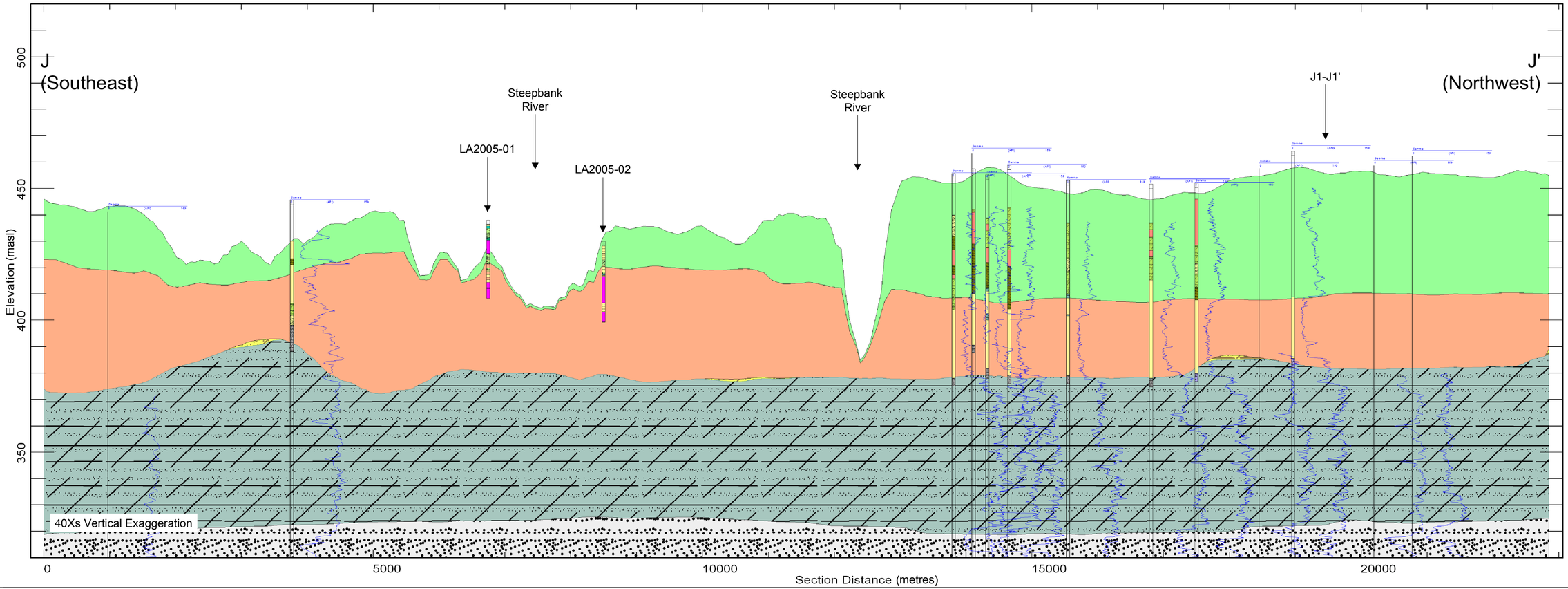


Figure 29. Geological cross-section along the Lewis Channel.