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Three-Dimensional Hydrostratigraphic Modelling of the Sylvan Lake Sub-Basin in the Edmonton-Calgary Corridor, Central Alberta

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Three-Dimensional Hydrostratigraphic Modelling of the Sylvan Lake Sub-Basin in the Edmonton-Calgary Corridor, Central Alberta

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Abstract

During a regional-scale groundwater study in central Alberta, a multilayer hydrostratigraphic model was constructed to represent the vertical and lateral distribution of depositional patterns that may affect groundwater flow. In the Edmonton-Calgary Corridor (ECC), the region with the fastest rates of urban and industrial growth in Alberta, hydrostratigraphic delineations provide a geological framework for the mapping and numerical modelling of groundwater flow and chemistry. Given the continued dependency on water across multiple sectors in the province, it is increasingly important for regulators of the *Water Act* to conduct comprehensive groundwater resource assessments. Due to the need to undertake more detailed studies for groundwater management, as well as the quantity of multisource geological and geophysical data within the 50 000 km^2 ECC area, the corridor has been partitioned into smaller, watershed-scale modelling domains. The first hydrostratigraphic modelling domain focuses on Neogene-Quaternary sediments and Upper Cretaceous−Paleogene bedrock units in the Medicine-Blindman sub-watershed (Environment Canada code 05CC) referred to in this report as the Sylvan Lake sub-basin (SLSB; ~5933 km^2). The SLSB was selected as a priority sub-basin due to the increasing pressure on water resources from unconventional resource development and municipal water supply for the Town of Sylvan Lake.

The hydrostratigraphic model of the SLSB shows the distribution of informal hydrostratigraphic units in the Paskapoo Formation and overlying Neogene-Quaternary succession and provides formal lithostratigraphic subdivisions for the bounding surfaces of the Paskapoo, Scollard, Battle, and Wapiti formations. The geological characterization of these units includes

1) compilation of existing continuous cores from Alberta Geological Survey investigations;
2) downhole geophysical logs and lithologs from the Alberta Water Well Information Database;
3) airborne resistivity surveys;
4) digital gamma-ray logs from oil and gas wells;
5) AGS stratigraphic picks made using raster and digital gamma-ray, density, sonic, and resistivity downhole logs from oil and gas wells; and
6) subsurface stratigraphic information from the Alberta Energy Regulator corporate database.

Structure elevation grids represent the bounding surface of each stratigraphic unit in the modelling domain interpolated using RockWorks15 and ArcMAP. Further internal characterization of the highly heterogeneous Paskapoo Formation is provided because it is a regionally significant bedrock aquifer in the study area. Slice mapping analysis was used to divide the formation into zones dominated by potentially permeable sandstone bodies using net-to-gross sandstone maps. All structure elevation tops as well as polygons delineating coarse-grained bodies in the Paskapoo Formation have been formatted for input into groundwater-flow models.

1 Introduction

Groundwater regulators in the province of Alberta have recognized the additional requirement of evaluating the cumulative effects of groundwater development. In order to enhance the current groundwater authorizations process and provide a mechanism for policy assurance, groundwater-flow modelling has been identified as a critical component, in addition to essential geological and hydrogeological mapping. Regulatory decisions are supported through improved groundwater characterization, which allows for the establishment of indicators and thresholds to assess groundwater availability. In an effort to advance groundwater management and deliver more geoscience information and knowledge to the Alberta Energy Regulator (AER) and Alberta Environment and Sustainable Resource Development (ESRD), the Alberta Geological Survey (AGS) established the Provincial Groundwater Inventory Program (PGIP). The AGS groundwater program involves a multiphase approach that starts with baseline investigations (geological and hydrogeological characterization) providing the geological framework and mapping the regional hydrology (Riddell et al., 2014) and hydrogeology. As a result, more-detailed hydrostratigraphic modelling is completed before constructing a groundwater-flow model, leading to a better understanding of the movement and connectivity of groundwater and surface water. This phased approach to groundwater resource assessment is currently underway in the Edmonton-Calgary Corridor (ECC; Figure 1), where significant population growth and associated development have increased the need for an inventory of groundwater resources.

The initial work of the PGIP was an investigation of the groundwater resources in the ECC as part of a groundwater atlas (Barker et al., 2011). The groundwater atlas provides geological and hydrogeological information for regional planners, regulators, policy-makers, and the public. However, as a result of highly discontinuous aquifer units, the complicated nature of the geology in the corridor, and the quantity of multisource geological and geophysical data, the area has yet to be modelled in three dimensions (3-D). Hence, the sub-basins were prioritized, and a series of smaller hydrostratigraphic models will be created over time (Figure 1). The first hydrostratigraphic model was created for the 5933 km^2 Medicine-Blindman sub-watershed (Environment Canada [EC] code 05CC; Water Survey of Canada, 2006), referred to in this report as the Sylvan Lake sub-basin (SLSB; Figure 2). The SLSB was the top priority due to the increasing demand on water resources from unconventional resource development and municipality needs for the Town of Sylvan Lake.

This report presents results of the geological characterization in the SLSB. The hydrostratigraphic model illustrates the Neogene-Quaternary deposits and shallow bedrock geology, which will contribute to the Geological Framework of Alberta (MacCormack, 2014), a regional 3-D geological model of Alberta, and the characterization of nonsaline groundwater resources (AER/AGS, 2014). Specific objectives of the hydrostratigraphic modelling include

1) classification of the hydrostratigraphic framework within the SLSB with special focus on coarse-grained deposits located in the Neogene-Quaternary succession above bedrock, as well as the geological heterogeneity that exists in the underlying Paskapoo Formation;
2) construction of a 3-D model consisting of 2.5-D structure tops of laterally extensive hydrostratigraphic units, which can be directly utilized in groundwater-flow models; and
3) most important, integration of this work into the AGS and provincial groundwater program to support the evaluation of the cumulative effects of current and future groundwater development.

2 Study Area

The SLSB is located in central Alberta, including parts of NTS map areas 82O, 82P, 83A, and 83B (Figure 1). This sub-basin is particularly important in the ECC as this is an area of increasing population

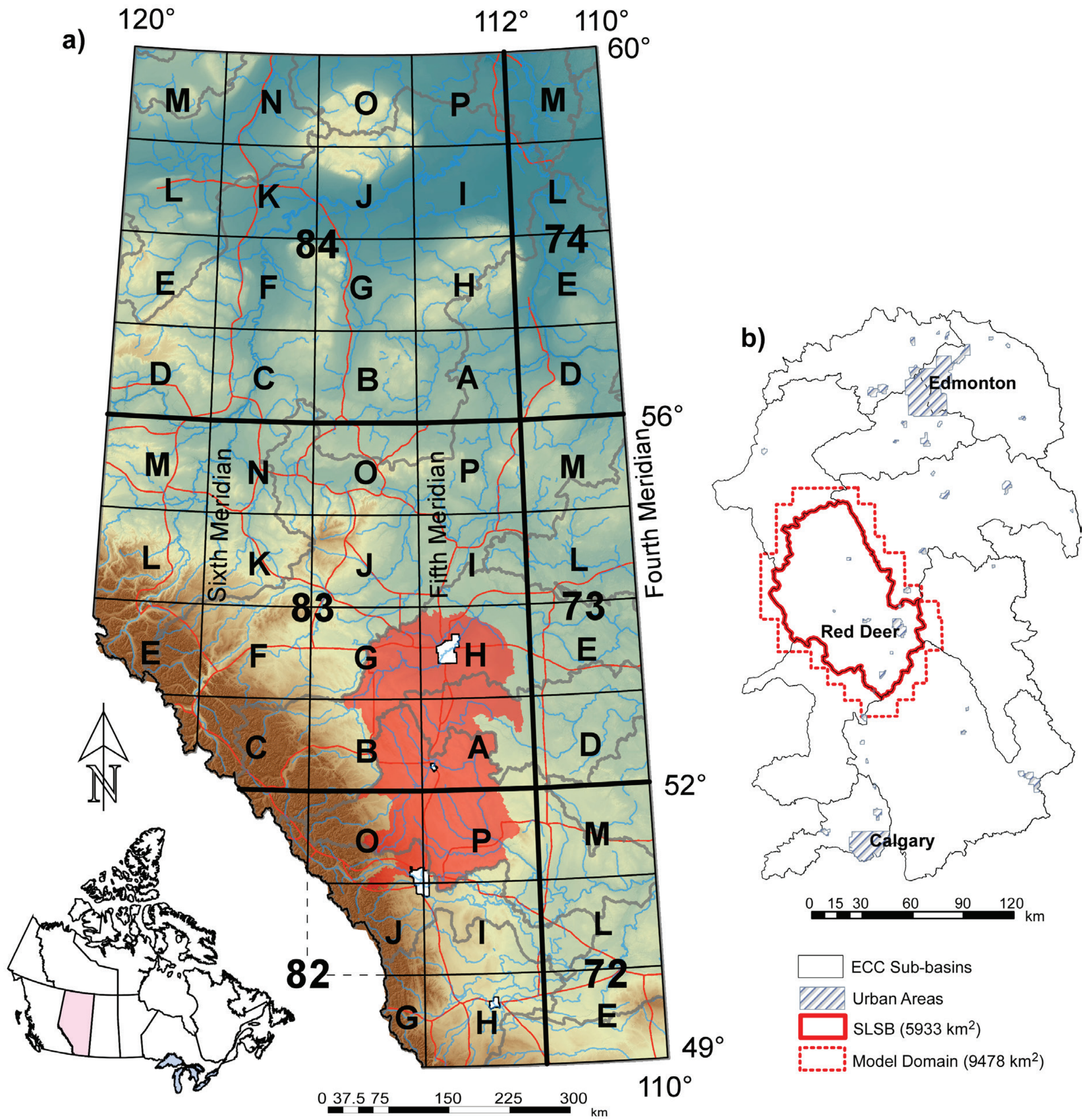

Figure 1. a) Map of Alberta showing the ECC study area highlighted in red. Surface topography (m asl), major rivers, watershed basins (outlined in grey), and highways in the province are also shown by red lines. b) Map of the ten watershed sub-basins, which define the extent of the ECC, as well as the location of the SLSB. A buffer of one DLS township (~10 km wide) was extended around the SLSB to prevent distortion of interpolations near the boundary, producing a 9478 km² modelling domain.

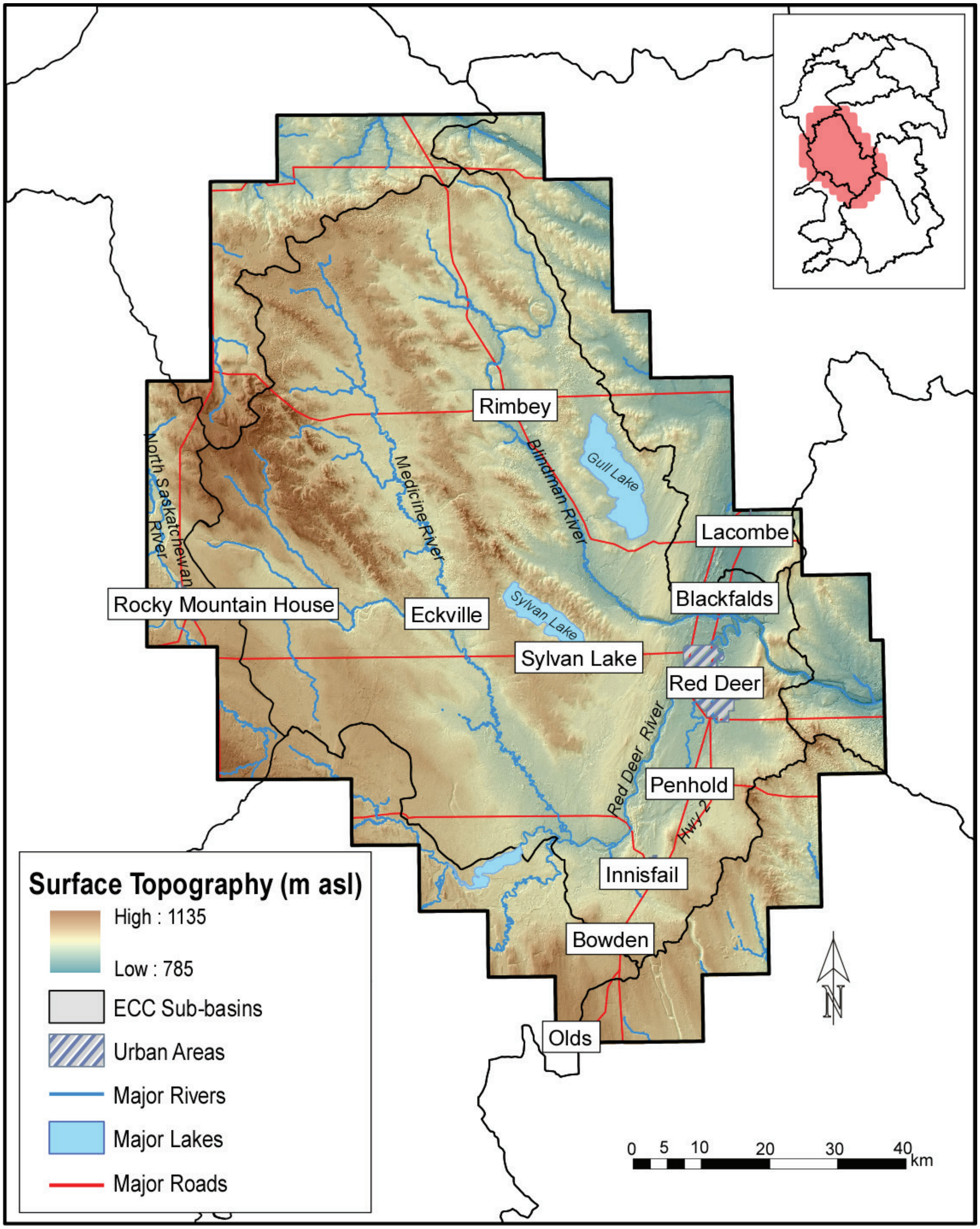

Figure 2. Map showing the land surface topography in the SLSB and adjacent townships. The study area is characterized by broad depressions and gentle slopes incised at its lowest part by the Red Deer River valley and bordered to the east and west by uplands.

growth (e.g., around the major population centre of Red Deer; Figure 2), abundant oil and gas activity, extraction of aggregate, as well as tourism around the two major lakes (i.e., Sylvan and Gull lakes; Figure 2). All these activities depend upon water resources and these resources are also relied upon by industrial, municipal, domestic, agricultural, and recreational water users. Due to its location within the Alberta Basin, the SLSB derives significant groundwater resources from near-surface bedrock units, as well as from overlying elongate bodies of coarse-grained Neogene-Quaternary sediments located at the base of buried valley systems. Targeted units for the sub-basin hydrostratigraphic modelling include shallow Upper Cretaceous–Paleogene strata, which encompass the base of groundwater protection (i.e., nonsaline water <4000 mg/L total dissolved solids; Lemay, 2009), as well as overlying sediments that constitute the aquifers for local-scale groundwater-flow systems and define the top of the hydrostratigraphic modelling domain.

2.1 Neogene-Quaternary Sedimentary Geology

In this part of Alberta, the bedrock surface is overlain by a heterogeneous cover of discontinuous Neogene-Quaternary sediments, which reach a maximum thickness of 130 m in the study area (Figure 3). This sedimentary succession is mainly composed of fluvial deposits (>2.6 million years before present), heterogeneous glacigenic materials deposited during the Late Wisconsinan (23–10 thousand years before present), and postglacial sediments (<10 ka). This succession contributes to the groundwater system because major paleovalley systems are incised into the Paskapoo Formation, a regionally significant bedrock aquifer complex (Figure 4 and Figure 5). At the base of the Red Deer paleovalley, sand and gravel overlie bedrock and underlie glacial and postglacial sediments. These basal sands and gravels form

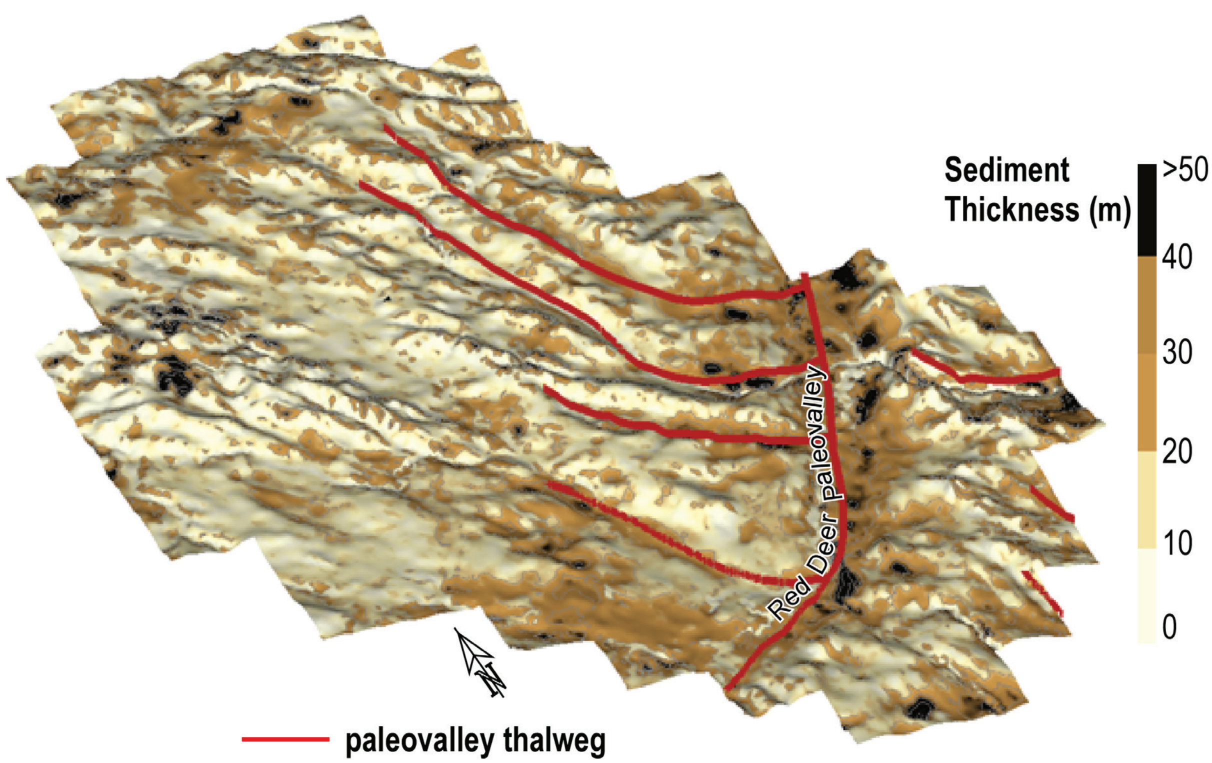

Figure 3. Sediment thickness in the study area, projected onto the 2.5-D bedrock topography grid (Atkinson and Lyster, 2010), along with the location of the Red Deer paleovalley.

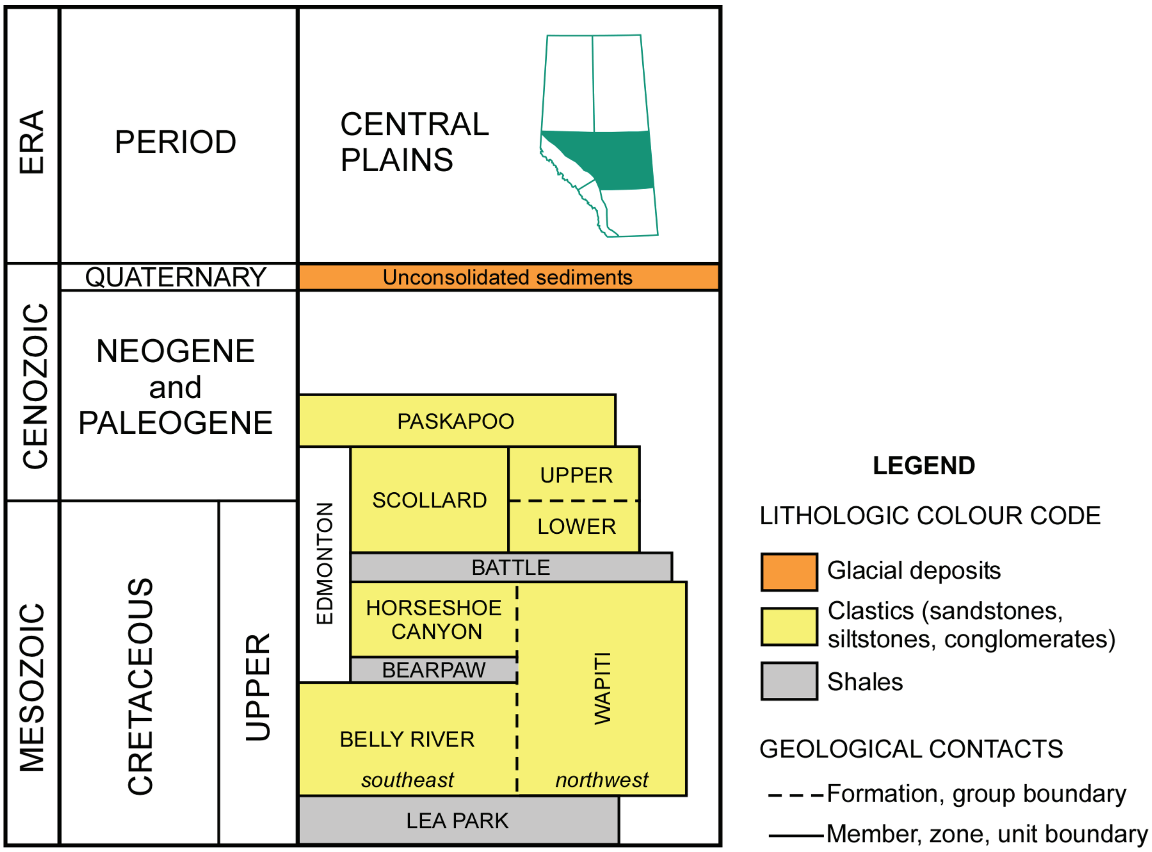

Figure 4. Stratigraphic column of the central Alberta plains (modified from Energy Resources Conservation Board, 2009).

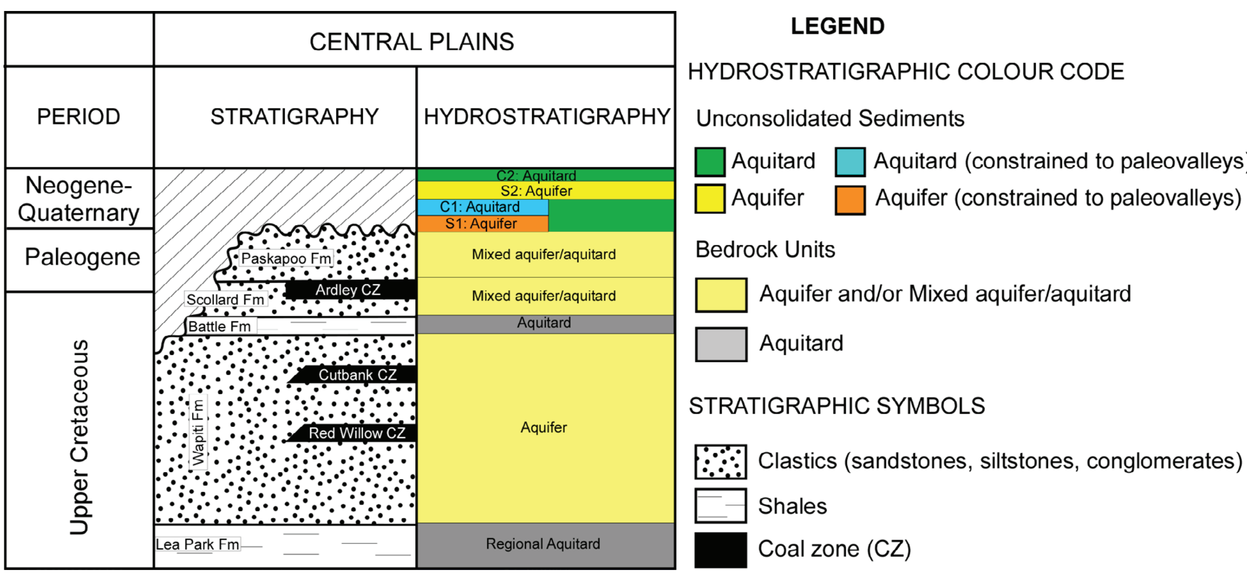

Figure 5. Stratigraphic and hydrostratigraphic units present in the study area. The classification of hydrostratigraphic units is based on texture of materials and emphasizes the delineation of bedrock and unconsolidated units into aquifer, aquitard, or mixed units (modified from Bachu and Michael, 2003).

part of the Empress Group, a preglacial unit constrained to paleovalleys and some adjacent terraces (e.g., Stalker, 1968; Whitaker and Christiansen, 1972; Proudfoot, 1985; Evans and Campbell, 1995), and are informally named in this report as the Red Deer basal aquifer. Sediments infilling and overlying buried valleys and adjacent terraces predominantly include glaciolacustrine-lacustrine materials; a range of diamictons, including till (a wide range of grain size); and glaciofluvial- fluvial sediments. Collectively, this succession exhibits an assortment of hydraulic properties that influence the nature of groundwater flow. A conceptual hydrostratigraphy for these unconsolidated units is outlined in Section 3.1.1.

2.2 Upper Cretaceous−Paleogene Bedrock Geology

Upper Cretaceous−Paleogene strata represented in the hydrostratigraphic model include (from oldest to youngest) the Wapiti, Battle, Scollard, and Paskapoo formations (Figure 4 and Figure 5). The base of the Wapiti Formation is defined by the top of the Lea Park Formation, a widespread fine-grained unit deposited during a Late Cretaceous marine transgression (Dawson et al., 1994). The Lea Park Formation was chosen as the base of the modelling domain as it acts as a regional confining unit suitable as a no-flow boundary in a groundwater-flow model (Michael and Bachu, 2001).

Directly overlying the Lea Park Formation is the Wapiti Formation. This formation consists of interbedded sandstone and siltstone with minor mudstone and coal deposited in a mainly fluvial environment, with local areas of lacustrine influence (Dawson et al., 1994; Fanti and Catuneanu, 2009). In the central and southern Alberta plains, units approximately time-equivalent to the Wapiti Formation include, from oldest to youngest, the Belly River Group, Bearpaw Formation, and Horseshoe Canyon Formation (Figure 4). The Belly River Group and Horseshoe Canyon Formation, both nonmarine to marginal-marine heterolithic clastic successions containing sandstone, siltstone, mudstone, and coal, are separated by the Bearpaw Formation, a marine mudstone-dominated unit. Where the Bearpaw Formation is absent, the Horseshoe Canyon Formation and Belly River Group cannot be differentiated and collectively comprise the Wapiti Formation (Figure 4). The Wapiti Formation has not been subdivided in the SLSB, as the Bearpaw Formation is absent due to nondeposition.

Directly overlying the Wapiti Formation is the Upper Cretaceous mudstone-dominated Battle Formation. This unit was deposited in a sediment-starved lacustrine environment, and has an average thickness of 10 m in the SLSB (Dawson et al., 1994; Hathway, 2011a). Where present the Battle Formation acts as a regional confining layer (Figure 5) due to its fine-grained lithology. However, a series of paleovalley systems are incised into and locally through the Battle Formation (Hathway, 2011a). In the Red Deer-Drumheller region these paleovalleys trend southeast, can be up to 10 km wide, and are infilled with sandy fluvial deposits of the overlying Scollard Formation.

The Scollard Formation is divided into two members. The Paleogene upper member contains thick, economically important coal seams (i.e., Ardley coal zone; Figure 4 and Figure 5), while the Upper Cretaceous lower member lacks coal. The Scollard Formation is an eastward-thinning wedge of nonmarine fluvial sediments. It generally consists of thick grey to buff sandstone and siltstone units interbedded with thin, olive-green mudstone beds and coal (Dawson et al., 1994). The lower part is dominated by coarse-grained clastic rocks, whereas the upper part is generally finer grained (Hamblin and Lee, 1997). Regionally, the Scollard Formation acts as an aquitard (Figure 5), although due to its heterogeneous nature it may act locally as an aquifer, especially where it includes permeable sandstone and coal units (Parks and Andriashek, 2009).

Overlying the Scollard Formation is the Paskapoo Formation, which is considered to be the most significant source of groundwater in the Canadian Prairies (Figure 5; Grasby et al., 2008a). The contact between the Scollard and Paskapoo formations is defined by the base of the lowest major sandstone interval situated above the Ardley coal zone (Gibson, 1977; Dawson et al., 1994; Figure 5). The Paskapoo Formation consists of an eastward-thinning succession of Paleogene nonmarine clastic sedimentary rocks—an erosional remnant of a much thicker clastic wedge deposited during and after the late stages of folding and thrusting within the adjacent Rocky Mountain Fold and Thrust Belt (Mack and Jerzykiewicz, 1989). This formation either outcrops or subcrops beneath the Neogene-Quaternary sediments over most of the study area northwest of the Red Deer River valley, westwards to the disturbed belt (Demchuk and Hills, 1991; Prior et al., 2013). The Paskapoo Formation is characterized by stacked, multistorey channel sandstone bodies that locally coalesce to form semicontinuous sandstone sheets, particularly near the base of the formation. The channel sandstones are encased in siltstone or mudstone.

3 Methodology

3.1 Hydrostratigraphic Framework and Data Input

3.1.1 Hydrostratigraphic Assignments in Unconsolidated Units

The hydrostratigraphy of sediments in the SLSB modelling domain was analyzed from a variety of datasets because no conceptual stratigraphic or hydrostratigraphic framework was available prior to this modelling effort. Simplifications of the Neogene-Quaternary succession were made to establish the vertical sequence of four hydrostratigraphic units (HSUs) above bedrock (Figure 6). Table 1 outlines the four hydrostratigraphic units assigned to the unconsolidated portion of the modelling domain. These hydrostratigraphic units have been arbitrarily named (i.e., C2, S2, C1, and S1; Table 1) and do not reflect the naming of specific groups, formations, or members; further high-quality information would be needed to facilitate formal stratigraphic nomenclature.

A primary dataset consisting of a variety of low-, moderate-, and high-quality data was compiled to model the four hydrostratigraphic units in the Neogene-Quaternary succession (Table 1). Continuous cores collected as part of an AGS drilling program in 2008 provided the most reliable data in the near-surface sediments (Table 2; Figure 7; Riddell et al., 2009). These continuous cores also provided a visual comparison between high-quality gamma-ray and resistivity geophysical logs collected by AGS and the 139 moderate-quality geophysical logs completed in the Neogene-Quaternary succession by water well

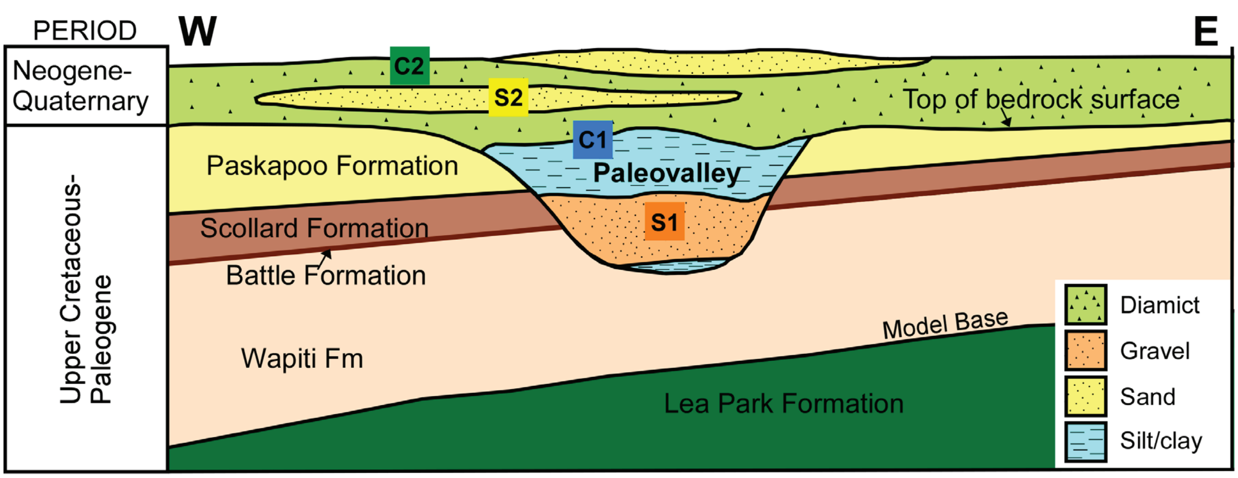

Figure 6. Schematic of the geological units present in the SLSB, as well as the vertical succession of conceptual hydrostratigraphic units identified within the Neogene-Quaternary units (modified from Slattery and Andriashek, 2012). Units are not to scale.

Table 1. Description of the hydrostratigraphic units of the Neogene-Quaternary succession.

Hydrostratigraphic Unit	Lithology	Criteria
C2	Clay, silt, or diamicton	Fine-grained unit composed of till blankets and stagnation moraines, lacustrine to glaciolacustrine sediments, as well as diamicton; found in upland areas and discontinuously overlies buried valleys; represents the majority of fine-grained materials in the study area.
S2	Sand to sand and gravel, silty sand	Coarse-grained unit composed primarily of fluvial to glaciofluvial sediments; found in upland areas and discontinuously overlies buried valleys, as intradrift sand or terraces adjacent to and underlying present-day streams, rivers, and lakes.
C1	Clay, silt, or diamicton	Fine-grained unit underlying coarse-grained sediments of S2; found in upland areas and discontinuously overlies buried valleys; this unit is closely related to C2 and may only differentiate lower bounding surfaces separating S2.
S1	Basal sand and gravel, silty sand	Red Deer basal aquifer composed of well- to poorly-sorted sand and gravel constrained to paleovalleys; this unit directly overlies bedrock and is covered by fine-grained sediment of C1.

Table 2. Model input data.

Data Type	Dataset	Comments
Borehole Reports	AGS continuous cores (Riddell et al., 2009)	High-quality information collected as a part of a drilling program in the ECC, including high-quality lithological, downhole geophysical, permeability, and thermal-conductivity data. These cores aided in extending hydrostratigraphic interpretations to sediments encountered in lower quality data.
	Water well lithologs (Alberta Environment and Sustainable Resource Development, 2013)	Drilling reports submitted by water well drilling contractors to the Alberta Water Well Information Databas (AWWID). Data considered low quality due to location inaccuracies and lithological ambiguities; however, water well data were a key component of the modelling process as the extensive data coverage across the sub-basin aided in identifying major aquifer/aquitard trends in sediments.
	AGS geologist bedrock stratigraphic picks	Digital and raster geophysical logs, including gamma-ray, density, sonic, and resistivity logs from oil and gas wells. These data were the primary data source in making subsurface stratigraphic picks in Alberta. These data are used in the Geological Framework of Alberta to interpolate 2.5-D grids for stratigraphic bedrock surfaces.
	AER corporate database	Bedrock stratigraphic picks used in the Geological Framework of Alberta.
Geophysical Data	Downhole geophysical logs (water wells)	Drilling records for water wells intermittently include geophysical logs and are categorized as moderate quality due to survey land location inaccuracies and the fact that geophysical tools can vary between contractors. These geophysical logs proved to be very useful as a visual estimate of fine- or coarse-grained materials in sediments.
	Oil and gas geophysical logs (Alberta Energy and Utilities Board, 2006)	High-quality digital gamma-ray logs collected after November 1, 2006, from oil and gas operations available to within 20 m of surface were used exclusively in the characterization of the internal slicing of the Paskapoo Formation.
	Airborne resistivity surveys (Slattery and Andriashek, 2012)	Extensive airborne resistivity surveys completed over the ECC show the distribution of the physical properties of sediments. These surveys provided a first-order visualization of coarse-grained materials that may represent major aquifer units located in the Neogene-Quaternary succession and near-surface bedrock units.
Gridded Surfaces	Digital Elevation Model (DEM)	DEM (25 m cell-size resolution) provided land surface topography (Figure 2) and elevation for borehole data.
	Bedrock Topography of Alberta (Atkinson and Lyster, 2010)	AGS Map 550 (Figure 3) used to constrain the lowest elevation of HSUs in the Neogene-Quaternary succession and the highest elevation of the stratigraphic bedrock units.
	Stratigraphic bedrock surfaces (i.e., Paskapoo-Lea Park formations)	Bedrock units included in the model were constructed for the Geological Framework of Alberta and clipped to the SLSB model domain.

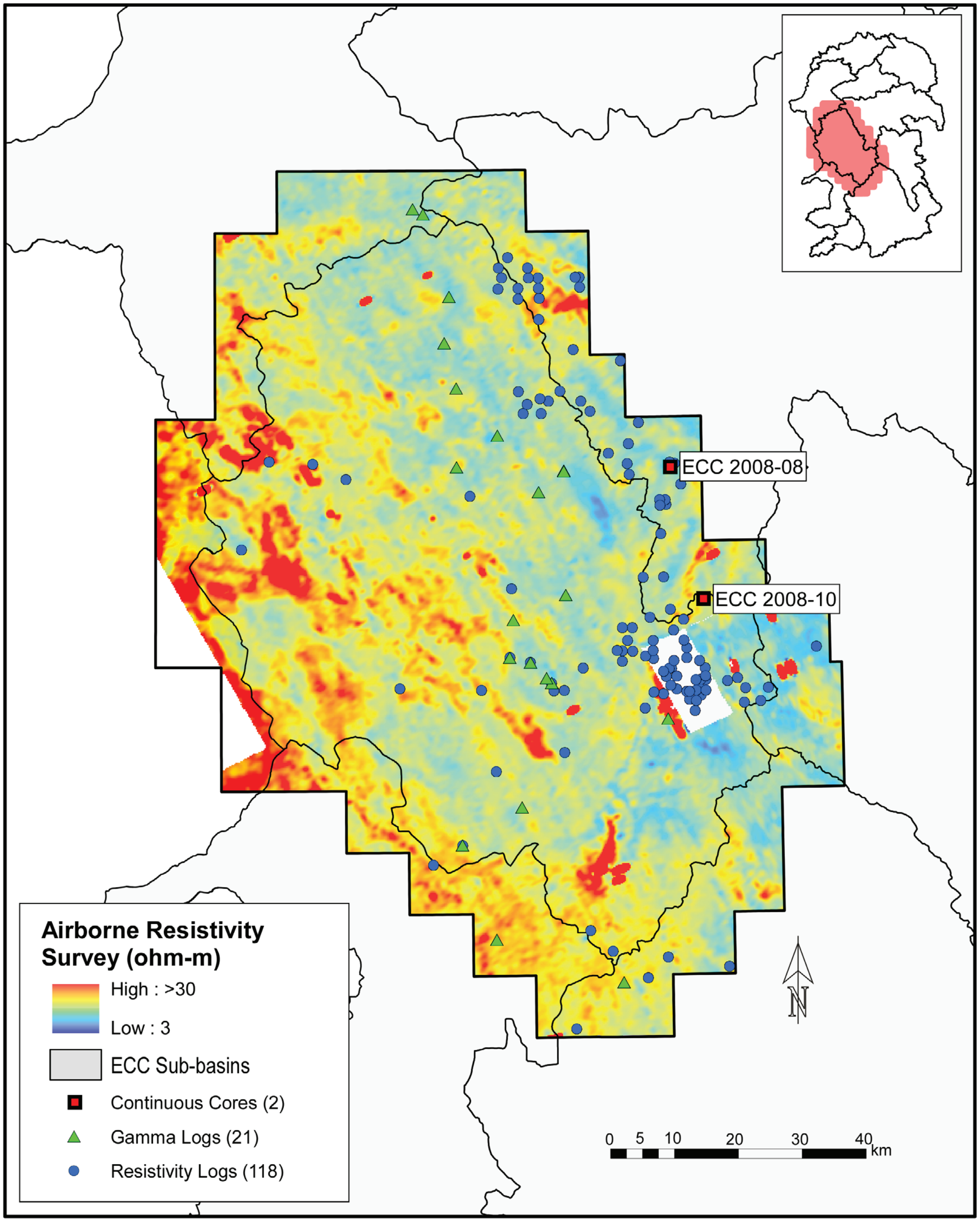

Figure 7. Distribution of moderate- to high-quality data points, as well as the 10 m depth slice of the airborne resistivity survey used to help develop the hydrostratigraphic architecture of the Neogene-Quaternary succession.

drilling contractors in the study area. Data from a total of 10 338 water wells provided by the Alberta Water Well Information Database (AWWID) were used in the study. These data were considered lower quality data because there are potential errors resulting from inaccuracies in location and lithological nomenclature submitted by water well drilling contractors. Historically, wells were typically located to the centroid of a quarter section, resulting in a possible 1 to ~10 wells being colocated with the same geographic coordinates. One well per geographic coordinate was selected to reduce the total number of water wells located in the same position. For each of the selected water wells, a litholog was available providing a description of materials encountered during the drilling process. Submitted reports typically include variable lithological descriptions, which were classified into 25 standardized material codes (Slattery et al., 2011) and subsequently used to broadly define hydrostratigraphic units (Table 1). Previously published information was also included to facilitate assignments of hydrostratigraphic units to point data, including selected thematic geological and hydrogeological maps—for example, airborne resistivity (Figure 7), sediment thickness, permeability of sediments above bedrock, regional recharge and discharge areas, existing well locations and depths, and major aquifers and buried valleys (Barker et al., 2011). All datasets were then imported into Paradigm's Subsurface Knowledge Unified Approach (SKUA) software in order to assign hydrostratigraphic codes to the borehole point data using 150 geological cross-sections. The hydrostratigraphic assignments identify the upper elevation of a given hydrostratigraphic unit (Table 1; Figures 8a and b).

3.1.2 Bedrock Formation Picks

To provide a simplified and accurate depiction of the Upper Cretaceous−Paleogene bedrock units (outlined in Section 2.2), strata were separated on the basis of lithostratigraphic assignments that partitioned sediments into genetically related packages. Bedrock stratigraphic picks (Figure 8c; Table 2) outlining the elevation of a unit as encountered in a borehole were taken from published (Hathway, 2011b) and unpublished high-quality AGS geologist stratigraphic picks and the AER corporate database. For this report, the Scollard, Battle, and Wapiti formations were delineated using their respective bounding surfaces, with no further characterization of internal lateral and vertical variations within those lithostratigraphic units. The bounding surfaces of the near-surface Paskapoo Formation were also derived in this manner; however, further internal characterization of the formation was necessary to satisfy the needs of subsequent groundwater-flow models.

3.1.3 Log Normalization and Slice Mapping in the Paskapoo Formation

Special focus was directed towards lithological heterogeneity in the Paskapoo Formation, as previous studies show that, at a regional scale, the formation is a highly heterogeneous aquifer system with transmissivity values ranging from 10^{-1} to 10^{-14} m^2/s (Chen et al., 2007). A three-fold formal lithostratigraphic subdivision of the Paskapoo Formation has been proposed (Demchuk and Hills, 1991), which includes a lower member dominated by amalgamated, multistorey channel-fill sandstone (Haynes Member); a middle member dominated by siltstone and mudstone with lesser sandstone (Lacombe Member); and an upper member with interbedded sandstone, siltstone, mudstone, and shale (Dalehurst Member). Considering this model, characterization of net-to-gross sandstone distribution (i.e., where net is the total amount of sandstone divided by the gross or total thickness of the chosen interval) within the Paskapoo Formation was undertaken to model these three discrete slices and zonate potential high permeability sandstone-rich areas to represent the highly discontinuous single and multistorey sandstone bodies that occur within the formation (cf. Lyster and Andriashek, 2012).

Slice mapping analysis of the Paskapoo Formation used available digital downhole gamma-ray logs from oil and gas wells. Prior to November 1, 2006, boreholes were not required to be logged to surface, and the geophysical logs would generally only extend to the base of surface casing (Alberta Energy and

Utilities Board, 2006). In the SLSB, however, 2507 new wells have been drilled since November 1, 2006. Of these wells, the authors had access to 951 wells that have digital gamma-ray log coverage to within 20 m of surface. Normalization of the digital gamma-ray logs collected through casing was necessary in an attempt to remove the effects of logging through surface casing (for methodology, see Quartero et al., 2014). Once gamma-ray logs in cased and uncased borehole segments were normalized separately, and anomalous points were removed (i.e., incomplete gamma-ray log coverage in a borehole), the gamma-ray logs were merged into a single normalized gamma-ray log. An additional 3270 available wells with digital gamma-ray logs (that were not logged to surface but had coverage within the zone of interest) were also normalized. A total of 4221 wells with gamma-ray logs were normalized in the SLSB.

A gamma-ray cut-off of ≤80 API was used to establish the spatial extent of coarse-grained sediments. This was chosen because a lower cut-off of ≤75 API missed some of the amalgamated channel-fill sandstones. The ≤80 API cut-off appeared to be the best compromise in calculating the net sandstone in a slice without including the finer grained overbank deposits. Applying this API cut-off, the normalized and merged digital gamma-ray logs were used to evaluate the Paskapoo Formation in the SLSB and establish the spatial extent of coarse-grained sediments.

3.2 Grid Interpolation and Model Creation

A multilayer hydrostratigraphic model was constructed using a 400 m cell-size grid for each 2.5-D bounding surface. Each component of the model (i.e., hydrostratigraphic assignments in the unconsolidated units, bedrock stratigraphic units, and slice mapping in the Paskapoo Formation) was modelled using different methodologies to define the structure elevation of a unit top and base. All 2.5-D model components were used to form a 3-D cellular grid to represent the hydrostratigraphic architecture of the SLSB (Figures 8b and d).

Different methodologies were used to create the component parts of the full 3-D model, as different input data were used to classify unconsolidated materials in the Neogene-Quaternary succession and the Upper Cretaceous−Paleogene bedrock units. The 2.5-D grids modelled in the Neogene-Quaternary succession used borehole point data coded for each hydrostratigraphic unit (Section 3.1.1; Figure 8a), which were interpolated using the inverse distance weighting (IDW^2) function of RockWorks15, with a minimum search radius of 16 points to create the model shown in Figure 8b. The bedrock topography grid (shown in Figure 2; Figures 8b and d) was used as an interface for including the underlying Upper Cretaceous–Paleogene bedrock units into the SLSB model. Each 2.5-D bedrock unit was interpolated separately and modelled across its provincial extent, as part of the Geological Framework of Alberta, using ordinary kriging in ArcMAP and clipped to the SLSB model domain (Figure 8c). As the full 3-D model was built in RockWorks15, each clipped bedrock unit taken from the Geological Framework of Alberta was re-interpolated in RockWorks15 at a 400 m cell size using the closest point whereby a grid node is set equal to the value of the nearest data point (Figure 8d). Once all unconsolidated units, bedrock units, and the middle and lower slices in the Paskapoo Formation (Section 3.2.1) were imported into RockWorks15, the model was built from the bottom upwards. Limited manual manipulation of grids was performed, with the exception of truncating all units below the land surface (i.e., DEM; Table 2), constraining all bedrock units to the top of the Paskapoo Formation (i.e., the bedrock topography) when unit elevations exceeded this surface, and clipping grids where units are known not to exist (e.g., lakes and paleovalleys that incise into regional surfaces).

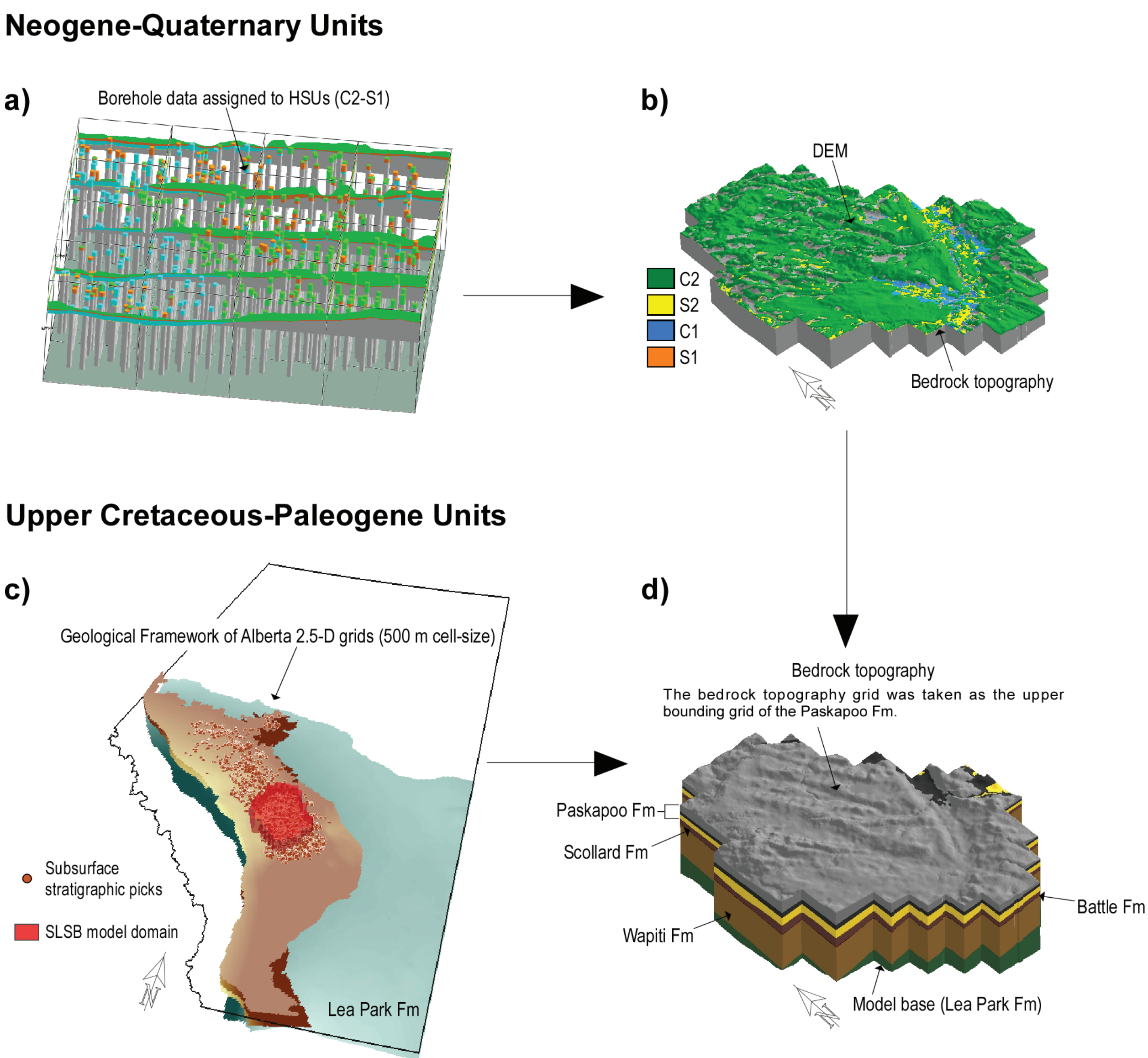

Figure 8. a) Fence diagram and borehole data penetrating the unconsolidated succession of a section of the SLSB model domain. The borehole point data were coded with hydrostratigraphic assignments and interpolated to create the 3-D model shown in (b). b) 3-D hydrostratigraphic model of the unconsolidated succession. c) Map showing the 2.5-D gridded Upper Cretaceous−Paleogene bedrock units modelled as part of the Geological Framework of Alberta. Each bedrock unit was clipped to the SLSB model domain and integrated into (d). d) 3-D model of the Upper Cretaceous−Paleogene units in the SLSB.

3.2.1 Integration of Slice Map Analysis

An analysis of rock properties using downhole gamma-ray logs was undertaken to subdivide the Paskapoo Formation into discrete slices and zonate areas that contain coarse-grained materials within the bounding structure grids that define the top and base of the Paskapoo Formation (Figure 8d).

An important component of the slice mapping analysis was the selection of the datum to initiate slice geometry and propagate slices up through the formation with increasing elevation. The angle at which slices are cut through the formation must be at an appropriate angle to determine the continuity of coarse-grained materials. Problematic data for the slicing include the base of the Paskapoo Formation and the Ardley coal zone. The base of the Paskapoo Formation is a regional unconformity, and is generally marked at the base of the first sandstone greater than 5 m thick above the Ardley coal zone (Gibson, 1977; Richardson et al., 1988; Dawson et al., 1994). This somewhat arbitrary pick can vary significantly in stratigraphic level. The upper Ardley coal zone is also not an ideal datum because it is not present everywhere in the study area, and the lower Ardley coal zone, while more continuous, still changes in stratigraphic level laterally and is not parallel to the base of the Paskapoo Formation due to the wedge shape of the Scollard Formation. To overcome these difficulties, a fifth-order trend surface of the base of the Paskapoo Formation was used for the datum. This structure surface honoured the regional trend of the base of the Paskapoo in the study area but avoided local vertical deviations from the trend resulting from the varying position of the lithostratigraphic contact (i.e., the lowest major sandstone situated above the Ardley coal zone).

In this study, rather than using slices of equal thickness for slice mapping (e.g., Lyster and Andriashek, 2012), a modified technique was used. A wedge-shaped geometry was employed for the slice thickness, as alternatively, slices of equal thickness parallel to the Paskapoo Formation fifth-order trend base would result in slices cutting time-equivalent units at progressively higher angles. Contrary to the fact that the original depositional geometry of the Paskapoo clastic wedge is unknown, it is likely that prior to post-depositional erosion, the Paskapoo Formation was thicker in the west and thinned to the east (Figure 9a). A second-order trend of the Scollard Formation isopach was used to create the wedge-shaped slices (described below), which was considered to be the most reasonable proxy for the thickness changes in the overlying Paskapoo Formation. This method assumes that the creation of accommodation space during the deposition of the Scollard Formation was similar to that created during the Paskapoo Formation and that there was no significant post-depositional erosion of the Scollard Formation. The different lithostratigraphic nature of the formations (e.g., presence of coal within the Scollard Formation) suggests that the first assumption may not be strictly true, and the base of the Paskapoo Formation (top of Scollard) is an unconformity. Nevertheless, at the basin scale, the overall wedge shape of the slices is believed to be reasonable, and this method provides more geologically reasonable results compared with equal thickness slicing techniques.

The use of the second-order trend of the Scollard Formation isopach and its application to the fifth-order trend surface of the Paskapoo Formation base is represented by

$$W = \left[20\left[\frac{I}{S}\right]\right] + E.$$

W is the structure elevation top of a wedge-shaped slice (m asl) at each oil and gas well in the study area (i.e., 21 488 total oil and gas wells in the study area; many wells did not include a digital gamma-ray log). The constant, 20, is the maximum desired slice thickness in the Paskapoo Formation (m). *I* is the value of the second-order trend of the Scollard Formation isopach (m) sampled at each oil and gas well. *S* is the maximum thickness of the Scollard Formation second-order trend isopach (m). And *E* is the elevation of the fifth-order datum of the Paskapoo Formation base (m asl) sampled at each oil and gas well.

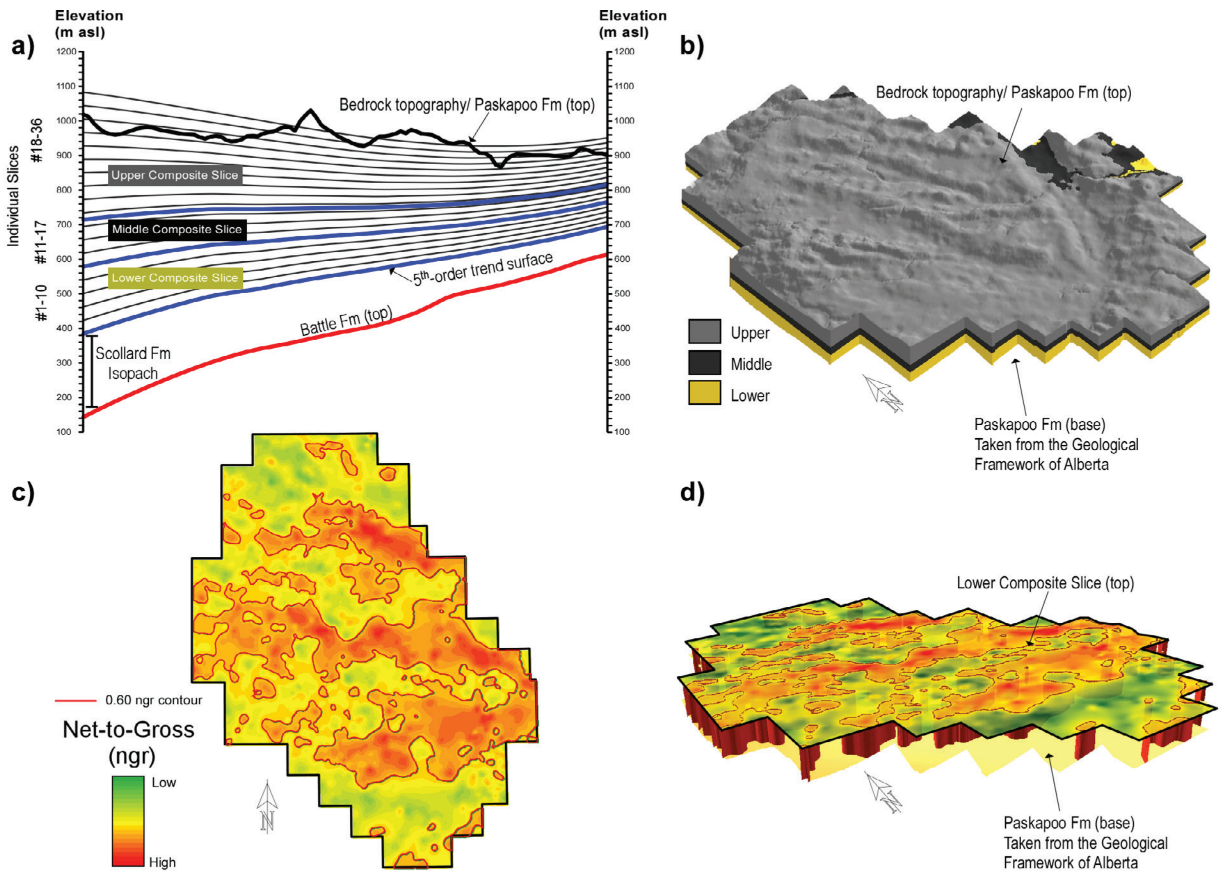

Figure 9. a) Cross-section showing the wedge-shaped geometry of the slices propagated through the Paskapoo Formation as well as the Battle Formation structure surface and the Scollard Formation isopach. To facilitate the visualization of slice geometry, only 20 of the 36 total slices are shown. b) 3-D model of the three composite slices in the Paskapoo Formation. Using ArcMAP, the elevation top for the composite slices were sampled at each oil and gas well in the study area (21 488 wells), and RockWorks15 was used to interpolate the grids using the closest point. The bounding surfaces of the Paskapoo Formation, including the bedrock topography and Paskapoo Formation base grids, were used to truncate the composite slices. c) Plan view of the lower composite slice net-to-gross sandstone values as well as the ≥0.60 net-to-gross contour. d) 2.5-D view of the lower composite slice net-to-gross values. The ≥0.60 net-to-gross ratio cut-off shown in (c) was used to produce polygons of coarse-grained sediments that maintain a constant lateral shape throughout the entire volume and vertically thin to the east with decreasing slice thickness.

Using this equation, a total of 36 wedge-shaped slices were propagated from the base of the Paskapoo Formation to the bedrock topography (Figure 9a). Normalized digital gamma-ray logs (i.e., 4221 logs) were used to calculate net sandstone (≤80 API) and net-to-gross ratios for the slices created in the Paskapoo Formation, and as slice thickness is not constant due to the wedge-shaped geometry, the net-to-gross ratio was gridded for each slice. Analysis of individual slices yielded three groups. Slices within each group were merged to form three composite slices: lower (slices 1–10), middle (slices 11–17), and upper (slices 18–36; Figure 9b).

Further zonation of sandstone bodies was performed in ArcMAP based on the net-to-gross ratios within the upper, middle, and lower composite slices (Figures 9c and d) derived from the merged normalized digital gamma-ray logs (Section 3.1.3). The ≥0.60 net-to-gross value is interpreted in this report to contain high permeability based on the connectivity of sandstone bodies in 2-D (Pranter and Sommer, 2011) and appropriate to characterize potential connectivity between sandbodies and the lateral extent of large sandbodies for input into a groundwater-flow model.

4 Model Results and Interpretation

A number of derivative products have been generated from the 3-D hydrostratigraphic model based on the methods described in Section 3 to show the interrelationship between mapped units, including a fence diagram (Figure 10; Appendix 1), structure elevation, and isopach maps (Appendix 2). A summary of the data points used for model creation and an assessment of the accuracy of modelled units are included below. Since the main objective of the hydrostratigraphic model is to provide input into a groundwater-flow model, a first-order interpretation will be presented to provide insights into the key hydrogeological settings of the modelled hydrostratigraphic units.

4.1 Neogene-Quaternary Unconsolidated Units

Four 2.5-D hydrostratigraphic grids (Figure 11) were modelled in the SLSB to depict unconsolidated sediments using the subsurface hydrostratigraphic assignments outlined in Table 5. The most important hydrostratigraphic unit in the Neogene-Quaternary succession for subsequent groundwater-flow models is HSU S1 (Figure 6; Table 1). This unit potentially contains the largest unconsolidated aquifer connected to regional groundwater flow. HSU S1 in part comprises Empress Group sediments, which are a basal coarse-grained unit, constrained to paleovalleys. However, the name Empress Group is excluded from this study since the lack of lithostratigraphic markers in water well lithologs and geophysical logs preclude the identification of HSU S1 as a preglacial, glacial, or postglacial unit (Evans and Campbell, 1995). In the SLSB model, basal sand and gravel overlying bedrock and infilling the Red Deer paleovalley and underlying HSU's C2 (Figure 22 and Figure 23), S2 (Figure 24 and Figure 25), and C1 (Figure 26 and Figure 27) were defined as HSU S1 (Figure 28 and Figure 29). The subdivision of coarse-grained aquifer units (HSU's S1 and S2) in paleovalleys and upland areas were separated by the intervening fine-grained unit of C1 (Figure 11) and capped by C2. To model these aquitards, isolated or thin units were merged into larger units of the same aquitard classification to facilitate modelling. No differentiation was made between diamicton, silt, or clay units. Hydrostratigraphic assignments of C2 and C1 were coded this way to highlight the spatial distribution of coarse-grained aquifer materials in the model.

Groundwater resources in the Neogene-Quaternary succession are potentially located in HSU S1 at the base of the Red Deer paleovalley (Farvolden, 1963a and 1963b)—making up the Red Deer basal aquifer—and in terrace sands and gravels of HSU S2. Modelling HSU S2 is important for understanding and quantifying groundwater-surface water interactions, as it has the potential to be hydraulically connected to the Red Deer River (Tóth, 1961; Clissold, 1968). Precise aquifer yield in sediments

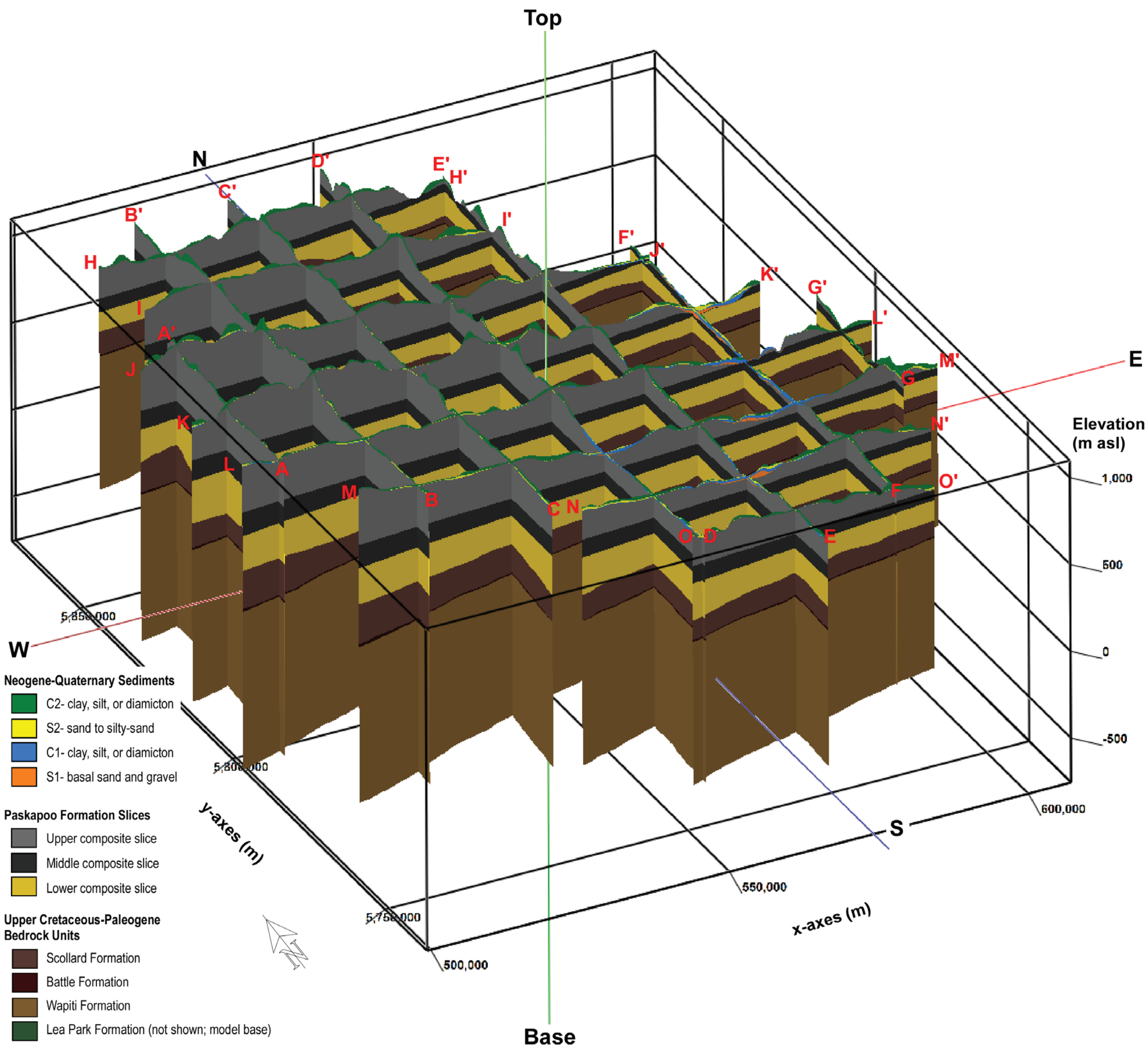

Figure 10. Fence diagram of the SLSB modelling domain showing the 11 hydrostratigraphic units (constructed using RockWorks15). Units are shown at 30× vertical exaggeration. Each cross-section is also provided in Appendix 1 (Figure 13−Figure 21).

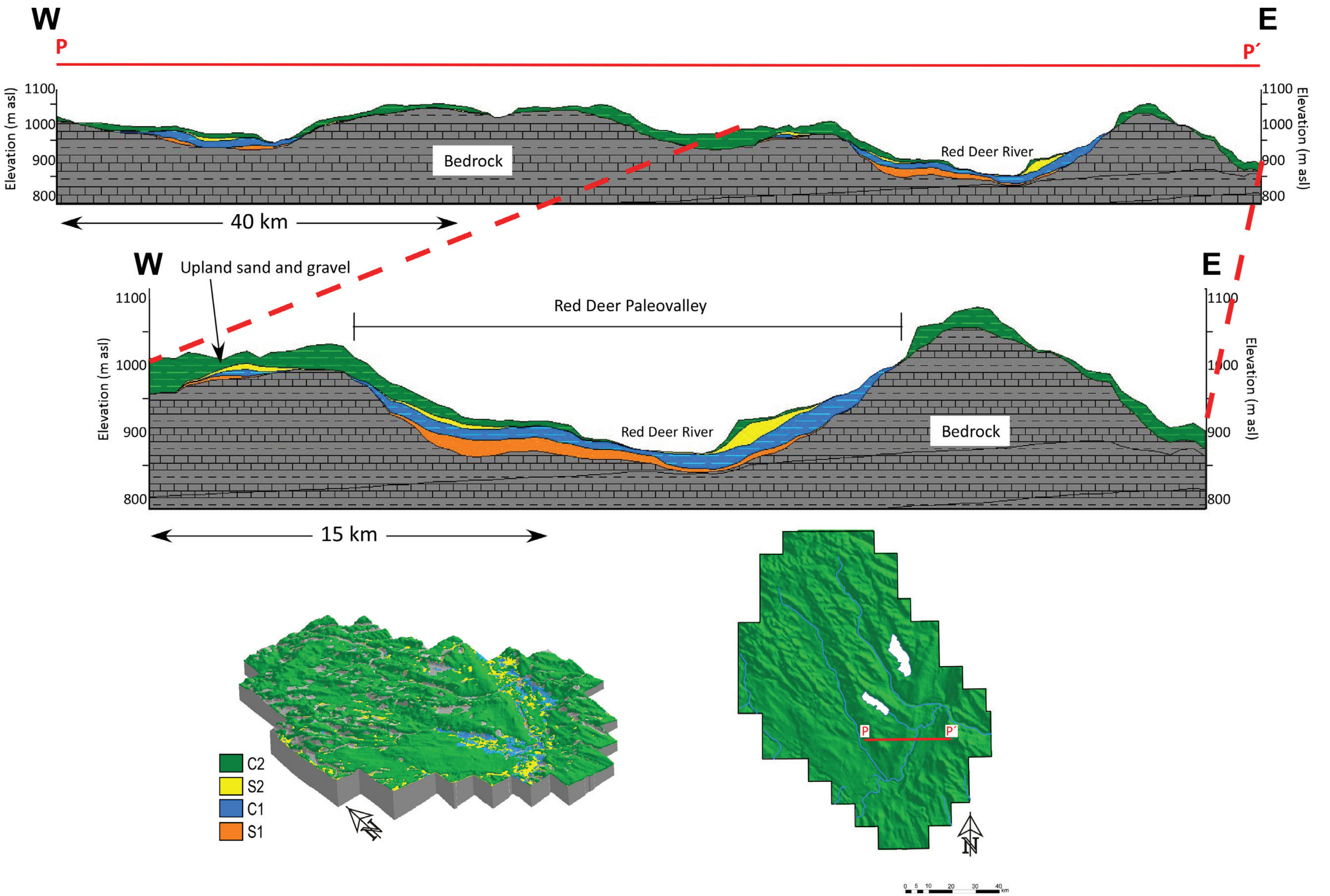

Figure 11. Cross-section P-P′ shows the major hydrostratigraphic units delineated in the Neogene-Quaternary succession across the Red Deer paleovalley.

overlying bedrock at a regional scale is not included in this report; however, a composite yield of all water-bearing units in the near-surface sediment and rock units are presented in Barker et al. (2011). The Red Deer basal aquifer located at the talweg of the Red Deer paleovalley may have aquifer layers that can support domestic supplies (i.e., especially in the corridor from Red Deer to Bowden, where the potential groundwater yield is 11–15 imperial gallons per minute; Barker et al., 2011). However, as aquifers in the unconsolidated sediments tend to have a higher concentration of dissolved solids and high iron content, the underlying Paskapoo Formation represents a more appropriate source of groundwater (Gabert, 1975; Huff et al., 2012; Barker et al., 2013a and 2013b). Modelling the potential aquifers and aquitards in the overlying unconsolidated sediments is important, as the sediments may influence the groundwater system particularly where the Red Deer basal aquifer is hydraulically connected to underlying bedrock aquifer complexes and, in turn, may affect the water quality (e.g., sulphates and hardness) in localized areas (Grasby et al., 2008a).

4.2 Sandstone Maps in the Paskapoo Formation

Delineating depositional elements that affect fluid flow in the Paskapoo Formation employed the use of slice mapping and zonation of slices using ≥0.60 net-to-gross sandstone ratios (Figure 9c). This method was used because the Paskapoo Formation is highly heterogeneous and it is more suitable to model rock properties (e.g., ≤80 API in gamma-ray logs) to infer hydraulic connectivity between units as opposed to a qualitative approach to mapping the geometry of hydrostratigraphic units. As discussed in Section 3.1.3, these slices do not provide a robust stratigraphic architecture of the formation but partition the unit into three distinct geological domains (Figure 12) as calculated from the normalized gamma-ray logs in each slice (Table 3). The three slices include an upper slice with the majority of net-to-gross values between 0.40 and 0.80 and constrained to the Paskapoo Formation top (Figure 30 and Figure 31), a middle group with a majority of net-to-gross values between 0.10 and 0.60 (Figure 32 and Figure 33), and a lower group with generally high net-to-gross values, the majority between 0.50 and 0.90 (Figure 34 and Figure 35).

Table 3. Number of normalized gamma-ray logs used to calculate net-to-gross sandstone values in each composite slice of the Paskapoo Formation model.

Composite slice	Number of normalized gamma-ray logs
Upper	980
Middle	2 415
Lower	3 134

The geometry, orientation, and stacking arrangement of coarse-grained materials determine the potential connectivity of sandstone bodies within the Paskapoo Formation slices. Results demonstrate that single- and multistorey sandstone bodies nested within the Paskapoo Formation show the possibility of preferential pathways for fluid flow along linear channel trends (Figure 12). These potential channel trends are especially prevalent in the lower composite slice, where westward-trending linear features have higher sandstone volumes (net-to-gross ratios) than other portions of the Paskapoo system (Figure 12). This lower composite group (slices 1–10) may be equivalent to the sandstone-dominated Haynes aquifer (cf. Demchuk and Hills, 1991; Grasby et al., 2008b; Parks and Andriashek, 2009; Lyster and Andriashek, 2012). The middle composite slice in the Paskapoo Formation, characterized by overall low net-to-gross ratios, is considered to be an aquitard layer, likely equivalent with the Lacombe aquitard (cf. Lyster and Andriashek, 2012). However, there are isolated areas of high net-to-gross values within this composite slice (Figure 12), which may be hydraulically connected to the underlying sandstone bodies, thereby limiting the ability of the aquitard to impede groundwater flow. The upper composite slice does not have

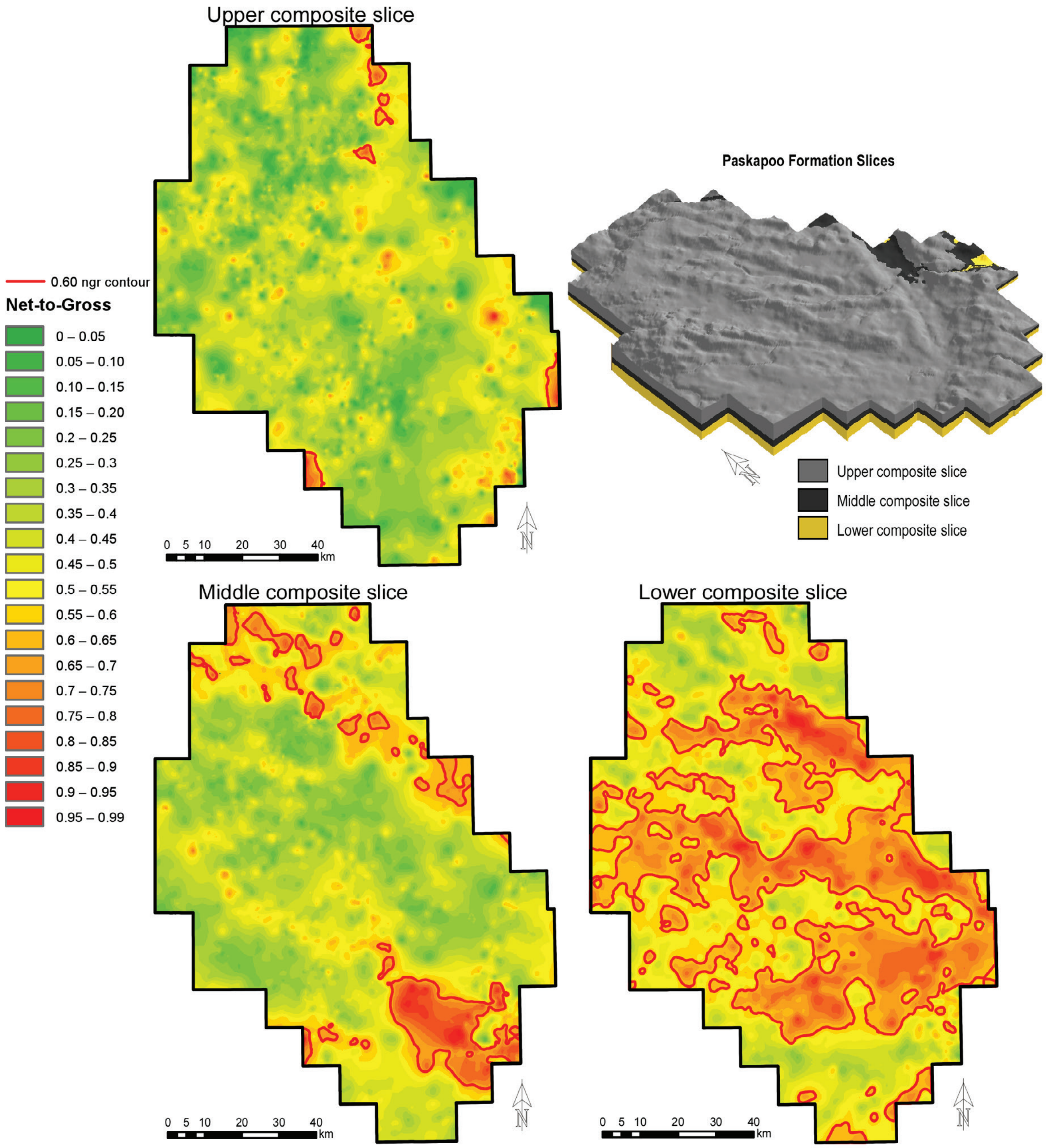

Figure 12. 3-D model of the Paskapoo Formation slices as well as plan view maps of the net-to-gross sandstone ratios of each composite slice.

clear trends in the net-to-gross sandstone maps; however, the characterization of the upper composite slice did not include the numerous water wells completed in the near-surface portion of this slice, potentially causing the complexity of the upper portion of the Paskapoo Formation to not be captured.

As the Paskapoo Formation is one of the most intensely used aquifers in the SLSB and other areas throughout central Alberta, characterizing it as a homogeneous unit with limited spatial variability would represent a major limitation of the SLSB model for input into a groundwater-flow model. Although the slice mapping and associated net-to-gross sandstone maps do not formally represent the internal stratigraphic components of the Paskapoo Formation, they provide important information on the orientation and dimensions of sandstone bodies. This provides improved understanding in building the groundwater-flow model and may help focus local-scale investigations for further subsurface studies or correlations within the unit.

4.3 Bedrock Formations

The majority of the modelling work focuses on units in the unconsolidated sediments and Paskapoo Formation, as most water wells are completed in the upper portion of the bedrock strata. However, the underlying bedrock aquifers are important for characterizing the regional groundwater-flow system. Four bedrock units were modelled below the Paskapoo Formation. These bedrock units include the Scollard Formation, a laterally extensive and thick unit that may act locally as an aquifer in the SLSB (Figure 36 and Figure 37); the Battle Formation, a relatively thin regional confining unit, absent in paleovalleys in the southeastern portion of the study area, which trend to the southeast (Figure 38 and Figure 39); and the Wapiti Formation, a very thick aquifer unit (Table 6) distributed across the model domain (Figure 40 and Figure 41). Mudstone or shale of the Lea Park Formation (or base of the Wapiti Formation; Figure 42) is continuous across the study area and provides the base of the hydrostratigraphic model.

Groundwater flow in the Paskapoo Formation is most likely to be affected by the confining properties of the Battle Formation (Figure 5). However, the model demonstrates that this confining unit is incised by paleovalleys that are infilled with Scollard Formation sands (Hathway, 2011a). These paleovalleys may form hydraulic pathways from the Scollard Formation into the underlying Wapiti Formation in areas where the Battle Formation is absent. Mapping these units is important because large-scale features in the bedrock units may influence the regional groundwater system.

4.4 Model Limitations

Because of the variety of data sources, 3-D modelling of the subsurface has inherent uncertainties and errors. To provide an estimate of model error in the SLSB, the root mean square error (RMSE) was used (MacCormack et al., 2013). The RMSE compares how similar interpolated grid values are to the original input data. This is a global estimate of error for each 2.5-D grid and provides neither indication of how error is distributed spatially in the model domain nor the accuracy of the input data. Table 4 provides the RMSE for each 2.5-D grid where available. The RMSE for the Neogene-Quaternary grids is within approximately ±6 m of the original hydrostratigraphic assignment. The highly discontinuous and, in some cases, thin sediment cover, as well as the numerous hydrostratigraphic assignments (~10 000) made from variable-quality borehole data in the unconsolidated units (especially HSU C2; Table 5), affect model accuracy. Further simplifications in near-surface sediments were made, as a 400 m grid cell size was chosen for the modelling effort, which may cause local deviations from the original data point, especially in areas truncated by the DEM and bedrock topography grids (Table 2).

The RMSE was not reported in Table 4 for the Paskapoo Formation slices because these 2.5-D grids represent a composite grouping of slices and do not define the structure elevation of a discrete hydrostratigraphic unit. However, a limitation of the slice mapping analysis is that water well lithologs were not used, and thus the characterization of the upper composite group may be improved through the integration of digital gamma-ray logs from oil and gas wells and water well lithologs (e.g., Lyster and Andriashek, 2012). All other error statistics listed in Table 4 are global estimates of RMSE for the 500 m grid created for the Geological Framework of Alberta. The RMSE values reported for the bedrock grids are not specific to the SLSB model as the Paskapoo, Scollard, Battle, Wapiti, and Lea Park bedrock units were clipped to the SLSB model domain (Figures 8c and d) and re-interpolated; however, the elevation differences between the original and re-interpolated bedrock grids are negligible.

Further limitations are introduced during the collection and interpretation of data. Some of the main issues are the abundant quantity of low-quality data in the study (i.e., water wells) including location inaccuracies and nonstandardized lithological descriptions made by water well drilling contractors. High- to low-quality data are also further modified through hydrostratigraphic assignments made to create a laterally extensive and mappable geobody. This process may incorporate assumptions and human error when simplifying complex geological data, as unit geometry, extent, and description are a product of the author’s conceptual understanding. This model is to be used in regional-scale groundwater studies, thus these mappable hydrostratigraphic units may be more complex or absent at the scale of a local investigation.

Table 4. Root mean square error (RMSE) summary statistics

Model Unit	RMSE
HSU C2	5.9
HSU S2	6.2
HSU C1	6.1
HSU S1	6.1
Paskapoo Formation – Upper composite slice	n/a
Paskapoo Formation – Middle composite slice	n/a
Paskapoo Formation – Lower composite slice	n/a
Scollard Formation	6.0
Battle Formation	4.3
Wapiti Formation	4.1
Lea Park Formation	5.9

5 Integration with Groundwater-Flow Models

The primary application of the hydrostratigraphic modelling in the SLSB was to produce 2.5-D hydrostratigraphic grids for input into a groundwater-flow model, as part of the AER/AGS and ESRD groundwater program. Appendix 2 provides structure elevation and isopach maps of each modelled grid. To optimize the 2.5-D grids for integration into a groundwater-flow model using the finite-difference method, a constant thickness of 0.10 m was applied where unit isopach maps equalled 0 m. This process involved taking the z-value of the underlying grid node to produce continuous grids across the modelling domain. Each continuous grid was exported to ASCII grid format and can be used as a framework for assigning geological information from the subsurface into groundwater-flow models or hydrogeological maps.

6 Conclusions

A new hydrostratigraphic model has been created for the SLSB as a part of the AER/AGS and ESRD groundwater program to understand the spatial distribution of subsurface depositional elements essential for quantitative modelling purposes. The subsurface was partitioned into eleven hydrostratigraphic units that describe the Neogene-Quaternary sedimentary succession and Upper Cretaceous−Paleogene bedrock units. Four of the eleven hydrostratigraphic units represent possible aquifers (i.e., HSU's S2, S1, Paskapoo Formation lower composite slice, and the Wapiti Formation), five represent confining materials of varying extent (i.e., HSU's C2, C1, Paskapoo Formation middle composite slice, and Battle and Lea Park formations), and the remaining two are a complex assortment of rock with presumably high- to low-permeability, which are not assigned as an aquifer or aquitard in a strict sense (i.e., Paskapoo Formation upper composite slice and the Scollard Formation). These eleven hydrostratigraphic structure elevation grids, as well as the zonated areas of ≥0.60 net-to-gross sandstone in the Paskapoo Formation, provide the hydrostratigraphic framework for the development of a groundwater-flow model.

Further mapping of groundwater flow and chemistry will ultimately determine the extent or absence of hydraulic communication in the SLSB, including the interaction between coarse-grained, potentially water-bearing units in the Neogene-Quaternary succession, primarily the Red Deer basal aquifer, with underlying permeable sediments zonated in the Paskapoo Formation, and the effect large-scale bedrock formations may have on the regional groundwater system, including the extensive paleovalleys, which incise into the regional confining unit of the Battle Formation. This hydrostratigraphic mapping effort is the first step to answering these questions. By providing a scientific approach to data collection and interpretation (as well as integrated geological and hydrogeological products), complex features, interactions in the subsurface, and, by extension, surface water are better understood. This integrated approach to geological and hydrogeological mapping provides support tools for decision-makers to evaluate the impacts of groundwater development and sustainability in the SLSB.

7 References

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Appendix 1 – Model Cross-Sections

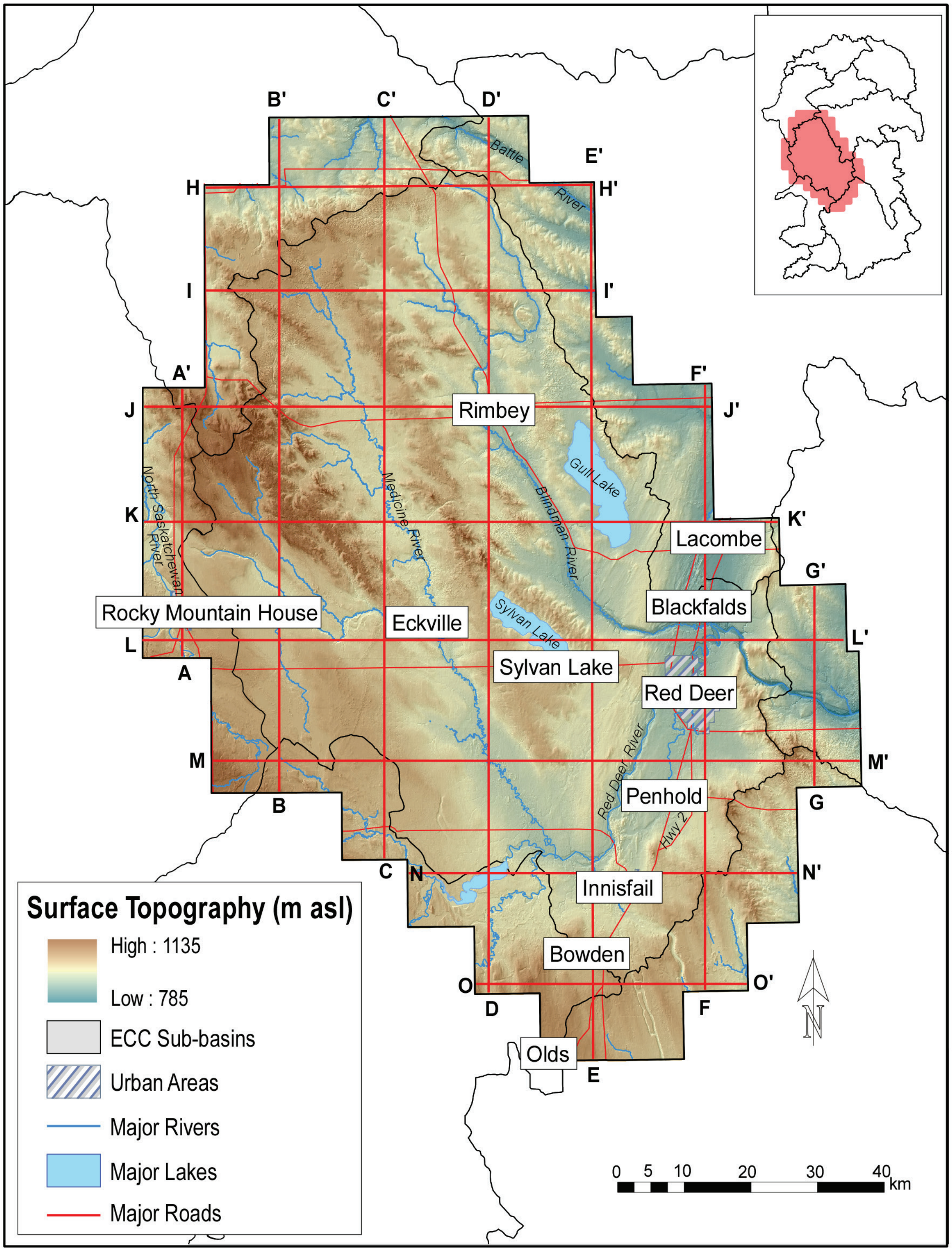


Figure 13. Location map showing the north-south (N-S) and east-west (E-W) system of cross-sections through the SLSB model. All cross-sections (Figure 14−Figure 21) show significant surface features (e.g., cities, towns, rivers, lakes, and etc.). Below cross-sections are 30× vertical exaggerated.

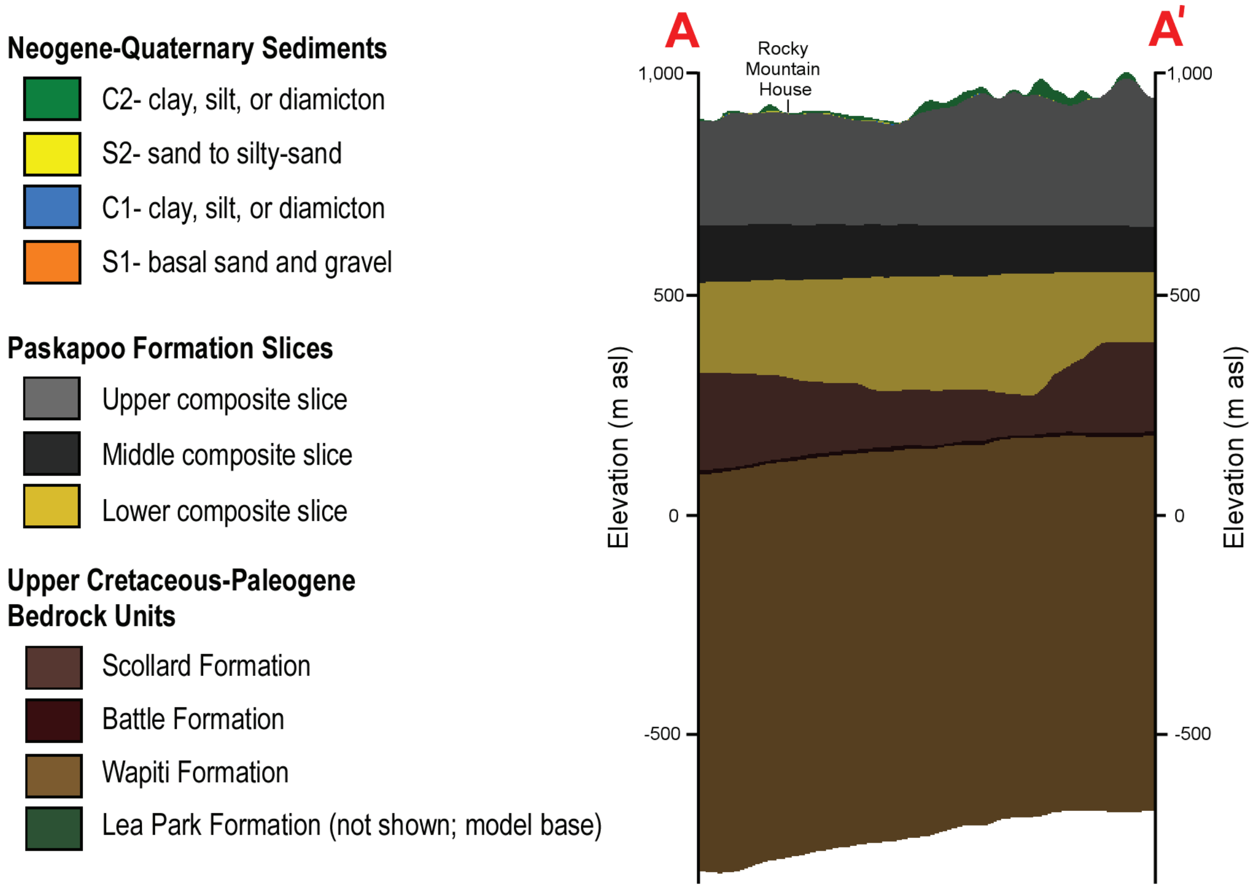
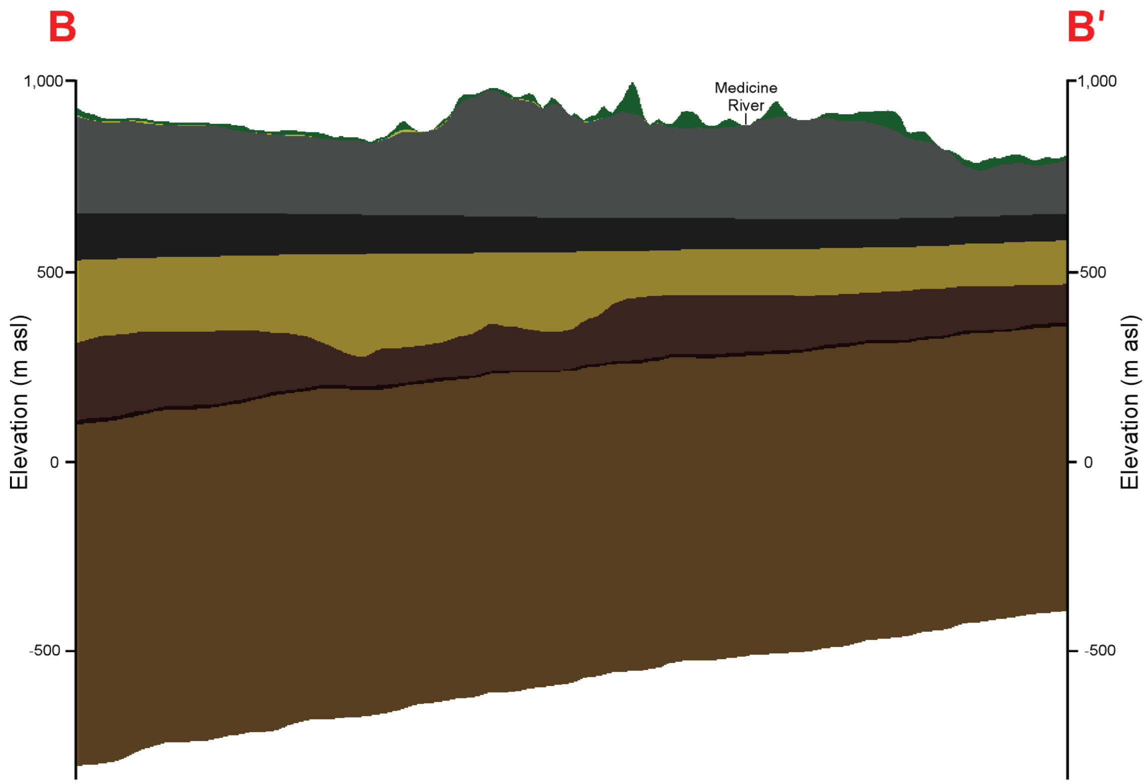


Figure 14. N-S-trending geological cross-section through the town of Rocky Mountain House. The legend for the corresponding hydrostratigraphic/geological units for the SLSB model is also shown. The legend applies to Figure 14–Figure 21.



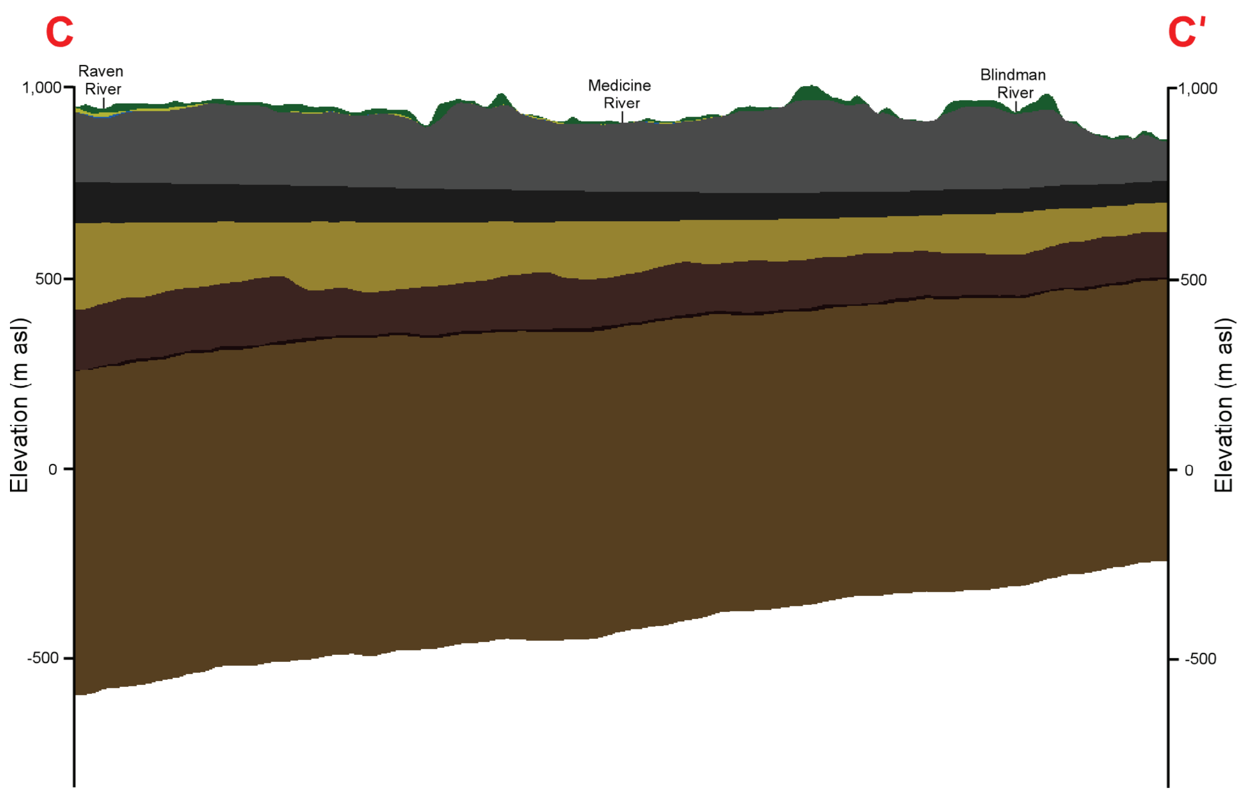


Figure 15. N-S-trending geological cross-sections with the locations of the Medicine, Blindman, and Raven rivers.

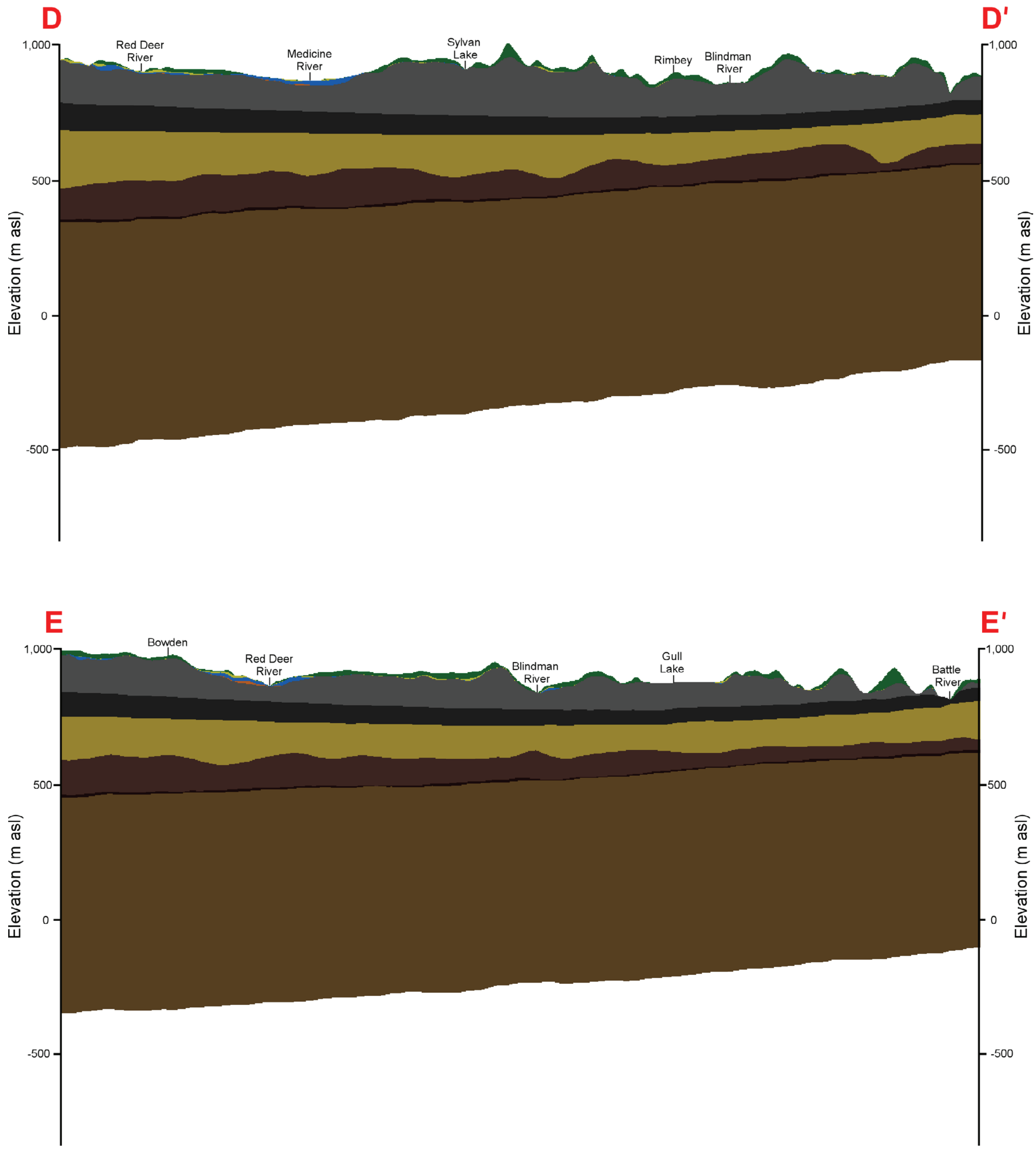
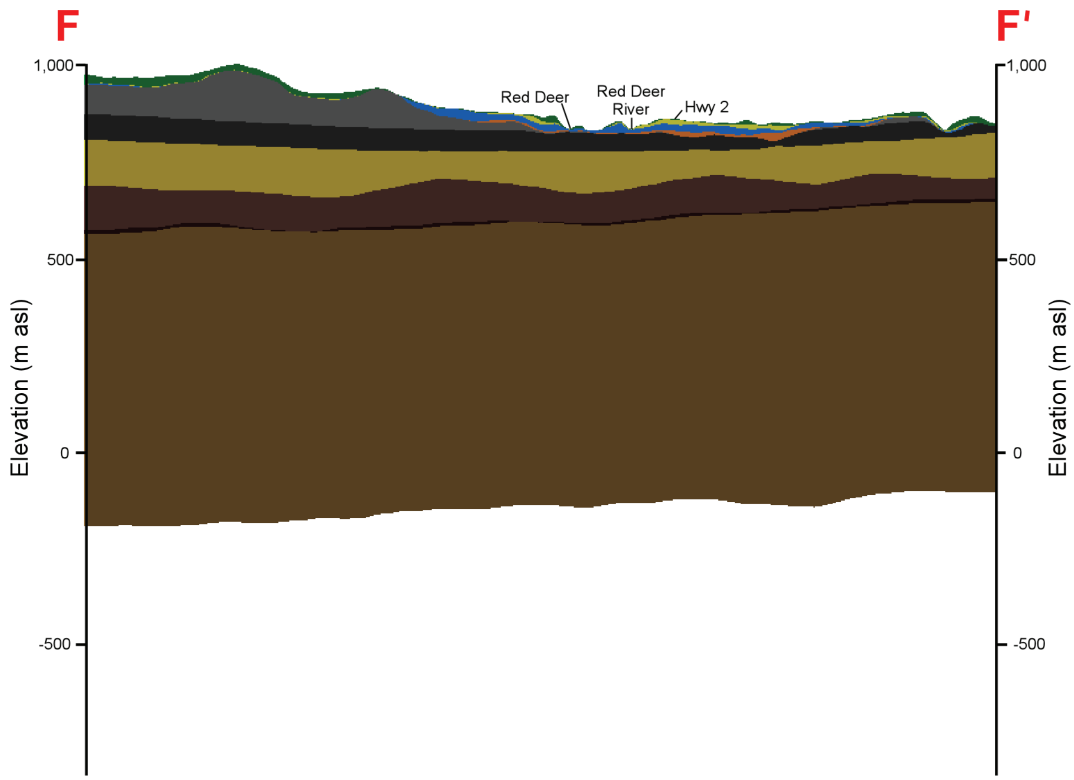


Figure 16. N-S-trending geological cross-sections with the locations of the major Red Deer River along with the smaller Medicine, Blindman, and Battle rivers, as well as the two major lakes (i.e., Sylvan and Gull) located in the SLSB. The towns of Rimbey and Bowden are also shown.



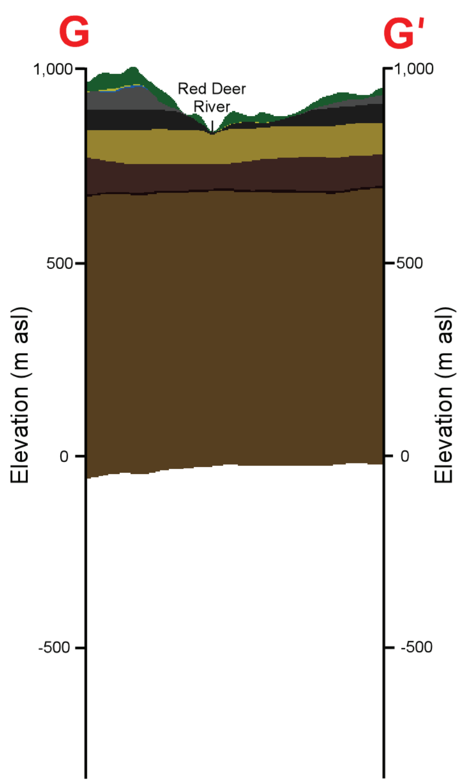
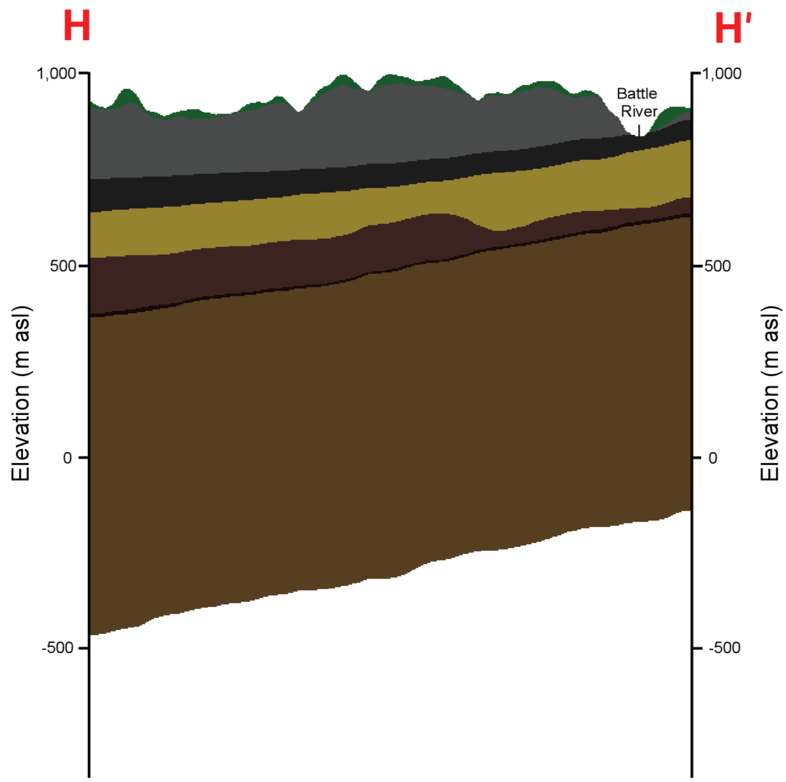


Figure 17. N-S-trending geological cross-sections with the locations of the Red Deer River and the City of Red Deer as well as the location of Queen Elizabeth II Highway (Hwy 2) through Red Deer.



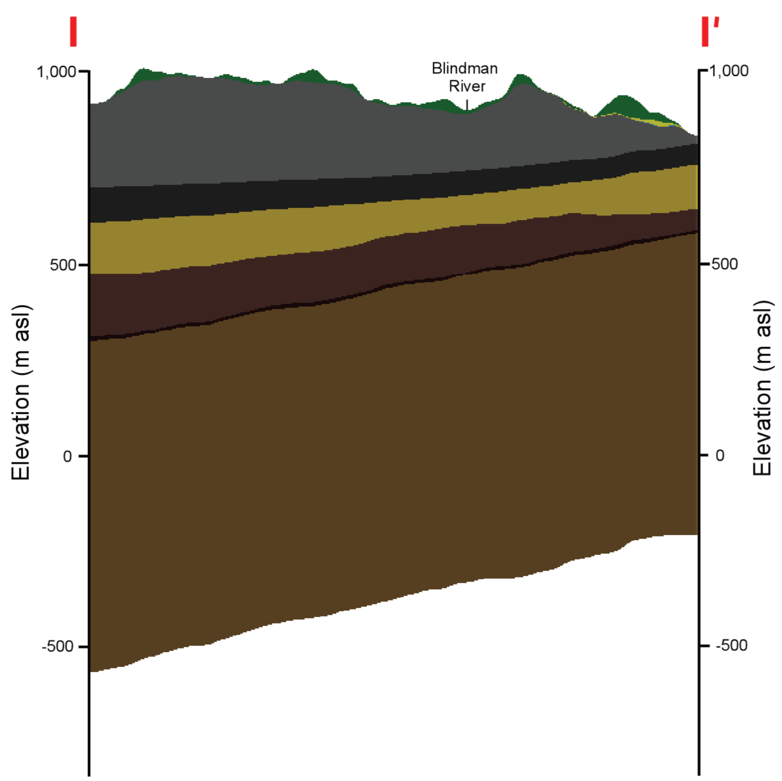


Figure 18. E-W-trending geological cross-sections with the locations of the Battle and Blindman rivers.

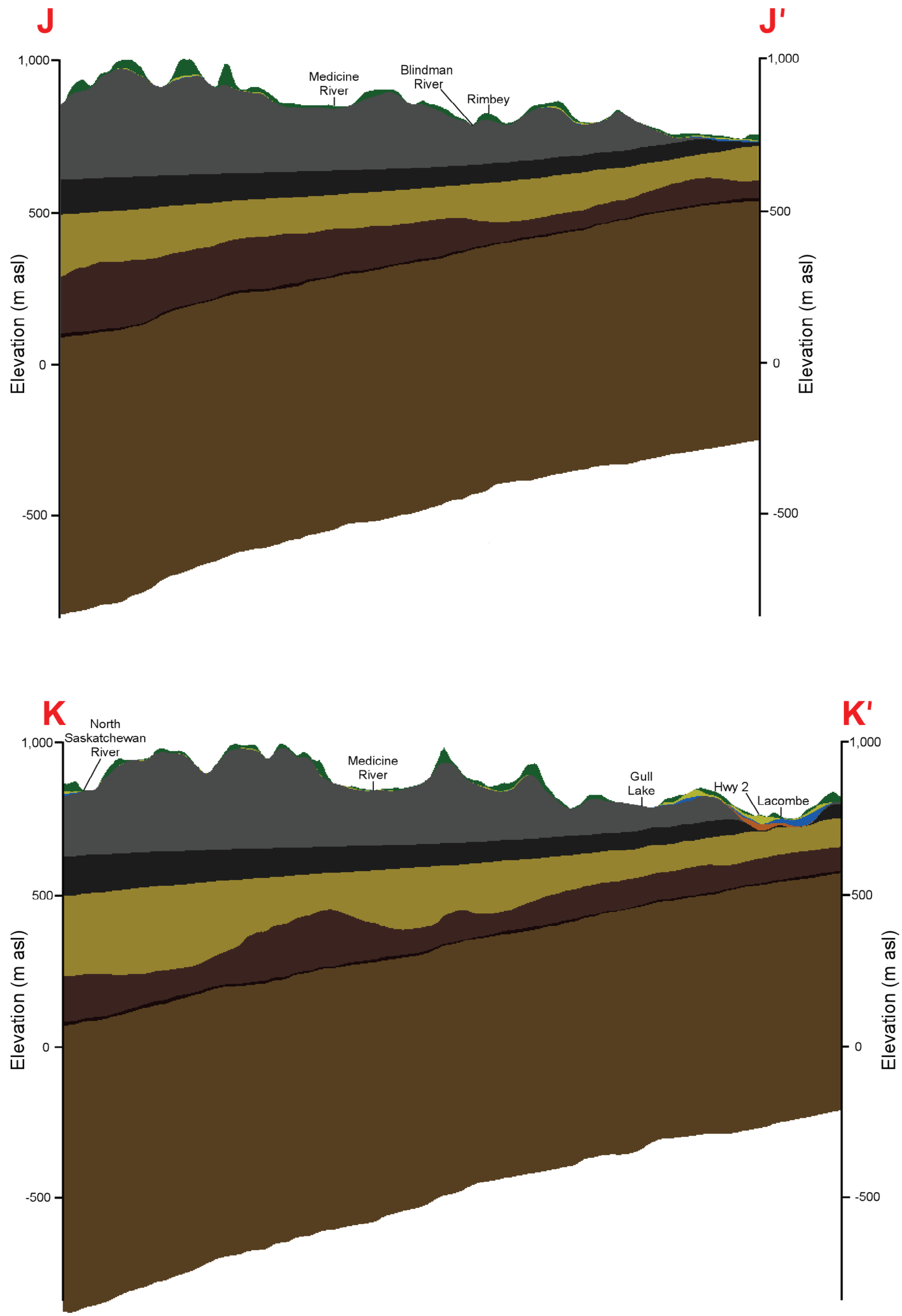
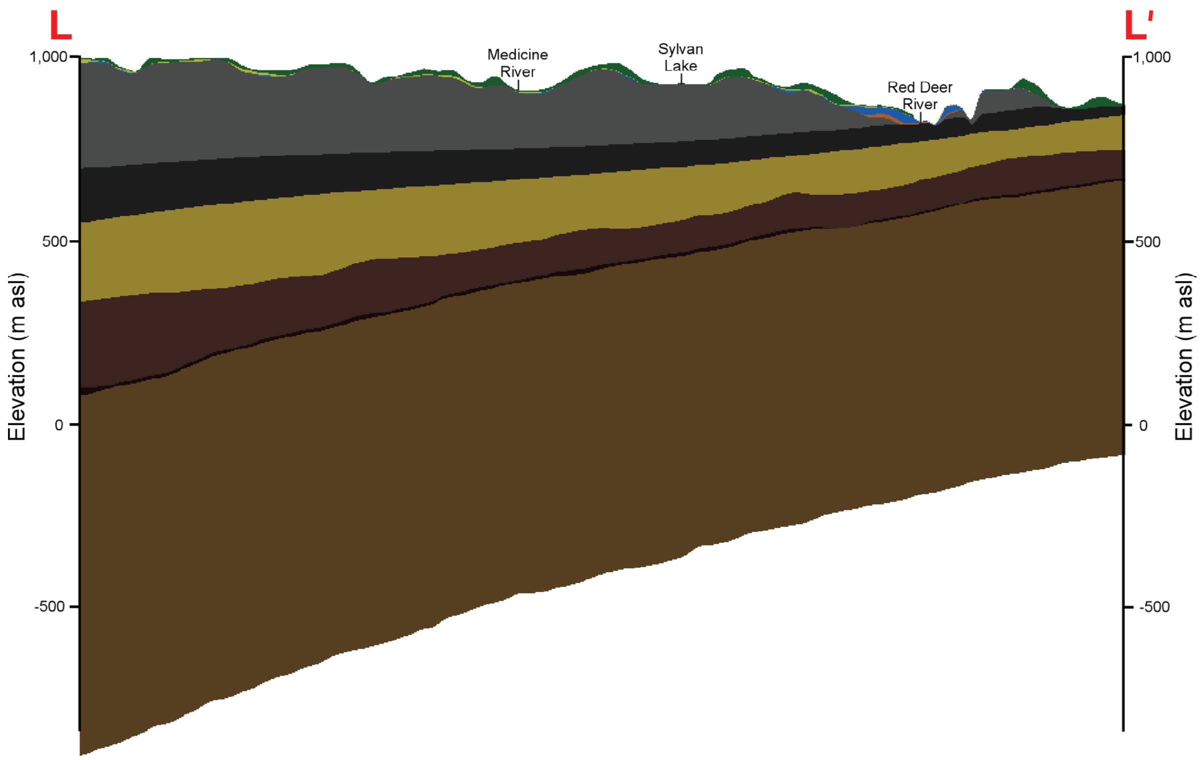


Figure 19. E-W-trending geological cross-sections with the locations of the major North Saskatchewan River along with the smaller Medicine and Blindman rivers, as well as Gull Lake. The towns of Lacombe and Rimbey and the location of Hwy 2 are also shown.



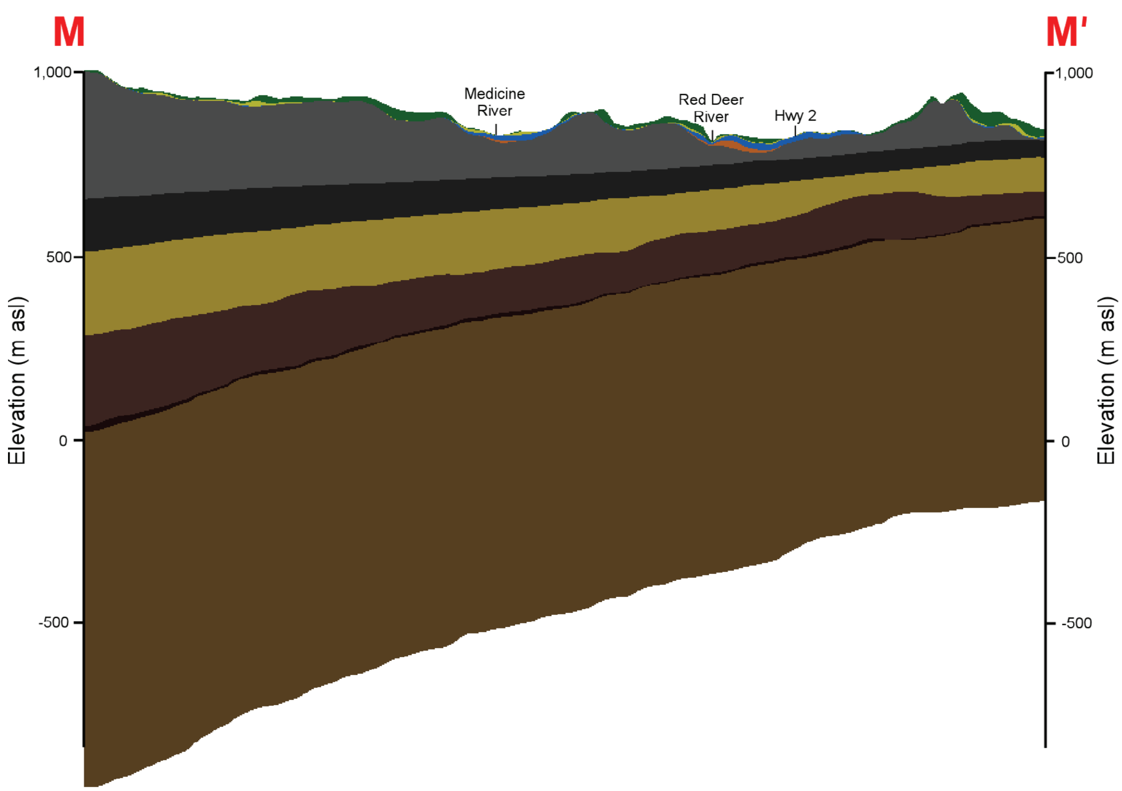


Figure 20. E-W-trending geological cross-sections with the locations of the major Red Deer River and the smaller Medicine River, as well as Sylvan Lake and Hwy 2.

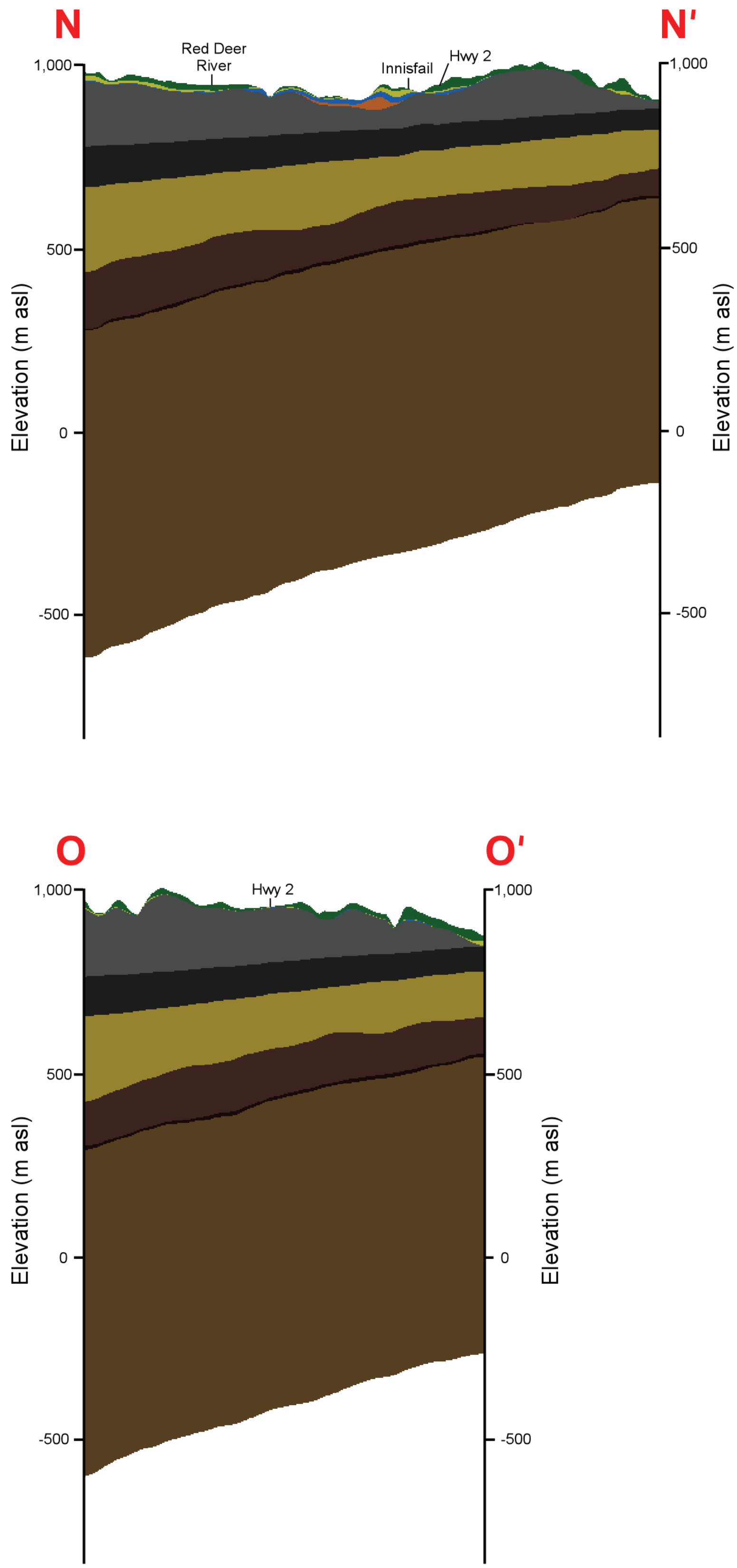


Figure 21. E-W-trending geological cross-sections with the location of the major Red Deer River. The town of Innisfail and the location of Hwy 2 are also shown.

Appendix 2 – Grid Elevations and Thickness Information

Table 5. Number of subsurface hydrostratigraphic assignments used in the SLSB model domain.

Model unit	Number of hydrostratigraphic assignments	Number of net-to-gross projected picks	Number of stratigraphic picks
HSU C2	8 532		
HSU S2	2 060		
HSU C1	1 705		
HSU S1	499		
Paskapoo Formation – Upper composite slice		21 179*	
Paskapoo Formation – Middle composite slice		21 473*	
Paskapoo Formation – Lower composite slice		21 488*	
Scollard Formation			5 934†
Battle Formation			7 993†
Wapiti Formation			8 721†
Lea Park Formation			95 642†

* Paskapoo Formation slices include the number of net-to-gross points sampled to every oil and gas log in the SLSB model that intersected the three composite slices.

† Provincial-scale formations picks extend outside the SLSB (Figure 8c). All formation picks needed to reproduce the lateral extent of the bedrock formation in Alberta are included.

Table 6. Grid statistics.*

Model unit	Elevation (m asl)				Thickness (m)			
	Min	Max	Avg	Std. Dev	Min	Max	Avg	Std. Dev
HSU C2	812.82	1 133.22	959.07	32.05	0	129.89	13.50	7.21
HSU S2	800.82	1 103.78	942.25	24.40	0	36.93	3.23	1.82
HSU C1	804.10	1 093.45	924.08	18.59	0	37.06	6.01	2.80
HSU S1	815.64	957.52	881.72	7.43	0	37.18	4.22	1.07
Paskapoo Formation – Upper composite slice	828.87	1 103.53	942.46	34.12	0	361.59	146.32	57.76
Paskapoo Formation – Middle composite slice	722.97	904.47	797.55	34.41	0	136.58	71.30	17.52
Paskapoo Formation – Lower composite slice	586.69	863.41	726.60	47.28	29.24	276.58	131.39	35.86
Scollard Formation	161.95	714.99	485.57	95.59	18.68	232.94	109.64	28.28
Battle Formation	161.95	714.99	483.48	95.72	0	21.64	7.54	1.62
Wapiti Formation	145.60	709.99	478.16	97.29	684.62	909.34	767.78	36.09
Lea Park Formation	−758.62	16.76	−289.62	131.72	n/a†	n/a†	n/a†	n/a†

* Grid statistics are for discrete grids and do not include the constant 0.10 m applied to a unit where isopach maps equalled 0 m (Section 5).

† Thickness values are also not available for the Lea Park Formation, as it forms the model base.

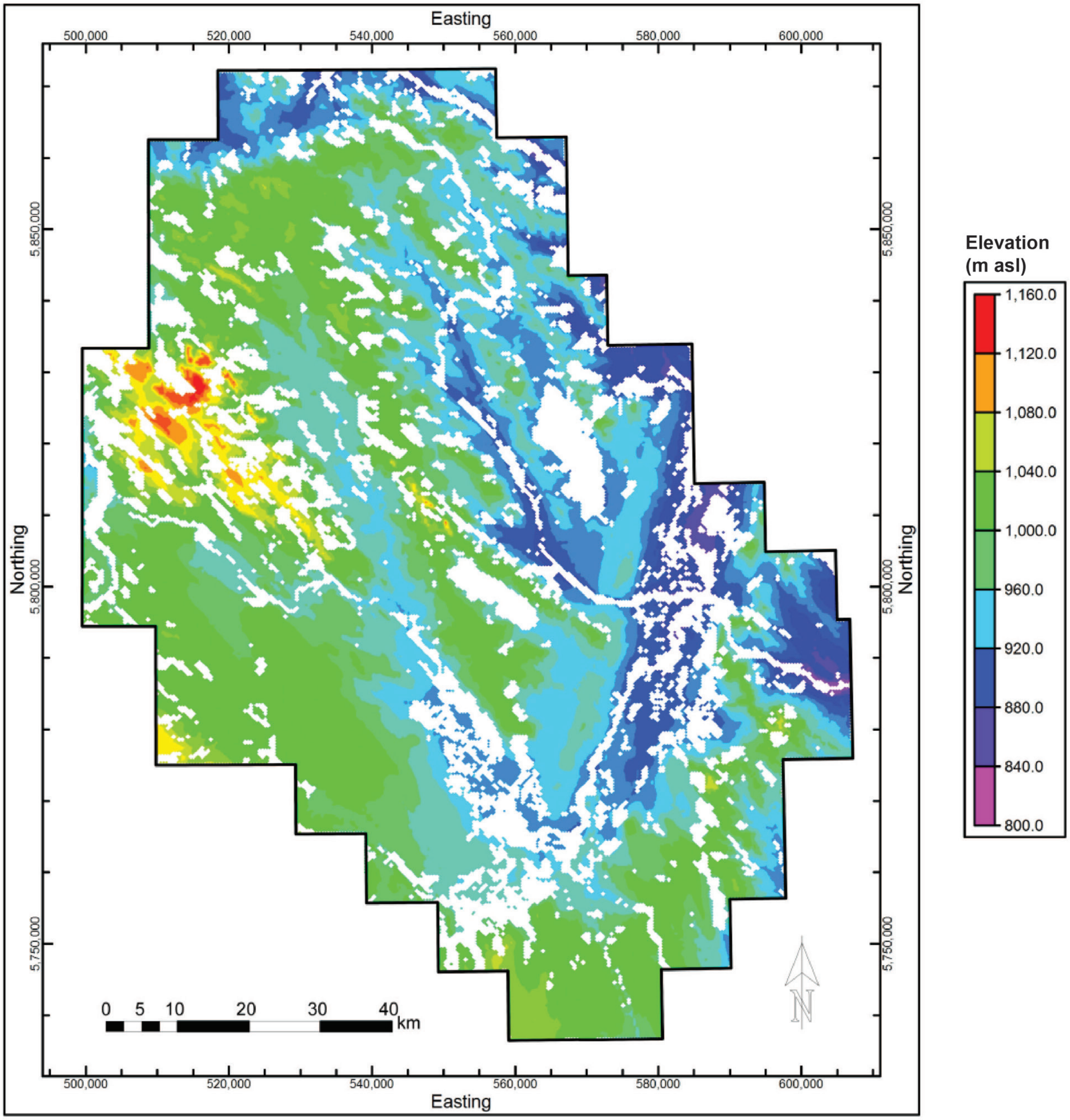


Figure 22. Structure elevation map of HSU C2 (top).

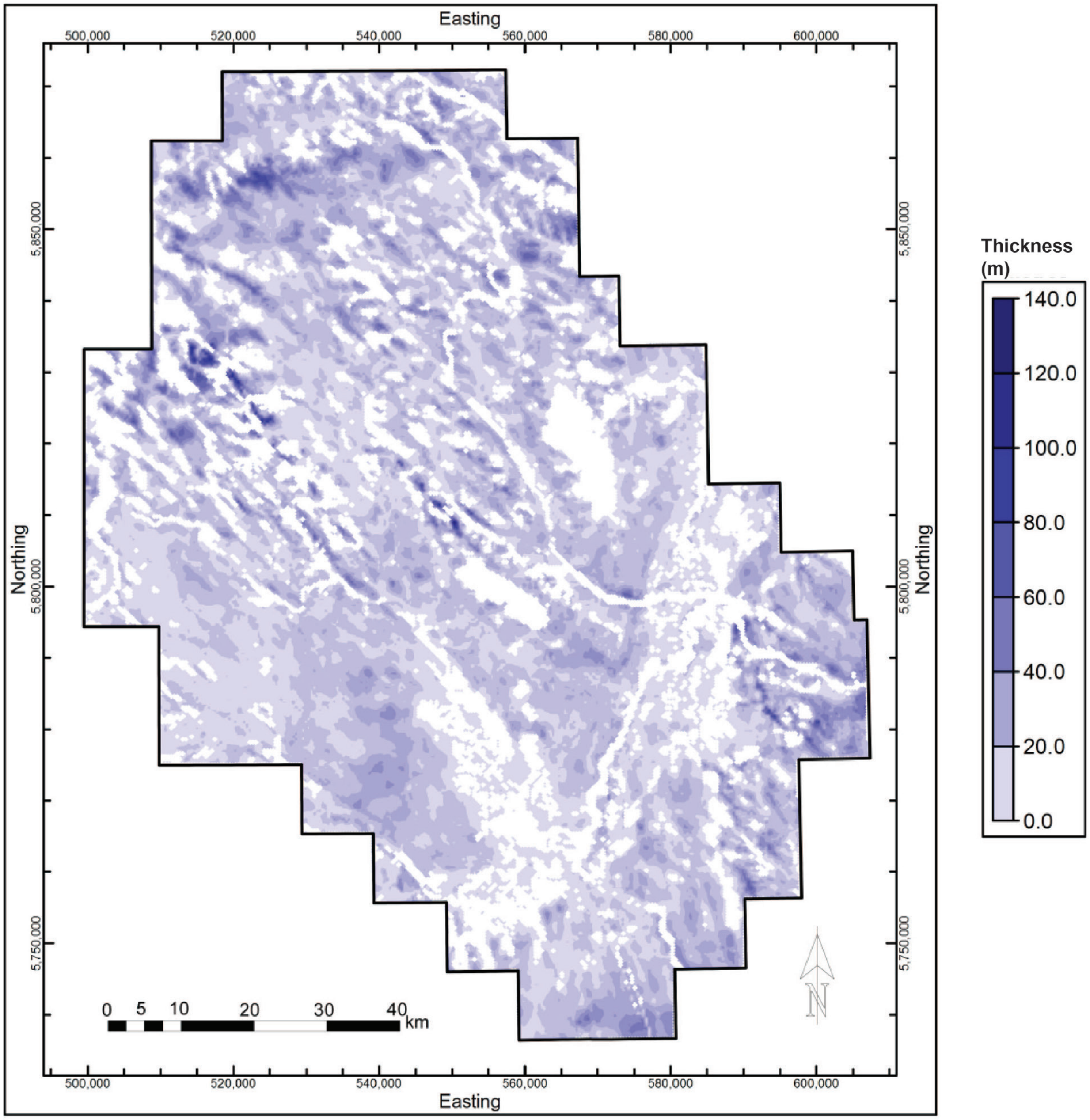


Figure 23. Isopach map of HSU C2.

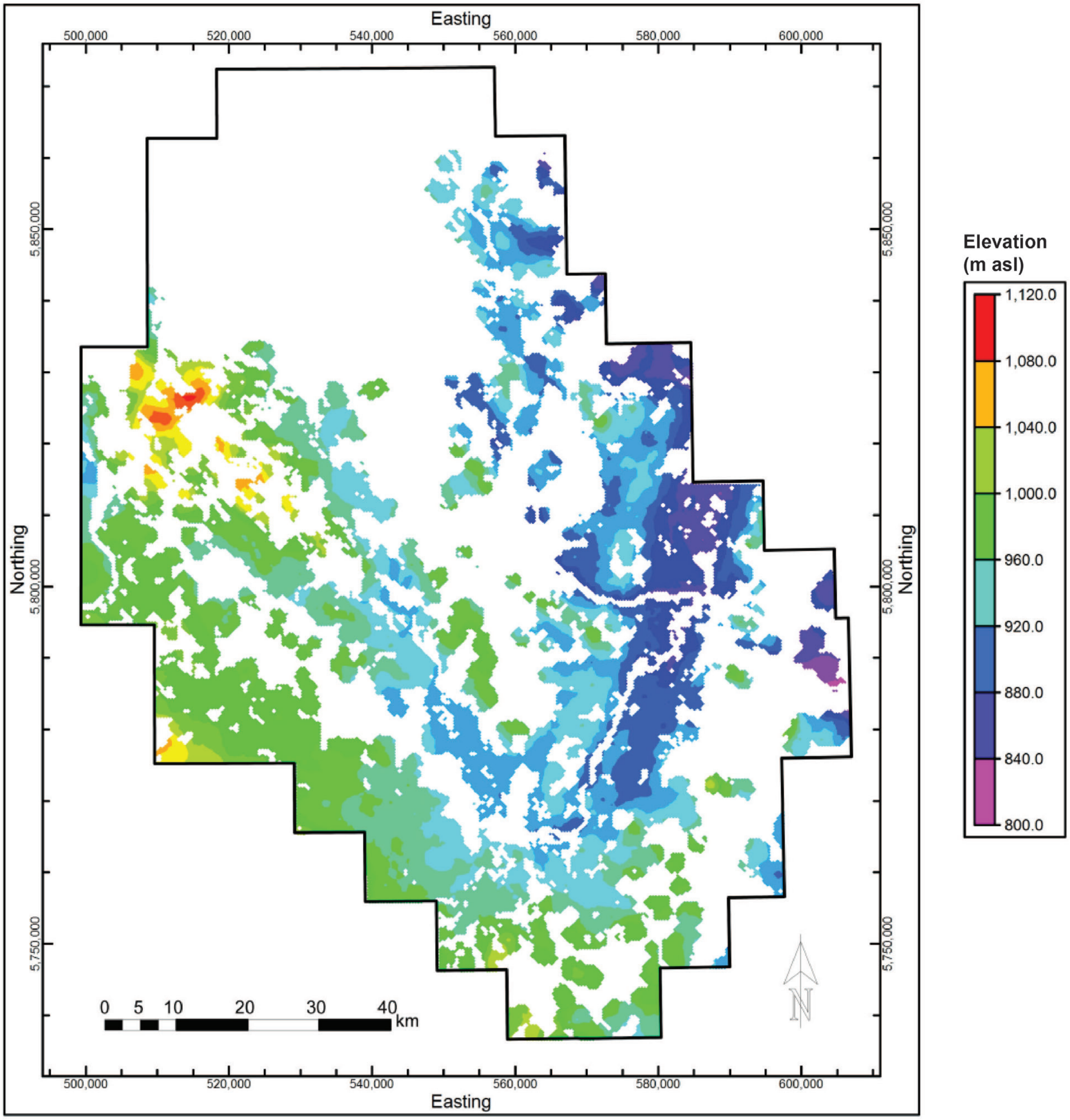


Figure 24. Structure elevation map of HSU S2 (top).

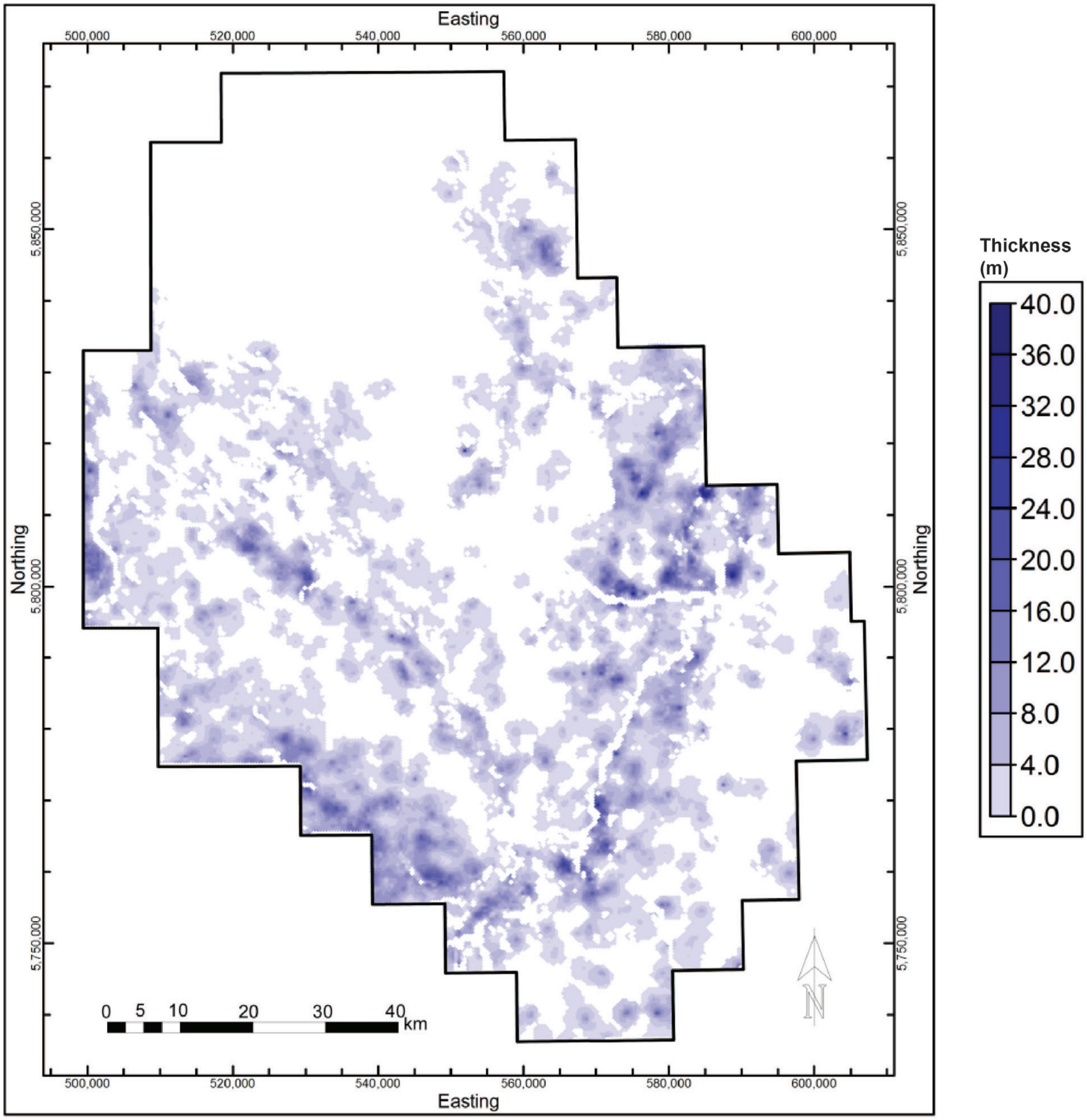


Figure 25. Isopach map of HSU S2.

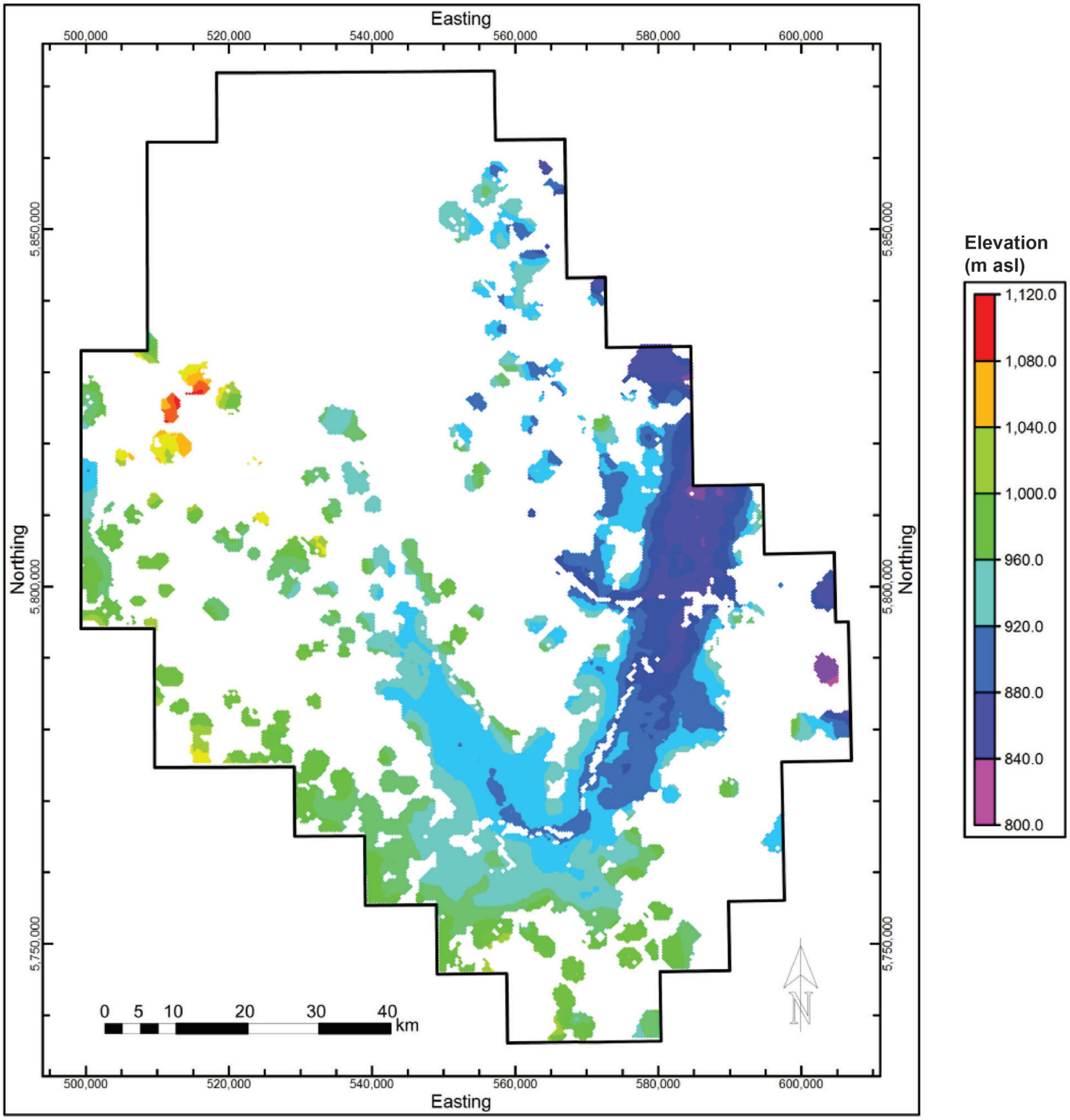


Figure 26. Structure elevation map of HSU C1 (top).

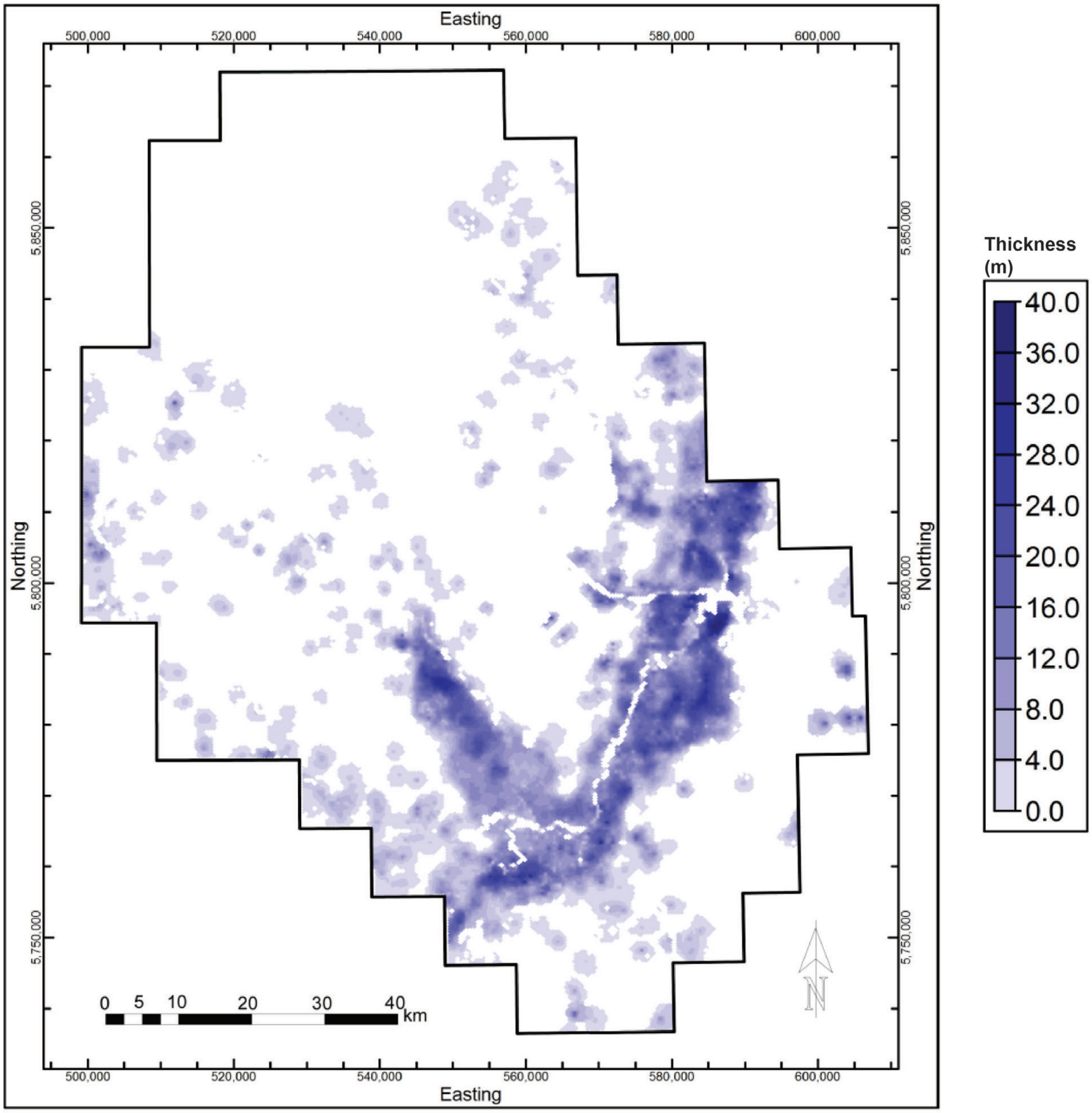


Figure 27. Isopach map of HSU C1.

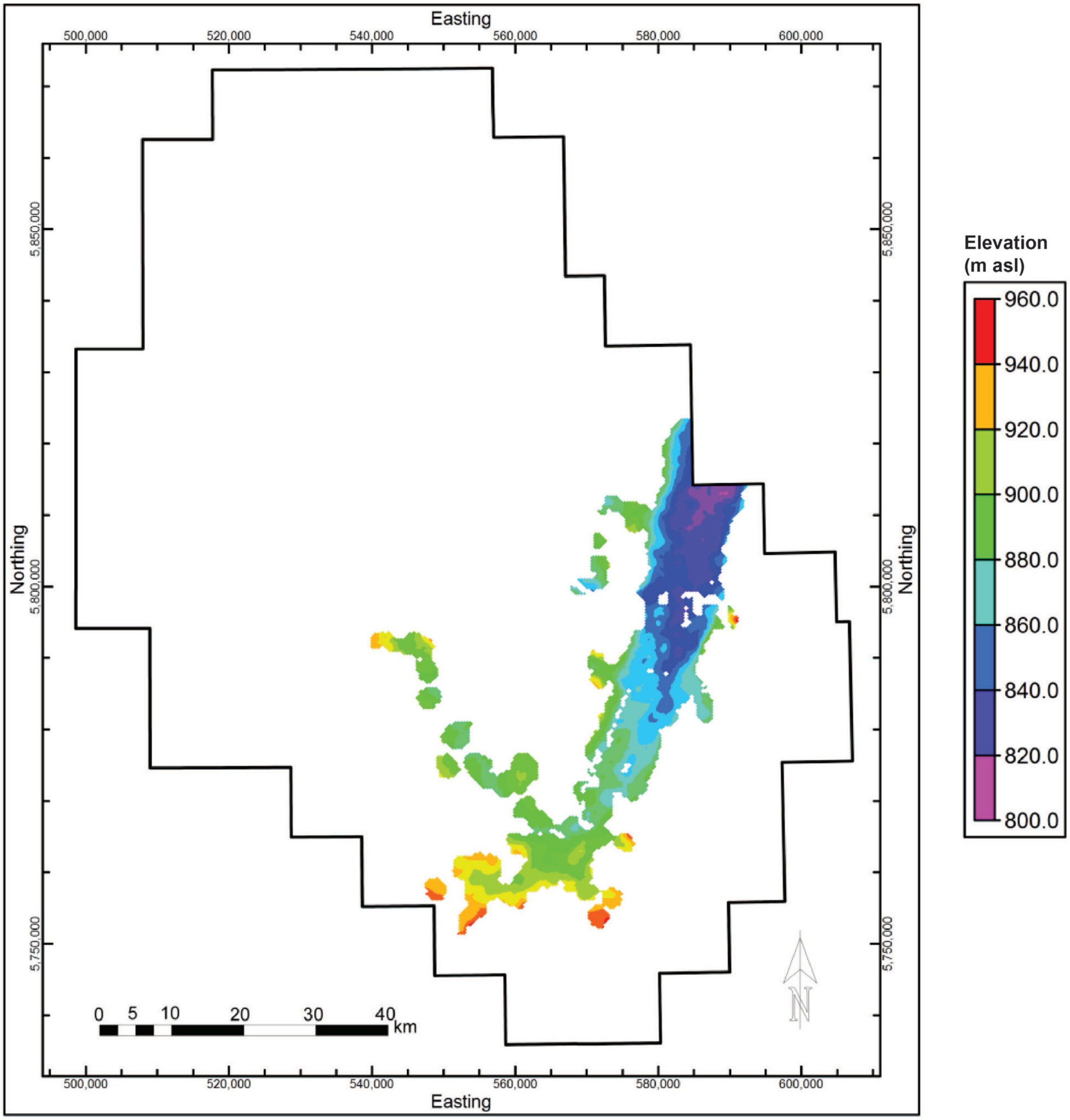


Figure 28. Structure elevation map of HSU S1 (top).

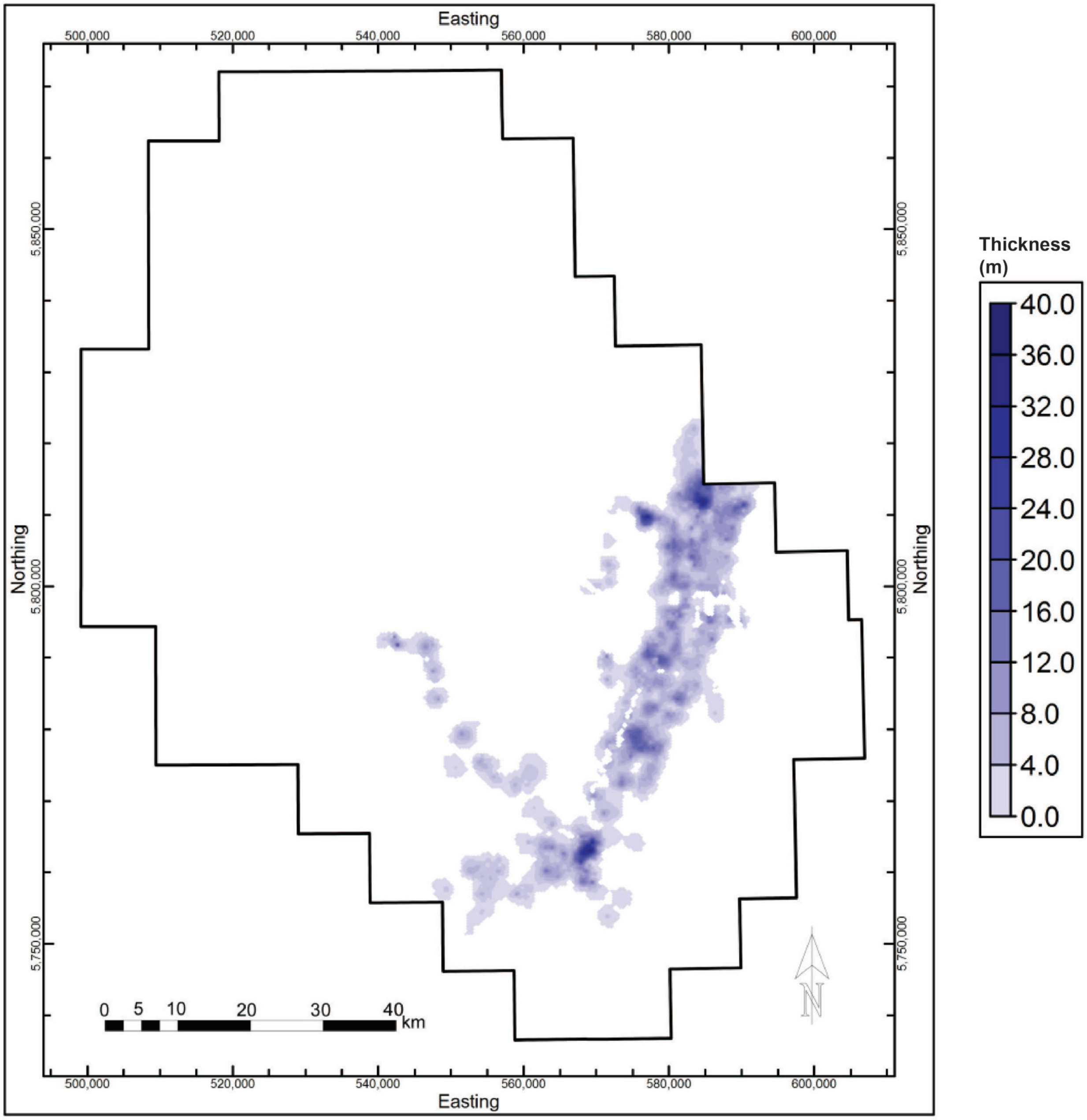


Figure 29. Isopach map of HSU S1.

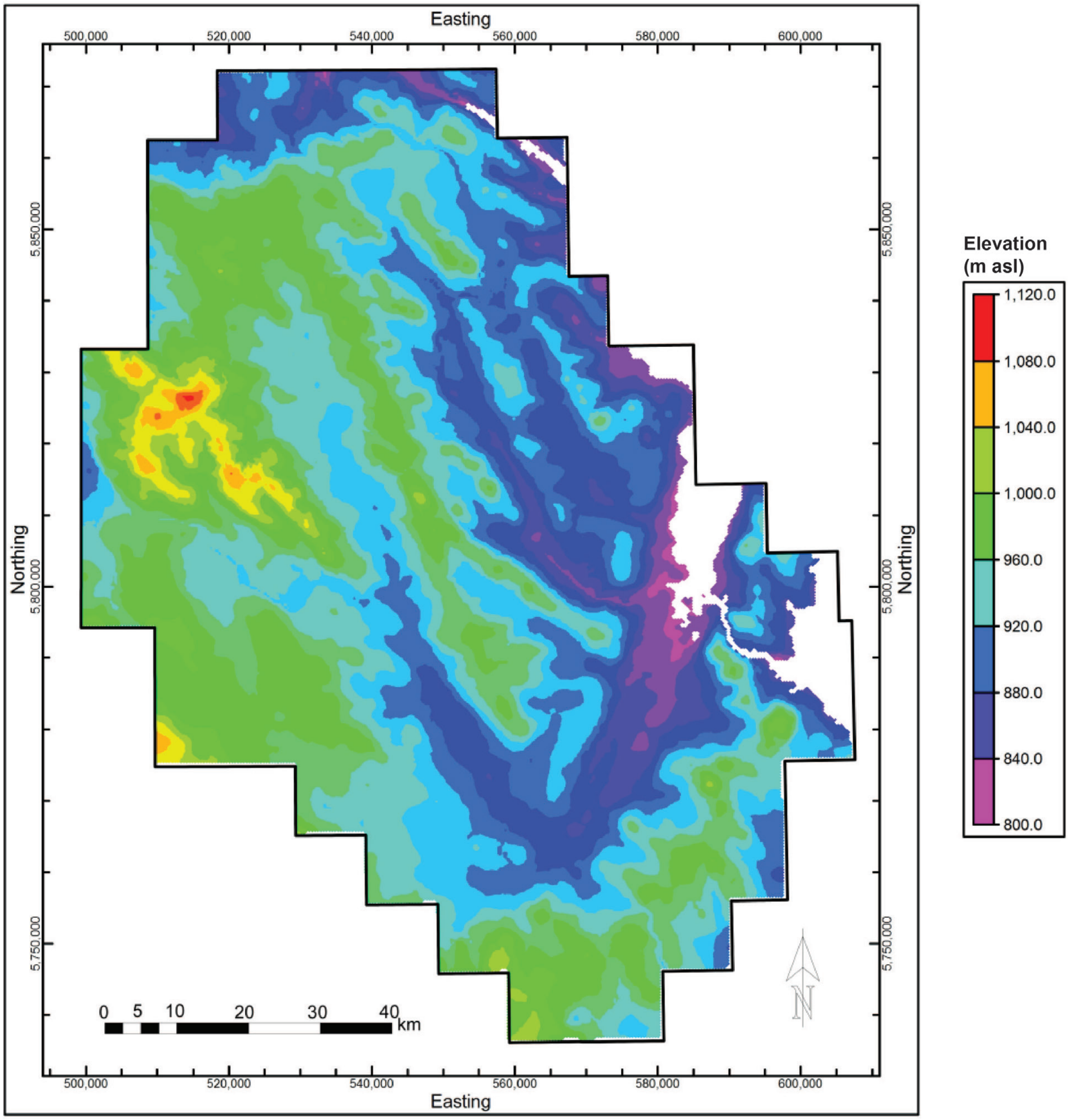


Figure 30. Structure elevation map of the Paskapoo Formation – upper composite slice (top).

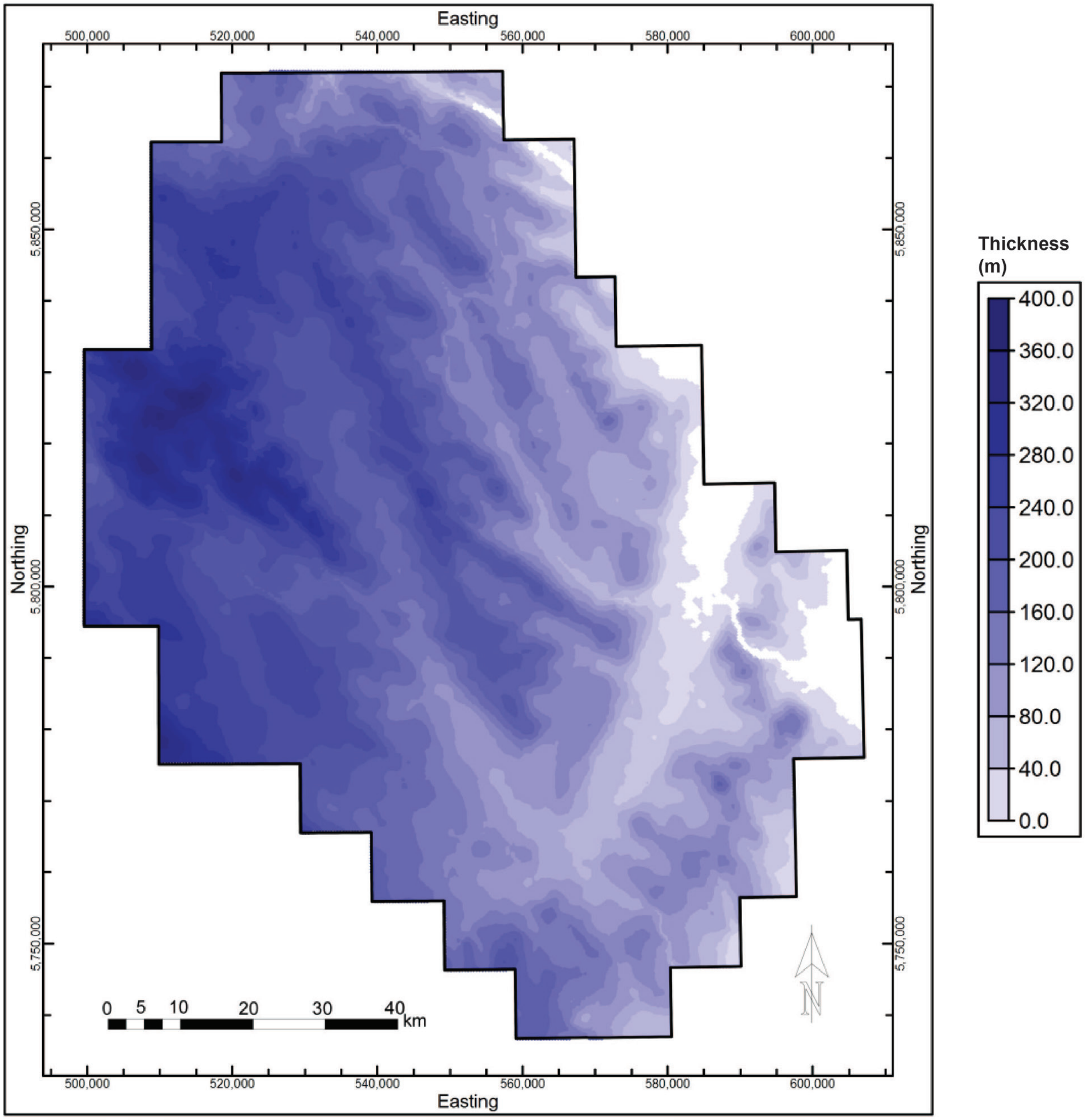


Figure 31. Isopach map of the Paskapoo Formation – upper composite slice.

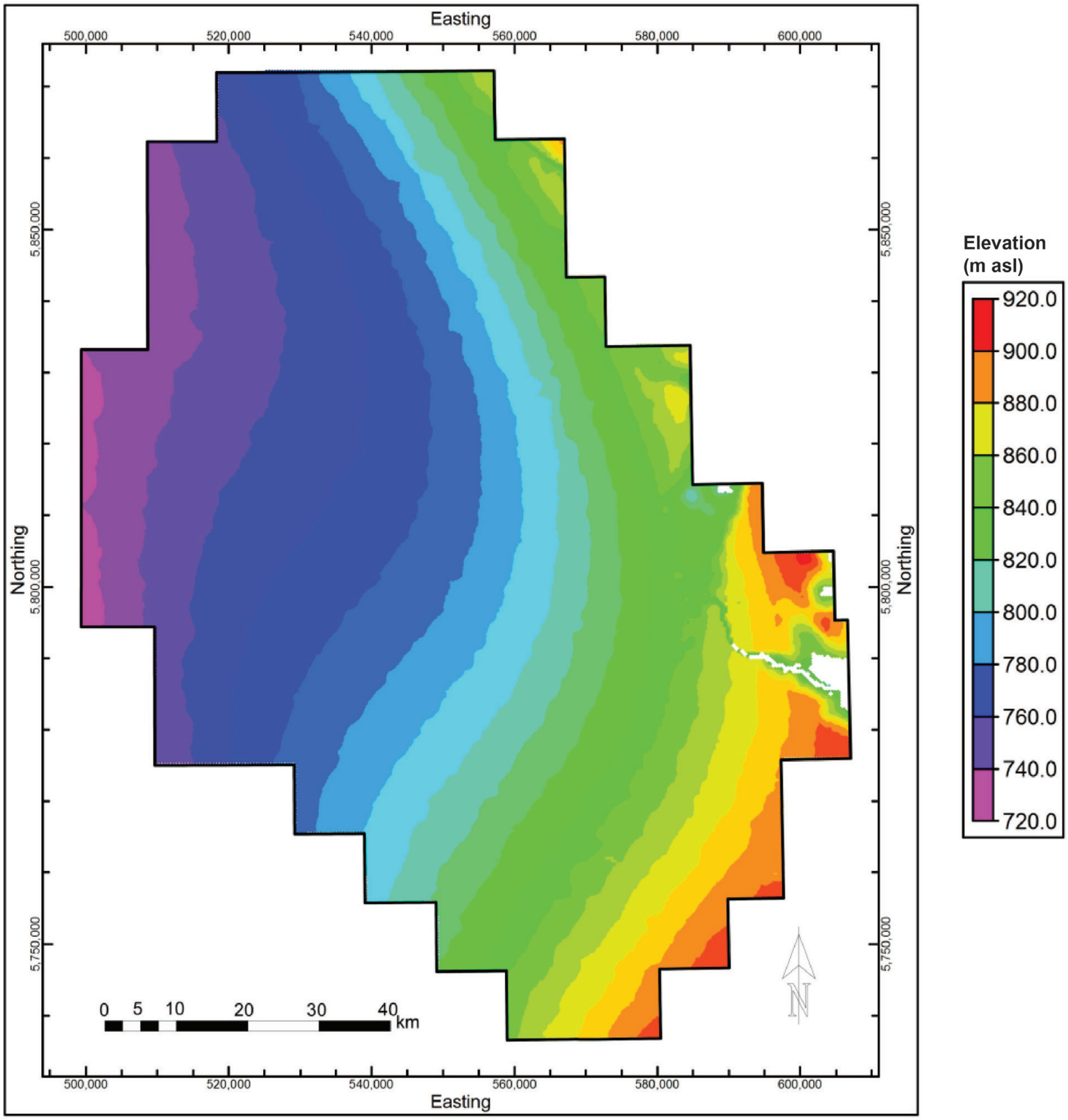


Figure 32. Structure elevation map of the Paskapoo Formation – middle composite slice (top).

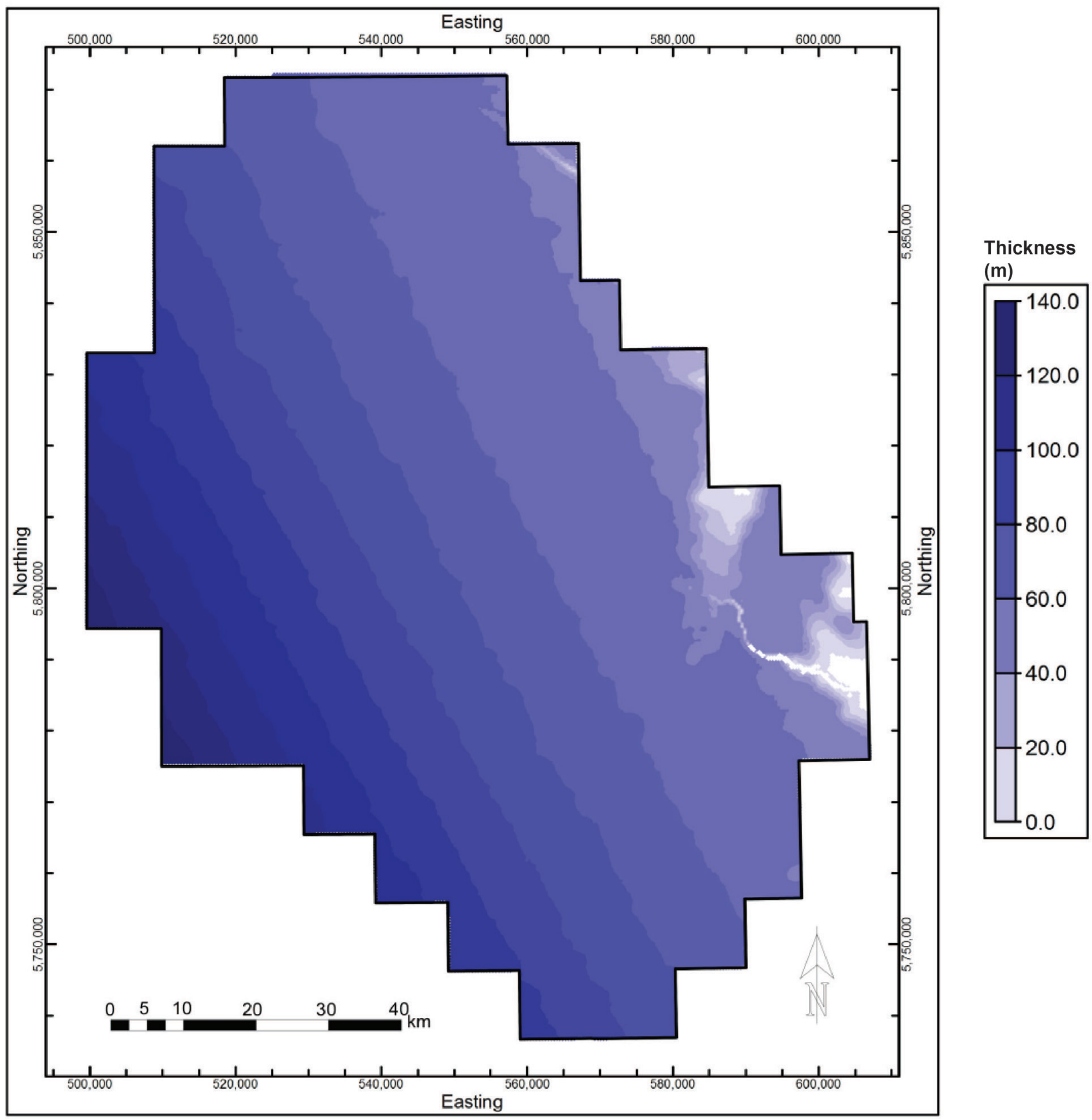


Figure 33. Isopach map of the Paskapoo Formation – middle composite slice.

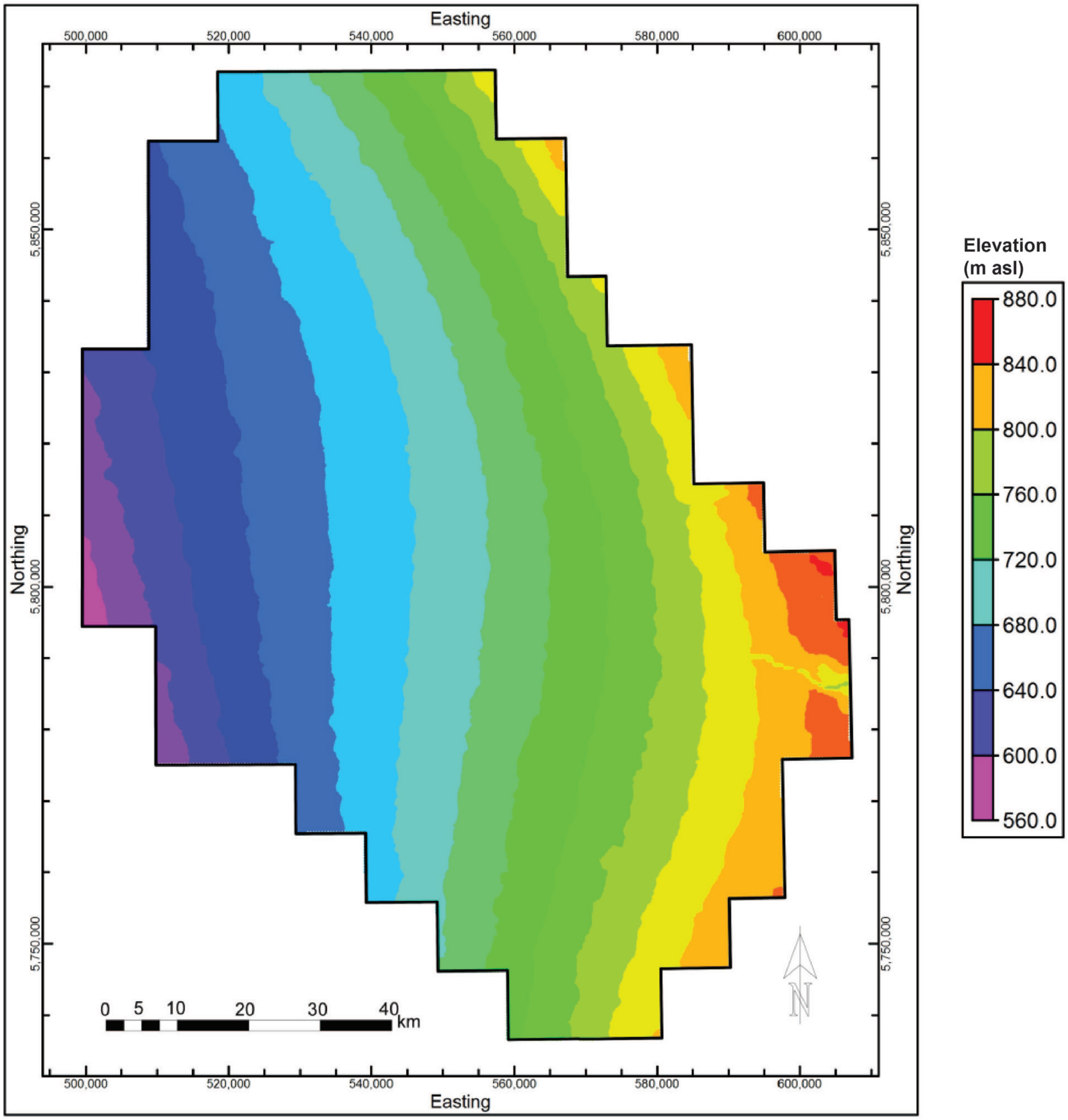


Figure 34. Structure elevation map of the Paskapoo Formation – lower composite slice (top).

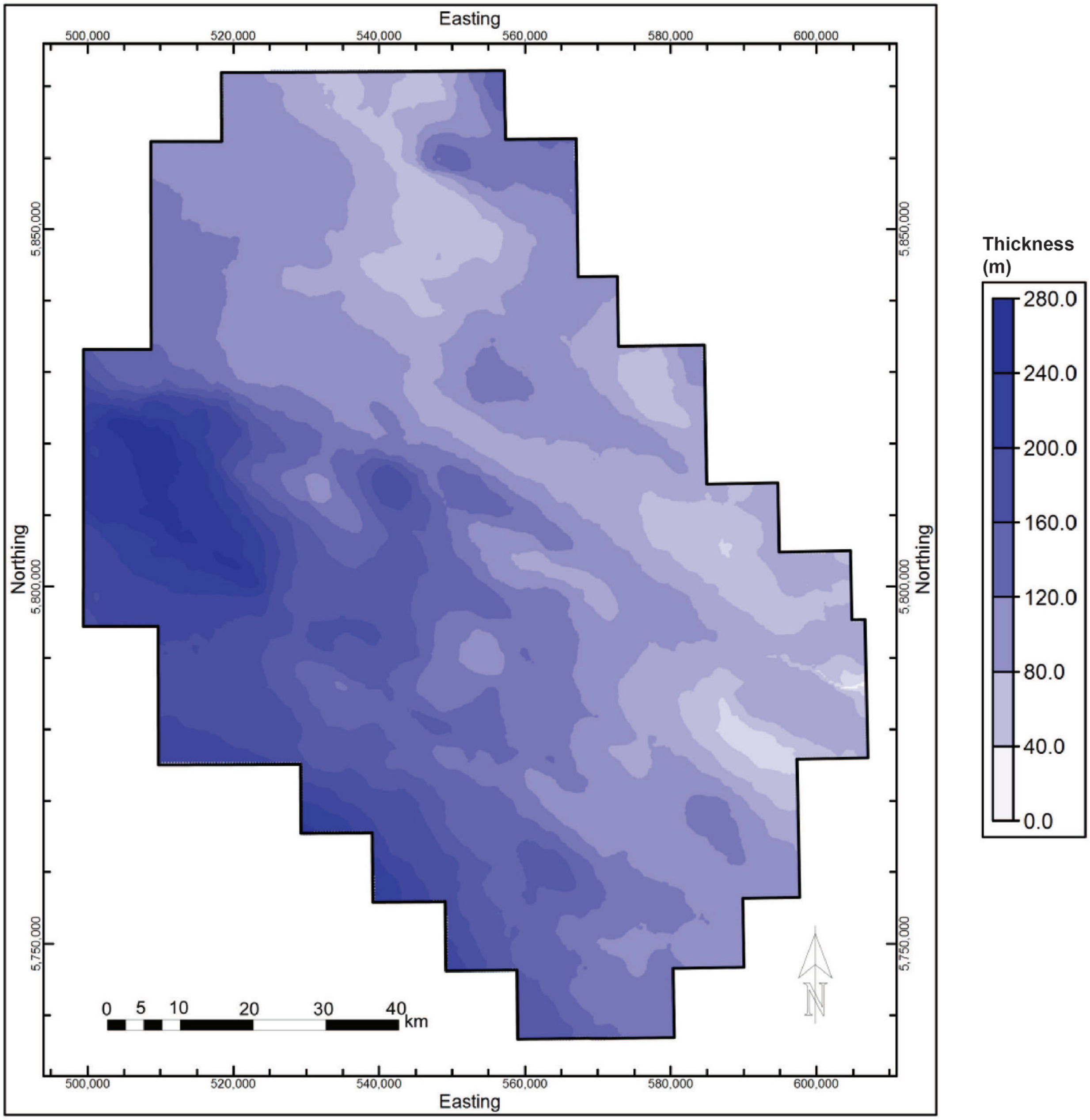


Figure 35. Isopach map of the Paskapoo Formation – lower composite slice.

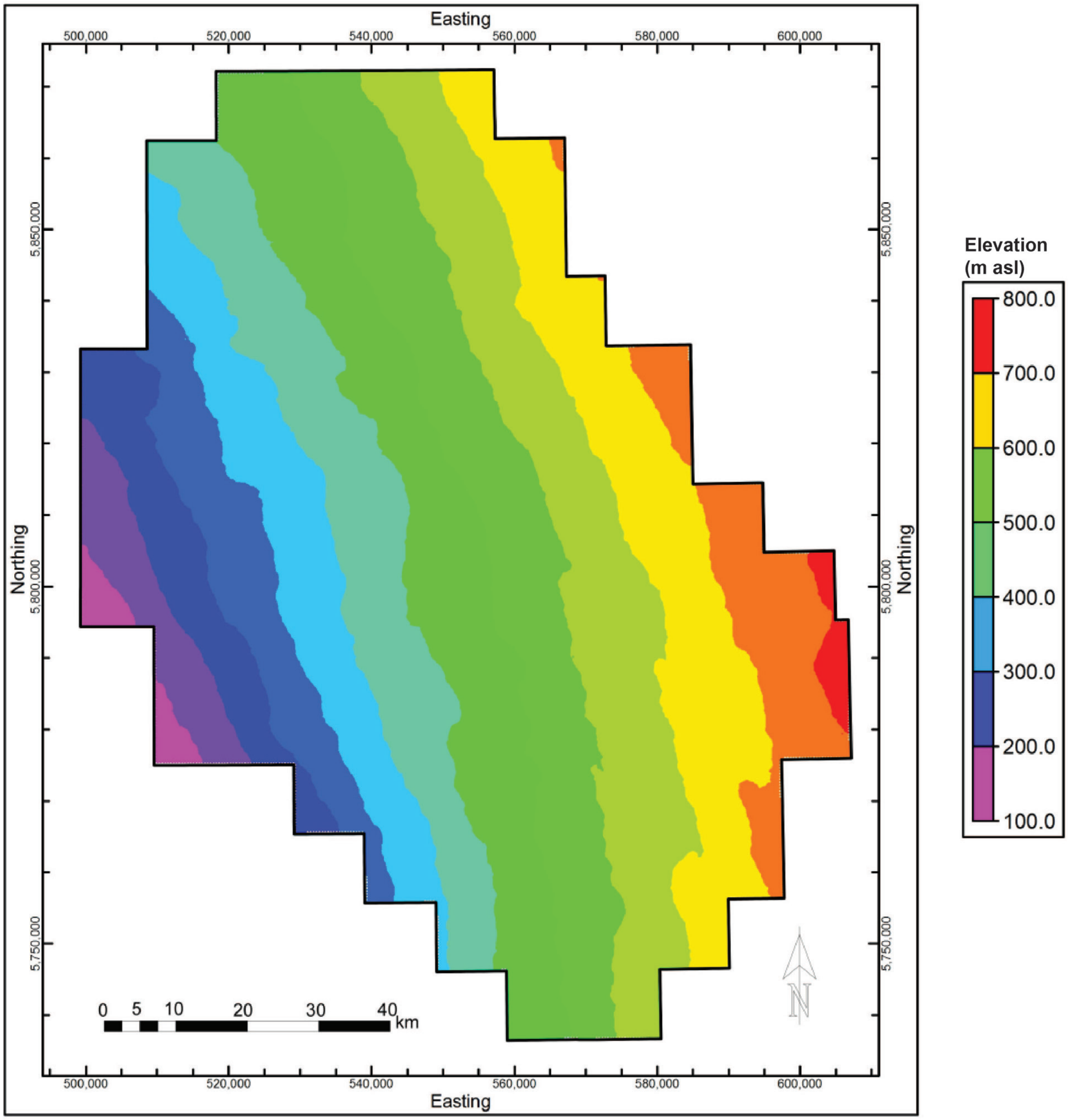


Figure 36. Structure elevation map of the Scollard Formation (top).

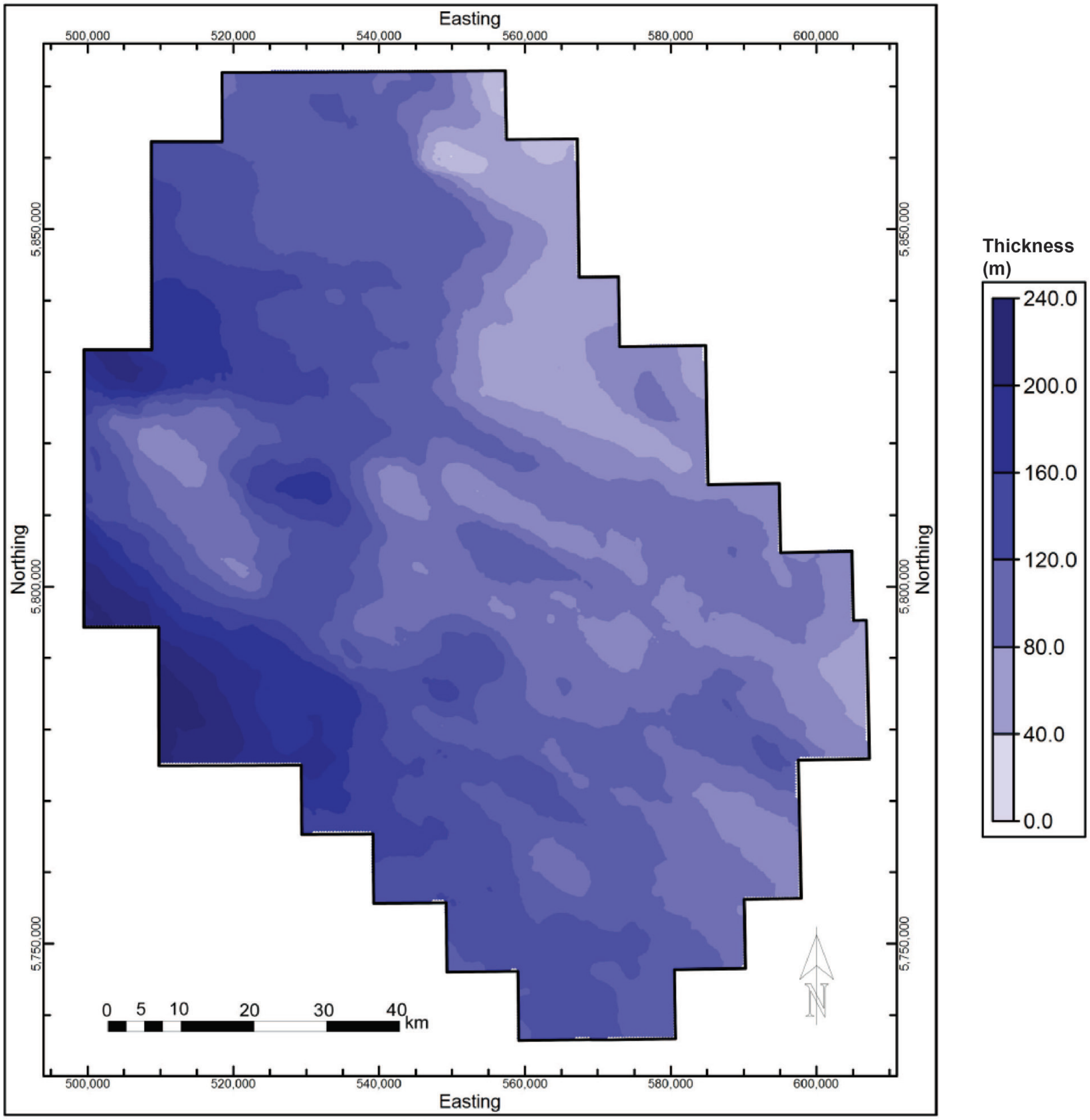


Figure 37. Isopach map of the Scollard Formation.

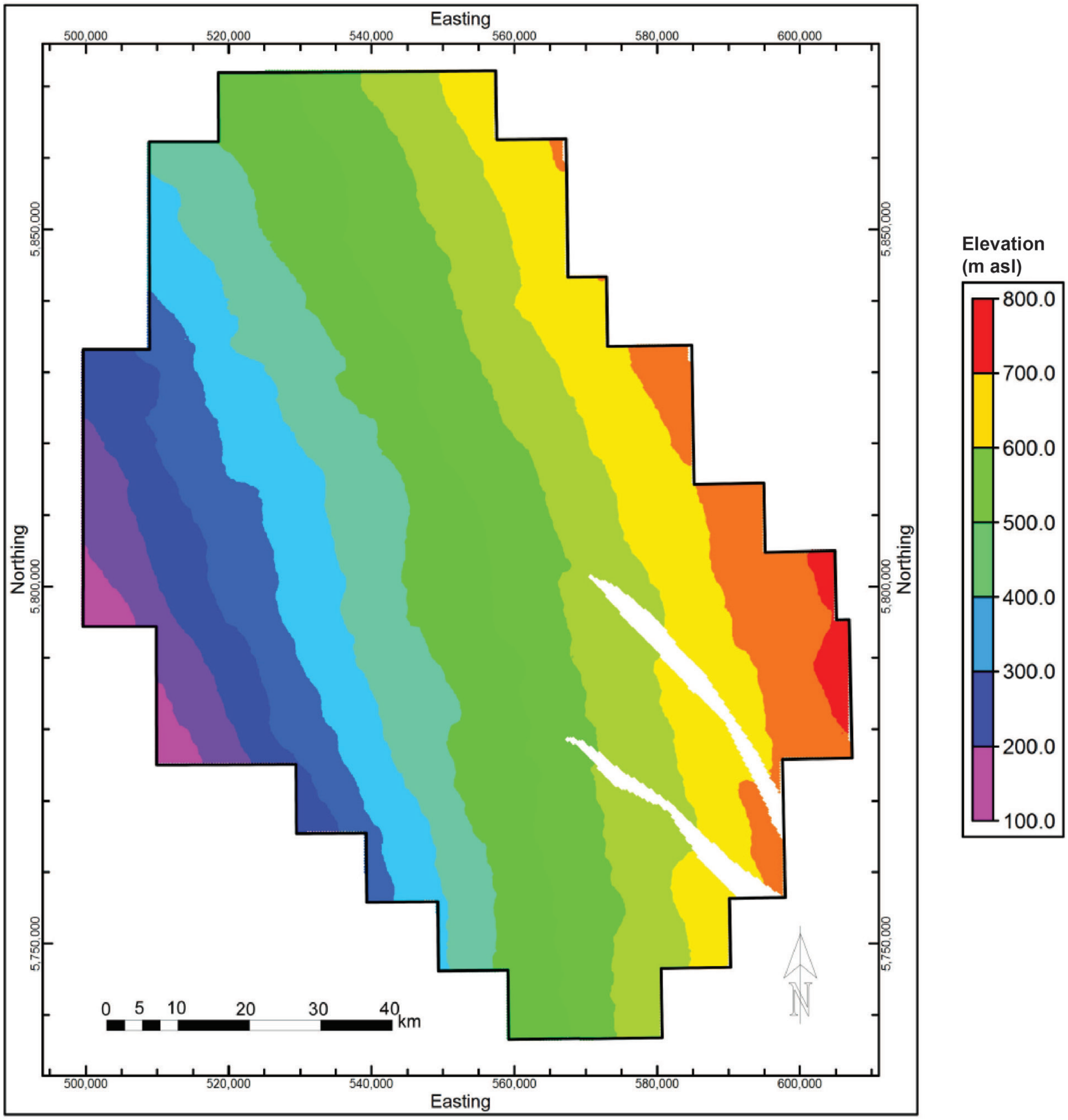


Figure 38. Structure elevation map of the Battle Formation (top). The two unshaded linear trends represent paleovalleys incised into the Battle Formation.

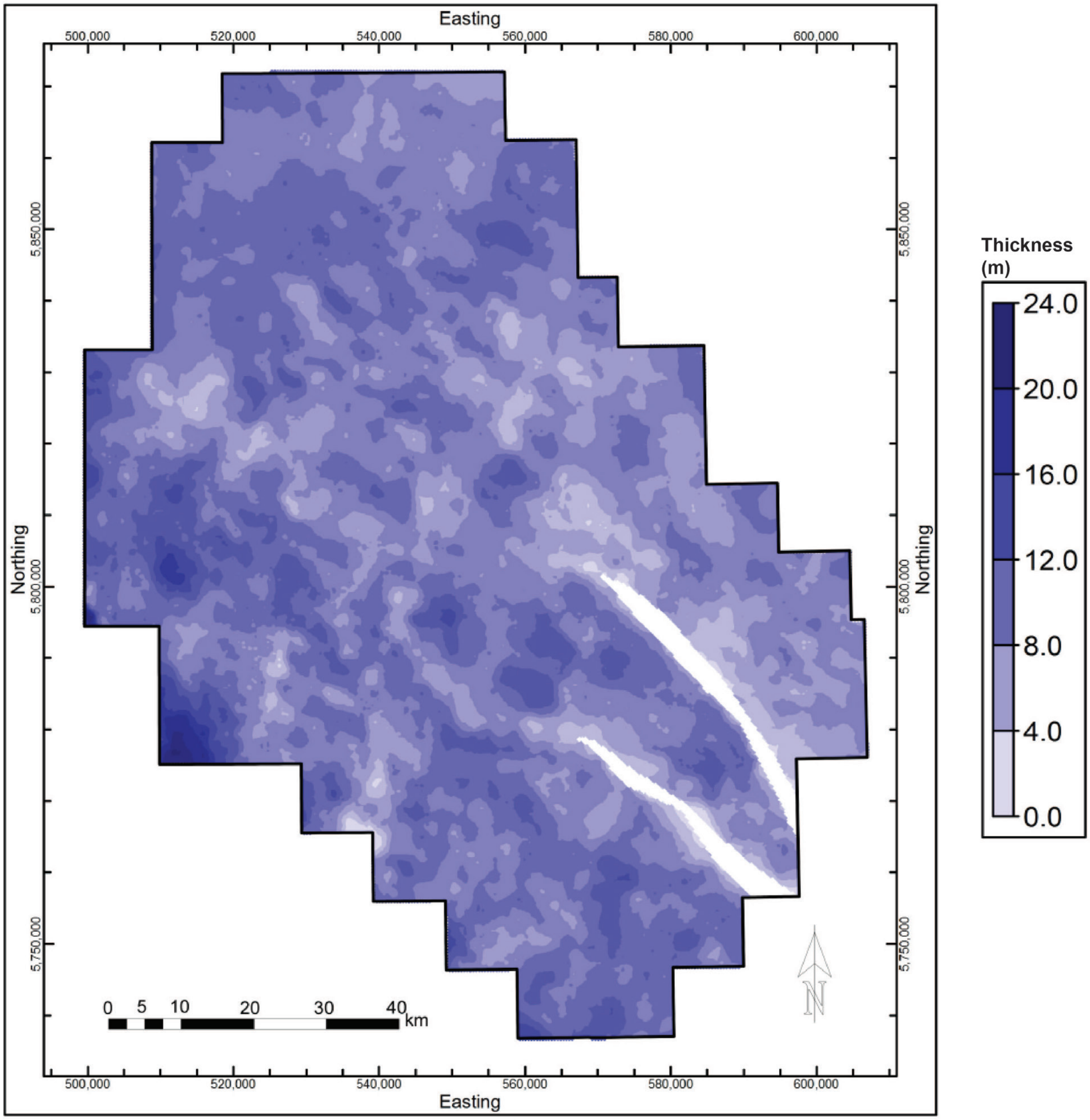


Figure 39. Isopach map of the Battle Formation.

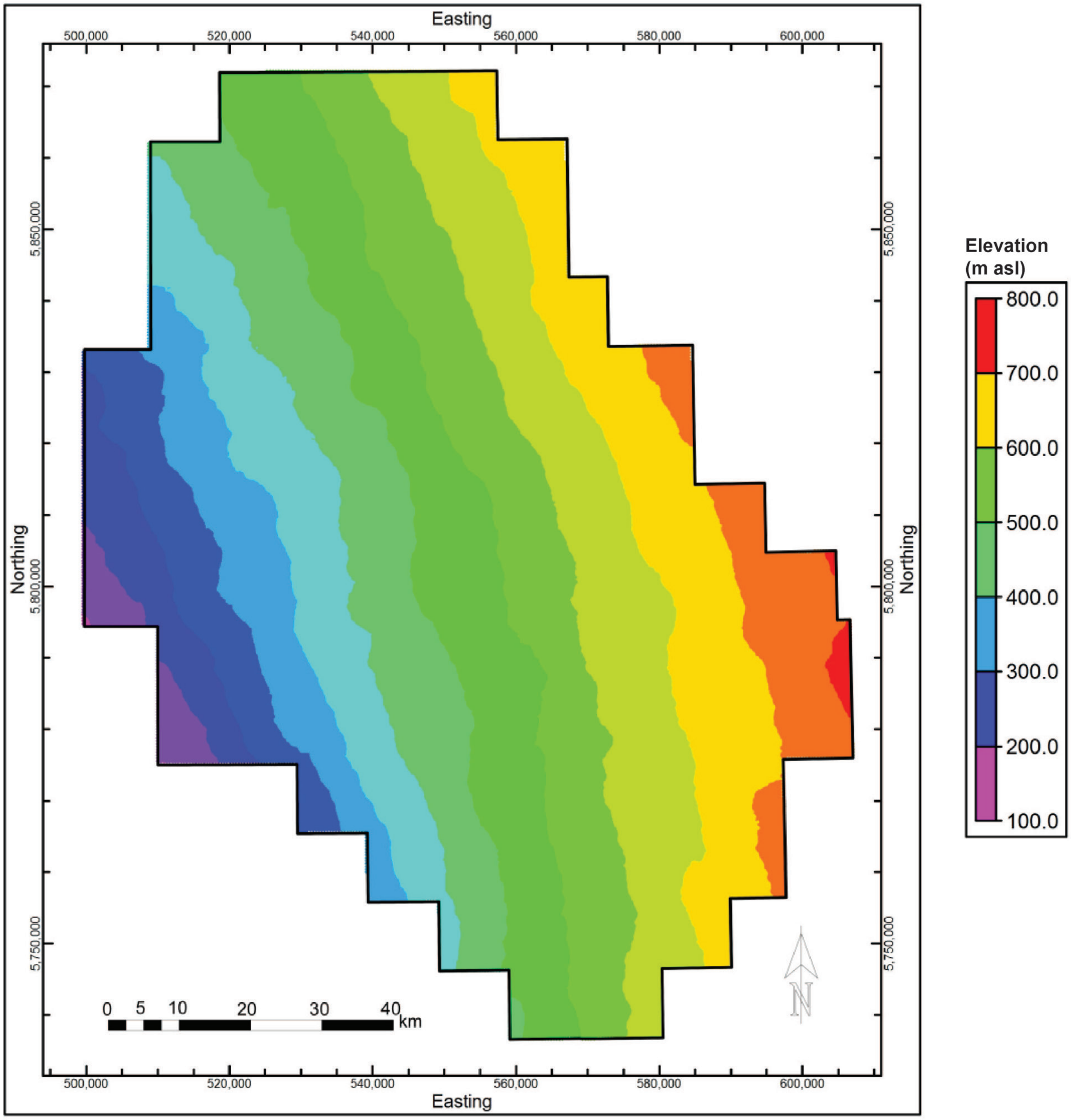


Figure 40. Structure elevation map of the Wapiti Formation (top).

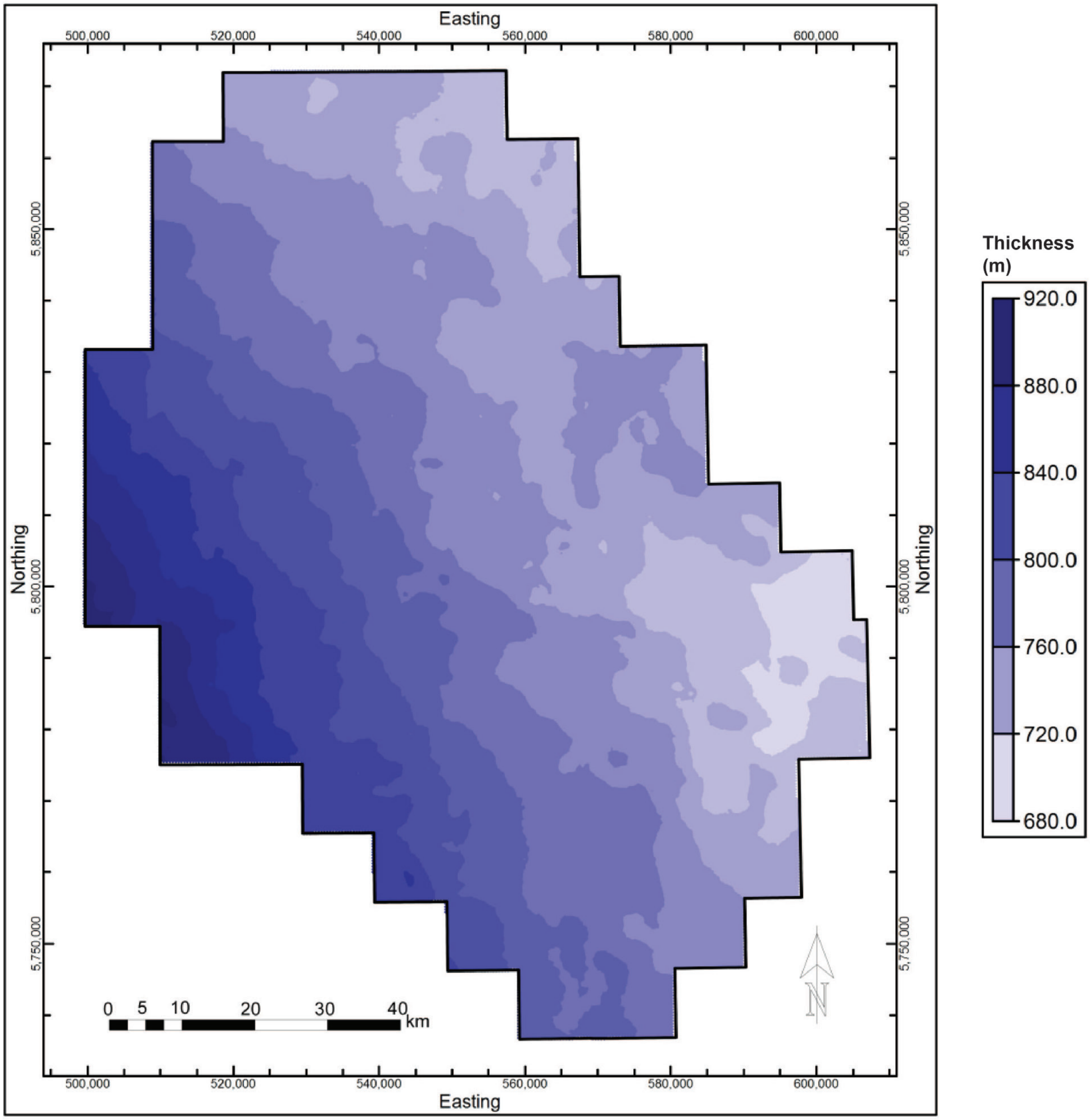


Figure 41. Isopach map of the Wapiti Formation.

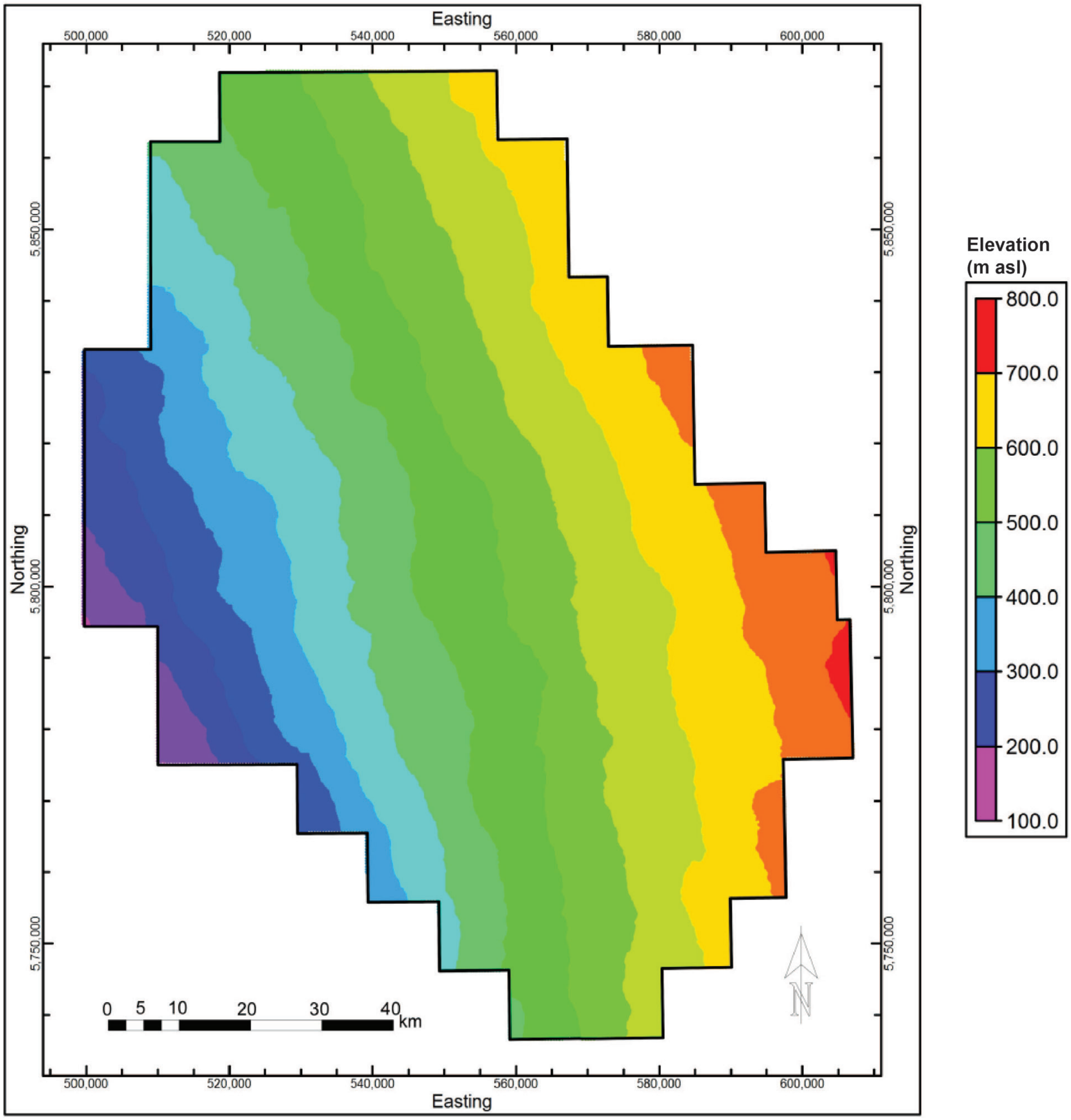


Figure 42. Structure elevation map of the Lea Park Formation (top).