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Controls on Fluid Flow Systems in Northern Alberta as Related to MVT Mineralization: A Contribution to the Carbonate-Hosted Pb-Zn (MVT) Targeted Geoscience Initiative

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Cover Photo: Saline spring discharge on Lambert Creek, 3.2 km upstream from the confluence with Harper Creek.

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Abstract

Large-scale fluid migrations control the mobilization, transportation and mineralization events that form Mississippi Valley-type (MVT) lead-zinc ore districts within a basin. Therefore, an analysis of the favourable features and components that control fluid flow related to possible MVT mineralization in the Alberta portion of the Western Canada Sedimentary Basin allows for the delineation of high probability areas for exploration.

For northern Alberta, the potential flow mechanisms responsible for MVT mineralization are reviewed, and the literature about past and present flow systems is summarized. Definition of the regional hydrostratigraphic framework and associated permeability values show that, the Keg River Formation, Presqu'ile barrier complex and Grosmont Formation represent the most favourable conduits for MVT ore-forming fluids in northern Alberta. Within these more prospective rock packages, more localized conduits of focused fluid flow, such as faults, breccias, shear zones, structural highs or stratigraphically thick to thin zones, have been identified and evaluated in the context of prospectivity for MVT mineralization. Some examples include the Great Slave Lake Shear zone and the Peace River arch area where there are a large number of pre-Carboniferous faults. As well, along the south-eastern portion of the study area some large faults are also associated with local structural highs. Lithochemical analyses of basement rock, a potential source of MVT metals, show an area of coincident high Pb and Zn concentrations east of the Peace River Arch and south of the Great Slave Lake Shear zone in the Ksituan region. Finally, mapping of formation water salinity in the Elk Point and Beaverhill Lake Groups identified high salinity water (>150 g/l Cl) needed for metal-mobilization around the Peace River Arch in the Beaverhill Lake Group and along the edge of the Prairie Evaporite in the Elk Point.

In conclusion, investigation of hydraulic heterogeneities, formation water salinity and metal sources suggests that around the Peace River Arch, along the Great Slave Lake Shear zone, between 118° and 116°W and at the margin of the basin, between 56.5° and 57.5°N would be good target areas for MVT exploration, in northern Alberta.

1 Introduction

The successful development of a Mississippi Valley-type (MVT) Pb-Zn ore district relies on the co-existence of large volumes of high salinity, metal-bearing water, warm temperatures, and a source of reduced sulphur for the duration of mineralization in a permeable, carbonate host rock. All of these components are present in abundance in sedimentary basins; however, they are rarely coexistent for long enough to accumulate an economic ore district. In addition, the high grades (5 to 10 wt%) and large tonnage in MVT deposits, combined with low solubility of Pb and Zn in basinal brines, suggest that a large volume of water is required for the formation of observed ore deposits (Anderson and Macqueen, 1982). Mass balance calculations have determined that ore-forming fluids containing a minimum of 1 ppm aqueous Pb and Zn must pass through the host rock for 0.2 to 5 Ma to concentrate the observed ore (Garven, 1985). The volume of ore-forming fluids is on the order of hundreds of cubic kilometres, suggesting that the flow system is active at a regional-scale (Bethke and Marshak, 1990).

In general, the flow system controls the timing of the ore mineralization, whereas the spatial location of an ore district can be a function of geological structure and permeability (e.g., breccias, karst or local basement highs) and/or chemical traps (e.g., mixing zones, redox barriers or temperature and pressure changes).

This report discusses regional-scale flow mechanisms, which become active during the evolution of sedimentary basins, in the context of MVT mineralization. This discussion includes a review of past and present regional flow systems, and possible sources of metals and highly saline water, needed for metal mobilization in northern Alberta. Fluid flow pathways (e.g., aquifers, faults) and fluid focusing features (e.g., facies changes, basement highs) are also identified. All these data are integrated to delineate potential target areas for MVT exploration in northern Alberta.

2 Regional-Scale Fluid Flow Systems in Northern Alberta

Of the many proposed fluid-flow models that explain the genesis of MVT Pb-Zn deposits, no single model best describes all MVT deposits. The flow regime associated with a MVT deposit must (a) be controlled by a constant driving force that can supply enough water, i.e., pore volumes, and (b) flow at a rate that accounts for the observed thermal anomalies, and is required to mobilize the metals (1-10 m/yr, Garven, 1985). A feasible genetic model for MVT deposits may require two or three of the following fluid flow regimes (Figure 1), depending on the mechanism for sulphate reduction and sulphide precipitation (see Leach and Sangster, 1993 for a review).

1) *Topography-driven flow* develops due to a hydraulic head difference between a topographic uplift near the deepest part of the basin and its erosional margin (Garven and Freeze, 1984). This situation often develops through tectonic rebound following orogenic activity. Garven (1985) simulated a gravity-driven flow system which generated sufficient flow rates (1-10 m/yr) to explain MVT ore districts, e.g., Pine Point, assuming a minimum of 1 ppm dissolved metal.

2) *Thermo-haline convection cells* often develop due to vertical temperature gradients and increased water salinities (Combarnous and Bories, 1975). In extensional settings, density-driven convection cells (0.1-1 m/yr) dominate as the gravity-driven flow system decays at the beginning of the flexural stage of rift basin genesis (Person and Garven, 1992), e.g., Nanisivik, NWT (Leach and Sangster, 1993).

3) *Tectonically-driven flow*: Oliver (1986) proposed that large brine migrations are induced by thrust

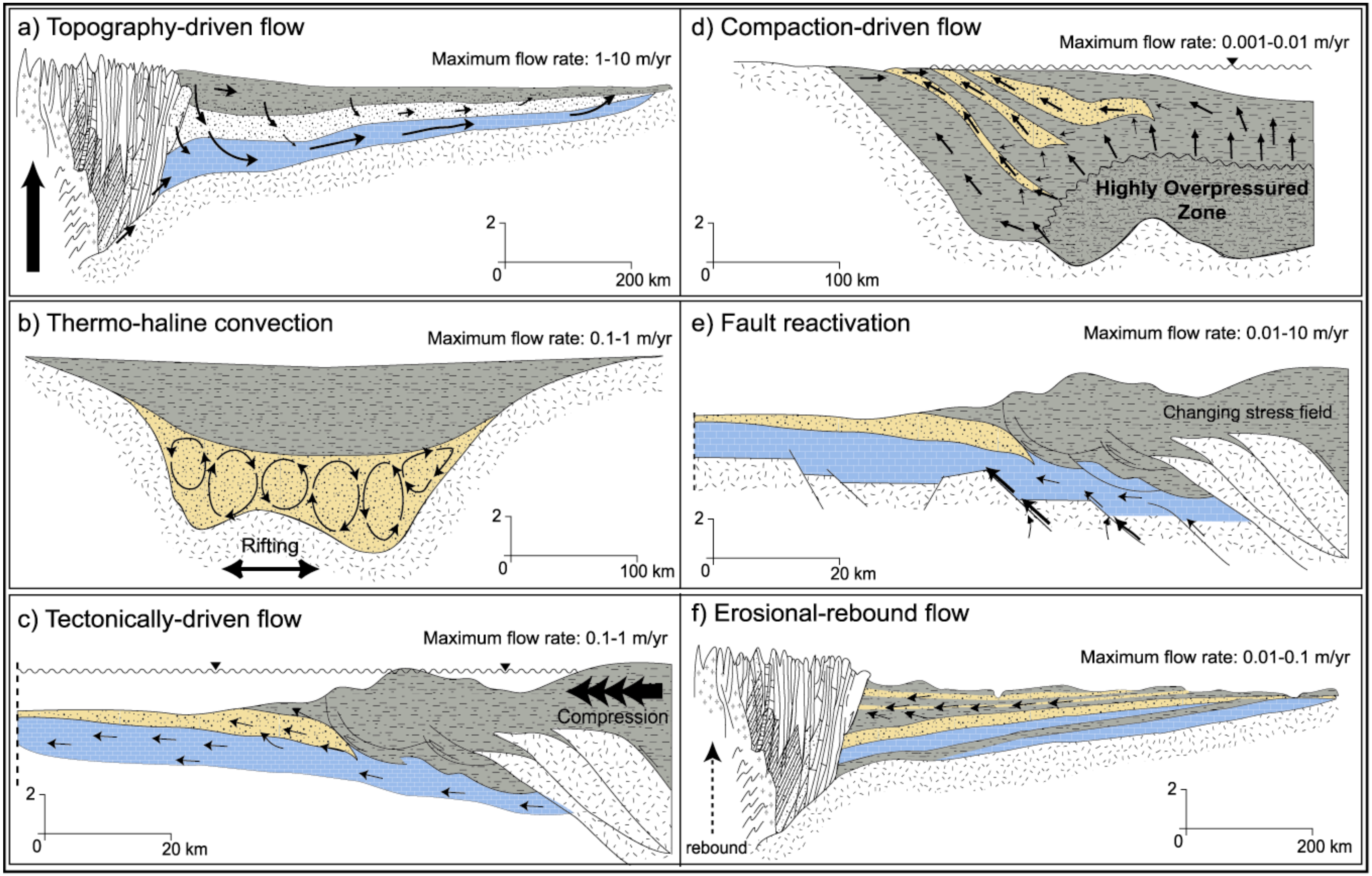

Figure 1. Basinal flow regimes: a) topography-driven flow due to tectonic rebound; b) thermo-haline convection during rifting; c) tectonically-driven flow during orogenic activity; d) compaction-driven flow; e) fault reactivation due to changes in the stress regime; and f) erosional-rebound flow. Small vectors indicate direction of groundwater flow. Large arrows indicate basinal forces or stresses. Note scale changes for each case. (Modified from Garven, 1995).

sheets 'overriding' sedimentary packages in foreland basins. However, Ge and Garven (1992) demonstrated that an insufficient volume of fluid is expelled during a compressional tectonic event to account for MVT deposits, despite the adequately high flow rates of 0.1-1 m/yr. Sufficient flow may be attained if brines are focused into aquifers, but the driving force in this flow regime persists for only ~10 000 years (Bethke and Marshak, 1990).

4) *Compaction-driven flow* is caused by a reduction in porosity during burial of basinal sediments (Jackson and Beales, 1967). However, Bethke (1985) demonstrated that steady-state compaction-driven flow rates (0.1-1 cm/yr) are insufficient to account for thermal anomalies in many deposits by advection of heat, and for the mass of ore in economic ore districts. An end member of compaction-driven flow is *episodic basin dewatering* from overpressurized compartments in a rapidly subsiding basin (Cathles and Smith, 1983). This mechansim is dependent on sedimentation of shaly material at 1 km/Ma as can be found in the Gulf Coast basin, USA, resulting in rapid explusion of water through confined aquifers.

5) *Tectonic reactivation of deep seated basement faults* due to an adjustment in the tectonic regime may result in the discharge of deep brines upwards along the faults (Campbell, 1967; Hitchon, 1993).

6) *Erosion-rebound flow* that induces underpressures can develop in low permeability strata during dilation of the rock matrix caused by unloading or erosion (Neuzil and Pollack, 1982). These conditions cause flow in the direction of maximum unloading, usually down-dip. This type of flow system is extremely slow and cannot account for MVT mineralization.

There currently is no universally accepted genetic model for MVT Zn-Pb ore districts (Sangster, 1990). Nonetheless, recent paleomagnetic, fission track and radiometric dating have confirmed the genetic connection between MVT deposits and orogenic activity adjacent to the parent sedimentary basin. This correlation is thought to corroborate the development of regional topography-driven flow systems in response to tectonic uplift along the orogenic belt (Leach et al., 2001). In support of these findings, the numerical modelling discussed previously has predicted that only the higher flow rates of gravity-driven flow systems (1-10 m/yr) can account for ore tonnage and formation temperatures of MVT deposits at the margins of the basin (Garven, 1985; Bethke, 1986).

2.1 Alberta Basin Flow Systems

In general, flow regimes are dependent on i) *parent basin configuration* or spatial distribution of physical properties, e.g., aquifer connection, permeabilities and compressibilities, and ii) *driving forces* active in the basin, e.g., tectonics, fluid salinity and heat flow. The Alberta basin has assumed a suite of configurations in response to various tectonic regimes (Porter et al., 1982). Initial tilting and erosion of the Precambrian basement was followed by a passive margin stage, characterized by carbonate sedimentation. This was followed by the onset of active compressional tectonics and significant clastic sedimentation during the Columbian and Laramide orogenies. Most recently, mechanical unloading, hydrocarbon generation, topographic rebound and glaciation have also altered the basin stratigraphy and driven fluids across the basin. Many of these stages were associated with fluid flow through existing aquifers at local and regional scales.

2.1.1 Present Day Regional Fluid Flow

A combination of driving forces, fluid types and permeabilities has produced the complex fluid flow patterns observed in the basin today. These fluid flow patterns across the Alberta basin are representative of ‘decayed’ topography-driven flow systems controlled by the Rockies and topographic highs in Montana (Bachu and Underschultz, 1992, 1993; Bachu, 1997). These patterns show that northern Alberta is a transition zone between the central Alberta flow system and the NWT flow system. The present day flow systems are inadequate for the development of an ore district, in that the flowrates are too slow (Bethke, 1986; Bachu, 1999); however, they do help to delineate permeable pathways, such as aquifers.

In the Peace River Arch area, the Colorado Group aquitard separates flow in the post-Colorado clastic wedge from the flow system in the underlying passive margin carbonate succession (Tóth, 1978; Tóth and Corbet, 1986; Bachu, 1995; Rostron and Tóth, 1997). Flow in the post-Colorado sequence is controlled by local topographic highs; that is, meteoric water recharges at topographic highs and local river valleys act as discharge zones. The flow system has reached equilibrium with topography (Parks and Tóth, 1995). Beneath this flow zone within sand lenses of the western portion of the Colorado Group, measured hydraulic pressures are lower than the lowest surface elevation in the basin, moving water southwesterly towards the disturbed belt. This underpressuring is interpreted as delayed adjustment to Cenozoic erosion due to the extremely low permeability of Colorado shales (Tóth and Millar, 1983). At the eastern margin of the basin, salinity and flow in all strata are controlled by local topographic relief (Barson et al., 2001).

Across northern Alberta, fluid pressures in the passive margin carbonate succession are sub-hydrostatic in the deep basin; nonetheless, the hydraulic gradient drives fluids updip to discharge in the northeast at the erosional margin. This flow system resembles gravity-driven flow (Bachu, 1995), but the pattern is difficult to reconcile with that in the overlying stiff, low permeability, Colorado shales. These shales restrict recharge into the underlying carbonate aquifers (Bachu, 1995). Tóth (1978), and Tóth and Millar (1983) proposed the carbonate flow pattern is a relic from an earlier period dominated by topography-driven flow that most likely was prevalent shortly after maximum burial. Considering parallel cross-sections further north along the NWT-Alberta border, the same slow topography-driven flow system exists. The flow system extends up through the sedimentary succession, because the Fort St. John Group strata, which are equivalent to the Colorado Group aquitard, are more permeable, thereby allowing hydraulic connection between the passive margin carbonate aquifers and the overlying foreland clastic aquifers. This connection is confirmed by evidence for intrusion of meteoric water into the deep basin at its western margin (Bachu, 1997).

2.1.2 Paleohydrogeology

For exploration purposes, an understanding of paleohydrogeology is more useful than present-day flow patterns in identifying potential ore-forming zones. For these reasons, a series of cross-basin studies have investigated stable and radiogenic isotopes, as well as solute chemistry of formation waters and fluid inclusions, to delineate the timing, direction and magnitude of paleoflow (Machel and Mountjoy, 1987; Nesbitt and Muehlenbachs, 1994; Nesbitt, 1995; Mountjoy et al., 1997; Nesbitt and Prochaska, 1998; Machel and Cavell, 1999; Mountjoy et al., 1999). In the Alberta basin, the Peace River Arch has acted as a major hydraulic and thermal divide, separating northern from central and southern regions of the basin (Mountjoy et al., 1997). Similarly, fluid flow history can be subdivided into the passive margin stage, characterized by local shallow matrix dolomitization and subsequent burial replacement dolomitization, and the Mesozoic and Tertiary flow systems of the clastic foreland controlled by tectonics along the western margin of the basin.

Until the Middle Devonian, the northern Alberta basin consisted of a series of evaporitic subbasins, separated by basement topographic highs, e.g., Peace River Arch or Tathlina Uplift, that may have controlled fluid flow at the time. By the end of the Devonian, basement highs had been buried by the extensive Devonian carbonates, which have been significantly dolomitized (Machel and Mountjoy, 1987; Machel and Anderson, 1989; Kaufman et al., 1991; Amthor et al., 1993, 1994; Mountjoy and Amthor, 1994; Drivet and Mountjoy, 1997; Mountjoy et al., 1997; Mountjoy et al., 1999; Mountjoy et al., 1999; Green, 1999; Duggan et al., 2001). Multiple diagenetic and epigenetic carbonate phases in the Devonian carbonates record various fluid events across the basin, whose genesis is hotly debated (Morrow, 1998). Generally, early matrix dolomite is associated with stylotization, suggesting a genetic connection with shallow burial (~500 m) and vertical compaction. High sedimentation rates (1 to 10 mm/yr) are needed to provide regional compaction-driven flow systems (Bethke, 1985). These conditions would have been rare in the passive margin succession, suggesting that local flow may have dominated.

A second dolomite phase, massive replacement dolomite, has been found in the carbonates across the basin, e.g., Grosmont Fm., Leduc reefs, Swan Hills reefs, Presqu'ile barrier reef complex and the Rimbey-Meadowbrook trend. These dolomites required large volumes of water carrying Mg, with the fluids being driven by many possible forces. Mountjoy and Amthor (1994) suggested that both topography-driven and tectonically-driven flow during the Antler orogeny dolomitized much of the basin. The northern limit of Antler tectonics has not been confirmed, but there is no evidence of compressional deformation in the disturbed belt adjacent to northern Alberta (Root, 1993; Colpron et al., 2000). Shields and Brady (1995) proposed that seepage reflux of seawater may have been responsible for the massive dolomitization, but this mechanism is dependent on thick packages of permeable rock. Morrow (1998) maintains thermo-haline convection of highly saline brine could also have accomplished such dolomitization. These systems may have been active in the Devonian and Carboniferous, but there is no evidence of high heat flow or localized sources of high salinity water.

Other carbonate deposition phases include fracture filling in the Peace River Arch area, which document multiple periods of fracturing that resulted in fluid focusing along fractures and precipitation of dolomite. Similar fracture-fill dolomite is found in northern Alberta in the Zama region (Lonnee et al., 2000) and at Pine Point, which suggests that tectonic adjustments have initiated fluid flow in the past. There is, however, no indication of the duration and magnitude of these flow systems for comparison with that required for MVT systems.

During the Laramide orogeny, rapid sedimentation of shales may have resulted in compaction-driven fluid flow as these high-water content rocks were dewatered during further burial (Bethke, 1985). As thrusting began, tectonically-driven flow may have been active during compressional pulses or loading (Oliver, 1986; Machel and Cavell, 1999). This type of flow only affects the foreland basin adjacent to the disturbed belt due to the limited duration of the driving force (~1000 to 10000 years; Ge and Garven, 1992), and therefore, cannot explain ore districts outside the disturbed belt. The last compressional pulse of the Laramide orogeny occurred during the Late Paleocene to Early Eocene (approximately 58 Ma; Fermor and Moffat, 1992; Willett et al., 1997). In the central portion of the Alberta basin, maximum burial caused oil and gas generation, which may also have caused overpressuring, especially in the deep basin (Allan and Creaney, 1991). Extensional faulting and erosion of the fold and thrust belt caused tectonic rebound of the foreland basin. This topographic uplift is understood to have initiated regional topography-driven flow through the foreland basin (Garven, 1985). Saddle dolomite and late-stage calcite cements in permeable carbonate conduits are thought to be related to fluid flow associated with the Laramide orogeny. Deep burial, high temperatures and highly saline parent fluids are characteristic of saddle dolomite formation, which occurred prior to late-calcite cementation. The chemical character of late-stage calcites suggests that they formed from mixed Cretaceous meteoric waters during topography-driven flow in the Tertiary (Qing and Mountjoy, 1992; Mountjoy et al., 1997). As erosion lessened the topographic gradient, this flow system decayed back to local-scale flow near surface as described today (Bachu, 1995).

In general, the above indicates a variety of fluid driving forces were active during the Phanerozoic, whereas current fluid pressures provide clues to only the most recent flow systems. Whole paleo-fluid flow systems must be inferred from fluid inclusions in diagenetic and epigenetic minerals in the context of MVT mineralization potential (Gregg and Shelton, 1989; Savard and Kontak, 1998). The feasibility of any of these flow systems to form a MVT ore district has been evaluated for some cases using numerical models.

3 Controls on Fluid Flow

In general, Zn-Pb mineralized zones or deposits are hosted by highly permeable, regional aquifers, which often narrow laterally or vertically towards the deposits (Leach and Sangster, 1993). More specifically within the aquifer, the ore is precipitated in zones of enhanced permeability and/or in areas in which fluids are focussed. Thus, the strata of a basin define the hydraulic framework during mineralization and heterogeneities within the main conduits of ore-forming fluids act to define the areas in which the ore accumulates.

3.1 Hydrostratigraphy

At a regional-scale, aquifers, which often are porous carbonates or coarse clastic units, act as conduits for fluids within a basin. The strata within the Alberta MVT study area can be subdivided into a series of aquitards and aquifers, based on lithology, porosity and Drill Stem Test (DST) data collected by the petroleum industry (Figure 2). The following discussion is a summary of material published in Bachu and Underschultz (1992, 1993) and Bachu (1997), as well as paleo-reconstructions in Mossop and Shetsen (1994).

The Precambrian basement is considered an aquiclude, since the permeability of tight crystalline rock (10^{-17} to 10^{-22} m^2) is orders of magnitude less permeable than sedimentary rock (Freeze and Cherry, 1979). The relatively permeable saprolite layer and the sandstones and conglomerates of Granite Wash Fm. (thickness = 0 to 182 m) fill the irregular topography of the basement rock; however, the discontinuous nature of this unit requires that it be considered only a local aquifer. The overlying sequence of redbeds, evaporites and microcrystalline carbonates act as an aquiclude across northern Alberta, except near the Peace River Arch (PRA) where eroded detritus was deposited. The intervening Ernestina Lake Fm. is relatively permeable and would be considered an aquifer in a more detailed analysis.

The Keg River and Winnipegosis formations form the oldest regionally extensive aquifer in northern Alberta. These platformal carbonates are capped by the Prairie Fm. halite in eastern Alberta and the laterally equivalent anhydrites and fine-crystalline dolostones of the Muskeg Fm towards the wests. These two formations form an aquitard-aquiclude pair across all but the northwestern corner of Alberta, where the Pine Point Group and the Sulphur Point Fm. of the Presqu'ile barrier act as a highly permeable aquifer. Following a period of subaerial exposure, the regionally extensive Watt Mountain Fm. was deposited across Alberta and is considered a thin aquitard.

Further regression led to the deposition of anhydrite, interbedded with dolomite and limestone, (Fort Vermillion Fm.) across the southern and southeastern portion of the study area. These evaporites grade to the northwest and prograde upwards into more permeable carbonates, which are included in the Slave Point aquifer. The limy shales and argillaceous micrites of the Waterways Fm grade laterally into the

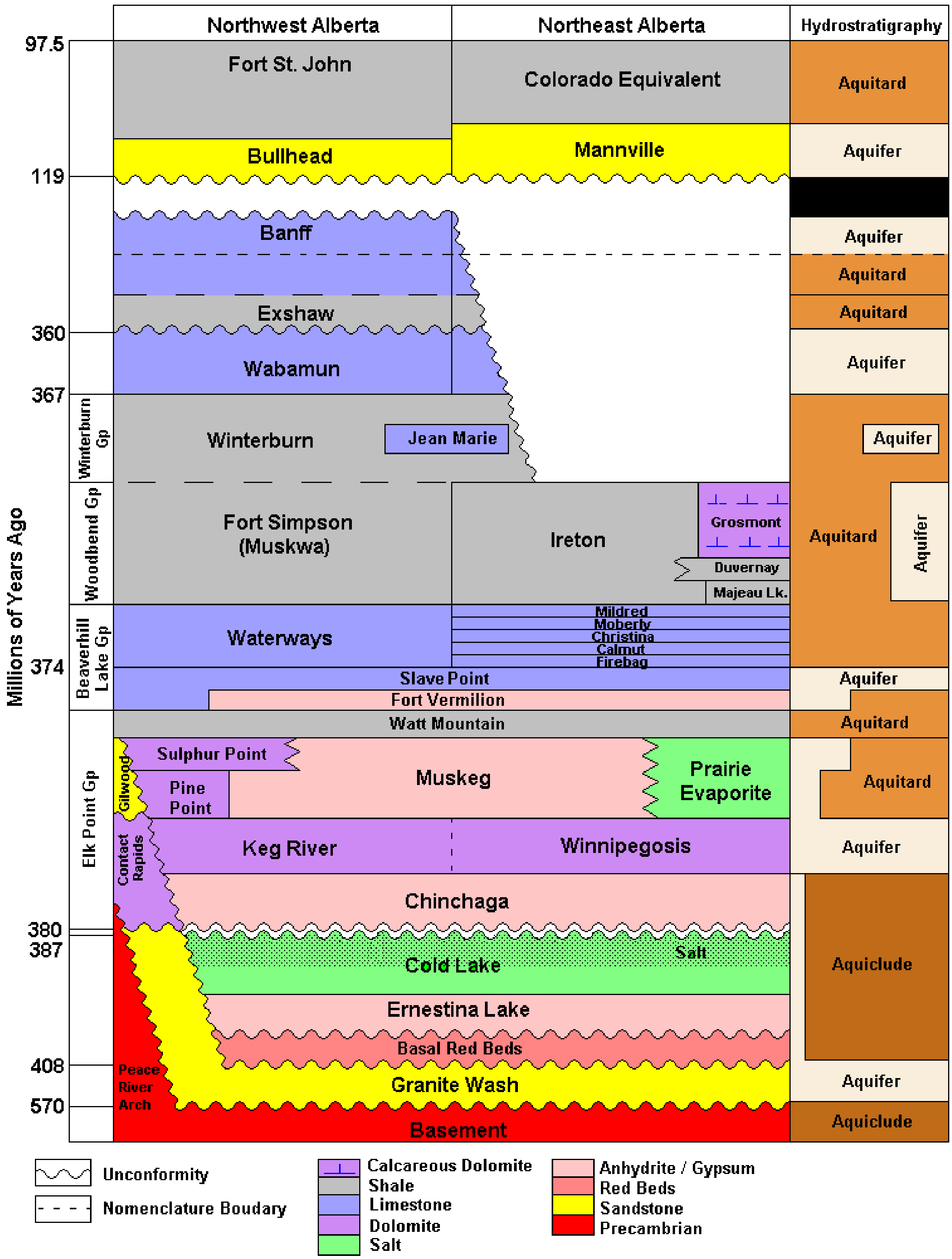

Figure 2. Hydrostratigraphy of Alberta north of 56°N. Classification of each hydrostratigraphic unit was done based on Bachu and Underschultz (1992, 1993), Bachu (1997) and paleoreconstructions of the basin (Mossop and Shetsen, 1994).

Fort Simpson shale to the north and upwards into the Ireton Fm. In combination, these units form a thick (>200 m) aquitard that stretches across the basin. These shales grade into the carbonate shelf of the Grosmont Fm. in the north central portion of the study area. North of the Peace River Arch the Winterburn Group is an aquitard. The overlying Wabamun Group is a permeable dolomitic limestone in the southern portion of the study area. To the north, the limestone becomes argillaceous and tight, making it a good aquitard. The black Exshaw Fm. shale and the lower portion of the Banff Fm. can be combined into a thick (55 to 200 m), regionally-extensive aquitard.

The upper Carboniferous, Permian, Triassic and Jurassic strata occupy only the south westernmost corner of the study area and therefore are ignored. In the western portion of the study area, the Cretaceous strata are a mélange of foreland clastics, which in combination are considered an aquitard. For the Mannville Group sandstones in particular, they extend across the southern portion of the study area and are thought to be an excellent aquifer. The overlying Colorado Group shales act as a barrier to fluid flow.

3.2 Permeability and Porosity

The permeability of strata controls large-scale, fluid flow patterns. Permeabilities of the Alberta basin strata vary over 20 orders of magnitude (Freeze and Cherry, 1979). Similarly, detailed studies of permeability variation in relatively homogeneous geological materials have identified permeability variations over four orders of magnitude in a one-metre distance (Sudicky, 1986). Thus, permeability values can be considered only as estimates of relative permeability rather than an absolute measure of the hydraulic conductivity of a rock. Permeability values for Alberta aquifers can be estimated from Drill Stem Test (DST) measurements submitted to the Alberta Energy and Utilities Board (AEUB) (Bachu et al., 1987). Table 1 contains maximum and average, well-scale, permeability and porosity values calculated from DST's, as determined from Hitchon et al. (1989), Bachu and Undershultz (1992, 1993) and Bachu (1997). Regional values are determined through scaling-up of core plug measurements and DST measurements (Cushman, 1984).

Table 1. Permeability and porosity data for northern Alberta compiled from Hitchon et al. (1989), Bachu and Undershultz (1992, 1993) and Bachu (1997). k is defined as the permeability of a tested interval. These values should be considered only ballpark estimates. Highlighted values are the most permeable strata.

Hydrostratigraphic Units	Maximum DST log k (m^2)	Average DST log k (m^2)	Average Porosity	Maximum Porosity
Cretaceous aquitard			0.31	0.35
Banff shale		-17.377		
Wabamun	-13.824	-16.097	0.11	0.34
Grosmont		-13.614	0.15	0.36
Ireton/Ft. Simpson	-14.886	-16.523	0.05	0.18
Waterways	-12.801	-16.032	0.05	0.18
Slave Point	-11.476	-15.155	0.058	0.386
Muskeg	-12.668	-16.046	0.083	0.255
Keg River	-11.623	-14.456	0.09	0.38
Contact Rapids	-13.851	-13.553	0.057	0.144
Ernestina Lake			0.101	0.119
Basal Redbeds			0.01	0.05
Granite Wash		-15.164	0.11	0.248
Basal Cambrian	-12.077	-15.222		
Precambrian Basement		-16.796	0.01	0.02

Well-scale permeabilities show that the Contact Rapids, Keg River and Grosmont aquifers are the most conductive for fluid flow. The Basal Cambrian, Keg River, Muskeg and Slave Point units reach the highest maximum permeabilities, suggesting that local regions have much higher permeabilities than the average. Generally, porosity decreases with depth due to compaction by burial. Again, the Keg River, Slave Point and Grosmont aquifers have the highest maximum porosity values, which may be related to karst zones. Similarly, the Granite Wash and Contact Rapids aquifers have relatively high porosities for their depth. On a regional-scale, the Keg River Formation and Grosmont Formation represent the most permeable and porous hydrostratigraphic units in the study (Hitchon et al., 1989; Bachu and Undershultz, 1992, 1993; Bachu, 1997). As a result, these carbonates should be considered the most favourable conduits for MVT ore-forming fluids in northern Alberta, at least based on recent permeability and porosity data.

3.3 Hydraulic Heterogeneities

In general, Zn-Pb mineralization occurs in areas of increased permeability and/or zones in which fluids are funnelled laterally or vertically. These types of hydraulic heterogeneities focus fluids within the main aquifer, allowing local concentration and deposition of ore, if temperature, pressure, reductant or other causative depositional conditions change favourably.

3.3.1 Fluid Funnelling

Fluids within an aquifer can be funnelled laterally by lateral facies changes or by basement highs. For instance, on the east and west sides of the Illinois basin, two arches are understood to have funnelled northward flowing ore-forming fluids into the Upper Mississippi Valley ore district (Bethke, 1986). These structures generated a higher fluid flux to the ore district, thereby providing more metal-bearing fluids. In contrast, in southeast Missouri, the Lamotte sandstone pinches out at Precambrian uplifts. As a result, northward flowing, metal-bearing fluids in this aquifer were forced vertically upwards into the Bonneterre dolostone, which caused Pb-Zn ore to precipitate (Gregg and Shelton, 1989). A similar effect can be achieved by lateral facies changes, which can funnel fluids into smaller and smaller volumes of porous rock; e.g., the Presqu'ile barrier narrows from a width of 200 km in the northwestern corner of Alberta to 10 km near Pine Point.

3.3.2 Permeability Enhancement

Zones of highest permeability will experience the highest fluid fluxes and thus have the greatest potential rate of metal-precipitation from ore-forming fluids. Diagenetic permeability enhancement is common in the carbonate rocks that typically host MVT deposits. Mineralization is preferentially found in breccias or karst, in faults zones and along fold hingelines. For example, the Upper Mississippi Valley ore district is found in complex networks of faults, which extend across an aquitard and into the basal aquifer, the source of the metals (Arnold et al., 1996). Also, at a regional-scale, the Pine Point ore district is located at the intersection point of the Presqu'ile barrier reef and the Great Slave Lake shear zone (Campbell, 1967). Finally, many MVT deposits are associated with overlying unconformities or disconformities, which document a period of subaerial exposure that may have initiated weathering and karstification of the host carbonate, which resulted in enhanced permeability and porosity. Later, more robust flow systems may further enhance the permeability of these areas of dissolution, potentially causing brecciation and enhanced karstification.

3.3.3 Heterogeneities in Northern Alberta

To identify large-scale heterogeneities, structure and isopach maps were generated for all major hydrostratigraphic units below the top of the McMurray Formation and some minor units in the the Middle Devonian sequence (Appendix A). Most of the units show uniform sloping strata across the study areas. All heterogeneities were identified by inspection of these maps and compiled into Figure 3.

The lower Paleozoic strata in northern Alberta contain a series of lateral facies changes and discontinuous aquifers. Figure 3a shows the areal extent of all the aquifers in the Paleozoic succession, except for the Beaverhill Lake and Keg River aquifers, which extend across all of northern Alberta. This distribution of aquifers could result in a complex flow system at a regional-scale. Fluids could be funnelled to the north along the Grosmont and Wabamun aquifers, whereas the Sulphur Point and underlying Pine Point aquifers, as well as the Gilwood Fm. would preferentially focus water to the northeast.

Figure 3b shows local highs (H), lows (L) and thin areas (T) within Devonian strata in northern Alberta. These zones were identified from isopach and structural contour maps (Appendix A). The major fault zones were extracted from a compilation of structural elements for northern Alberta (Pana et al., 2001). The following conclusions can be drawn from this figure:

- Highs in the Keg River in the southeast corner of the study area are at the margin of the basin, typically where MVT districts form.
- The lows in the Winterburn Fm. are in the low permeability section of this unit and therefore are of little interest (Figure A.9).
- The basement high along the Great Slave Lake Shear Zone (GSLSZ) could be a good target for exploration as it is underlying the Presqu'ile barrier; however, the barrier is at least 800 m below ground surface in this area (Figure A.27).
- The high and associated low of the Keg River Fm. in the western part of northern Alberta is close to the GSLSZ and might also have promoted mineralization (Figure A.16). In fact, Turner and McPhee (1994) have reported 3.1% Zn (with 0.05% Pb) over 21 m in the Keg River Fm. in this region, but at ca. 1300 m depth.

Faults act as major conduits for fluids. Hundreds of faults have been identified in the study area (see Pana et al., 2001); however, our interest lies in pre-Carboniferous faults, which may affect mineralization in the Devonian carbonates. The basement rooted GSLSZ in northwestern Alberta is not only a conduit for fluids, but also a potential source of metals. There are several large pre-Carboniferous faults sub-parallel to and in the vicinity of the GSLSZ (Pana et al., 2001). In addition, many faults have been identified around the PRA (Pana et al., 2001) due to repeated tectonic uplift and its proximity to the disturbed belt (Figure 3b). Other pre-Carboniferous faults can be found skirting the erosional limit of the basin and in the southeastern portion of the study area (Figure 3b).

4 Controls on Mineralization

Mineralization processes that lead to important MVT ore districts require a large supply of reduced sulphur and dissolved metals. Both components are abundant in sedimentary basins, but are not always in a chemically available form for mineralization.

The sources of metals are most likely the underlying Precambrian basement or siltstone and argillite within the Phanerozoic sedimentary package, although every formation along the flowpath of an ore-

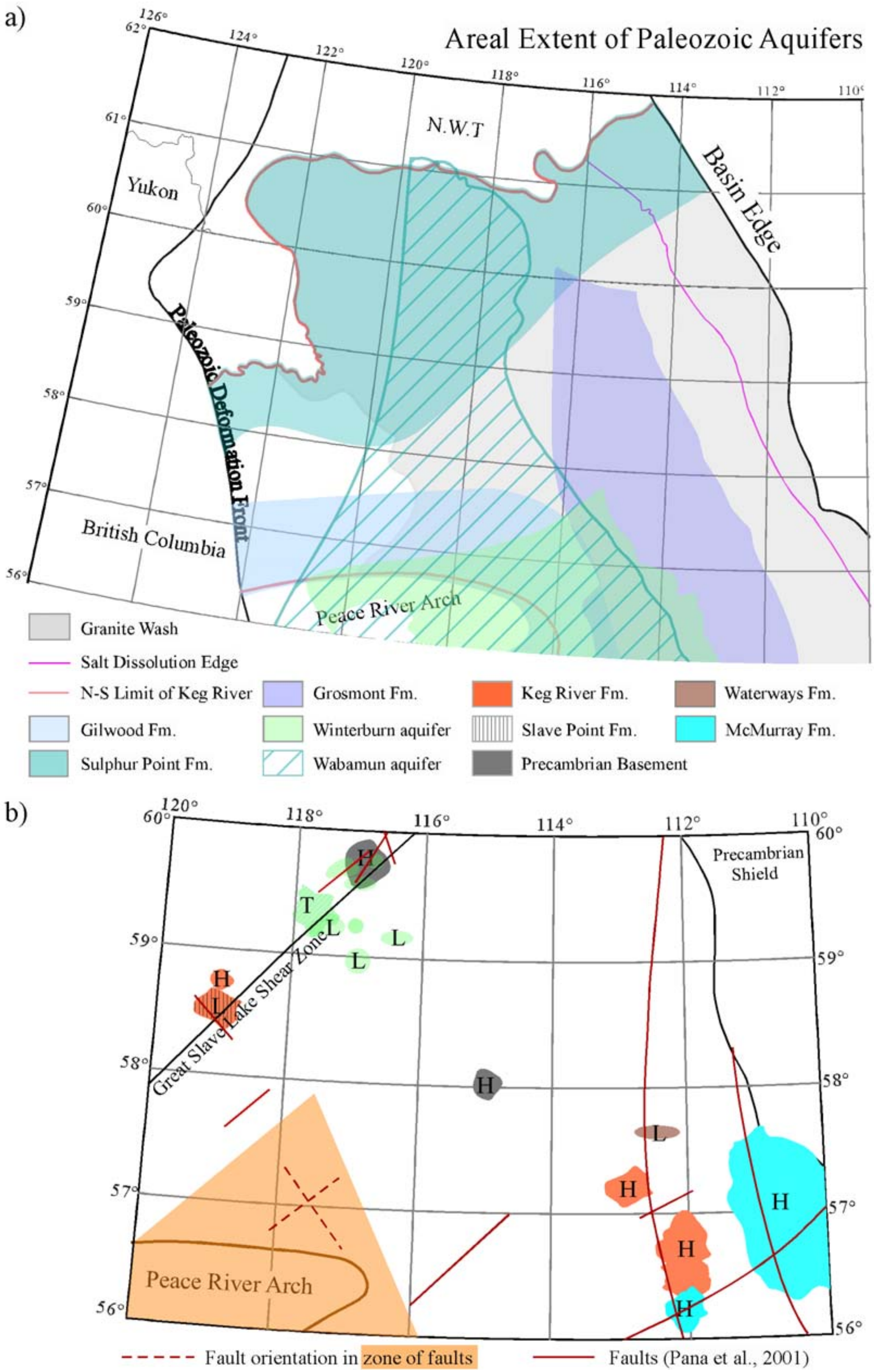

Figure 3. a) Areal extent of Devonian aquifers in the northern Alberta basin; and b) local highs in strata of northern Alberta. L = low, H = high, T = thin areas of the associated aquifer, as well as, selected pre-Carboniferous faults.

forming fluid has been proposed. A minimum of 1 ppm Pb and Zn must be mobilized out of these rocks, under an appropriate regional flow regime, to explain the high ore grades found in MVT deposits (Sverjensky, 1984). Laboratory and field measurements of formation waters reveal a direct correlation between water salinity and concentrations of dissolved Zn and Pb. As salinity increases, measured in-situ pH decreases and higher order metal chloride complexes ($Me^{2+} \rightarrow MeCl_2^0 \rightarrow MeCl_4^{2-}$) progressively dominate (Hanor, 1996). Calculations show that more than 150 g/l Cl are required at 100°C to mobilize 1 ppm of Zn or Pb from a source rock for transport to an MVT host rock (Hanor, 1996).

Sulphur is ubiquitous in the subsurface as aqueous sulphate; however, reduction of this sulphate to H_2S is necessary for formation of sulphides. Reduction occurs in sedimentary basins by bacterial sulphate reduction (BSR) at temperatures below 80°C and thermochemical sulphate reduction (TSR) at temperatures above 125°C (e.g., Machel, 2001). Reduced sulphur can be transported as a dissolved phase, but not in the presence of Pb or Zn unless the pH is below 3 (Anderson and Macqueen, 1982). In the Alberta basin, significant amounts of H_2S are generated in the deep basin by TSR and at shallow depths biogenic H_2S has also been recorded. Simpson (1999) showed that H_2S has been transported as a dissolved phase up to 200 km.

4.1 Metals in Alberta Basement Rock

Although metals can be derived from almost any local rock body, the upper several metres of the Precambrian basement rock are highly weathered and friable. The sandstone and conglomerate of the Granite Wash may also be a good source of metals. The relatively high permeability of these units would allow for easy extraction of metals by highly saline water. In Figure 4, metal concentrations in the Precambrian basement rock across northern Alberta are plotted. These plots derive from lithogeochemical analyses of samples collected by R. Burwash, Department of Earth and Atmospheric Sciences, University of Alberta and the data resides in a basement sample database (Pana et al., 2002) in preparation at the Alberta Geological Survey.

The data show a band of high metal concentrations east of the PRA. High Pb and Zn are coincident east of the PRA and south of GSLSZ in the Ksituan (Ks) region. Generally, the amount of Zn is greater than that of Pb, as is the case for most MVT ore districts, worldwide. The limited data coverage make further conclusions difficult.

4.2 Formation Water Salinity

Approximately 150 g/l aqueous Cl is necessary to mobilize metals from rocks at 100°C; higher concentrations are needed for lower temperatures and vice versa. Figure 5 shows the salinity (Total Dissolved Solids or TDS g/l) of formation waters in the Elk Point aquifer system (i.e., in the Sulphur Point, Pine Point, Winnipegosis, Contact Rapids and Keg River formations) and the Beaverhill Lake system (Slave Point and Waterways formations). The data are stored in the AGS water chemistry database which is derived from data and information collected by the AEUB from the petroleum industry. The data have been culled according to Hitchon and Brulotte (1994), and Hitchon (1996).

The water salinity varies from 20 to 220 g/l in the Beaverhill Lake aquifer, whereas the Elk Point aquifer system reaches 320 g/l. The samples containing more than 150 g/l Cl are plotted individually in red. In the Elk Point map, the high-Cl samples almost exclusively correlate to the regions where the Prairie Fm. halite overlies the aquifer. Similarly, in the Beaverhill Lake the highest salinity waters exist around the PRA. More specifically, they are associated with the continental sabka facies of the Fort Vermillion Fm. There are only three instances of waters with greater than 150 g/l Cl, but there are over 91 waters with greater than 100 g/l Cl.

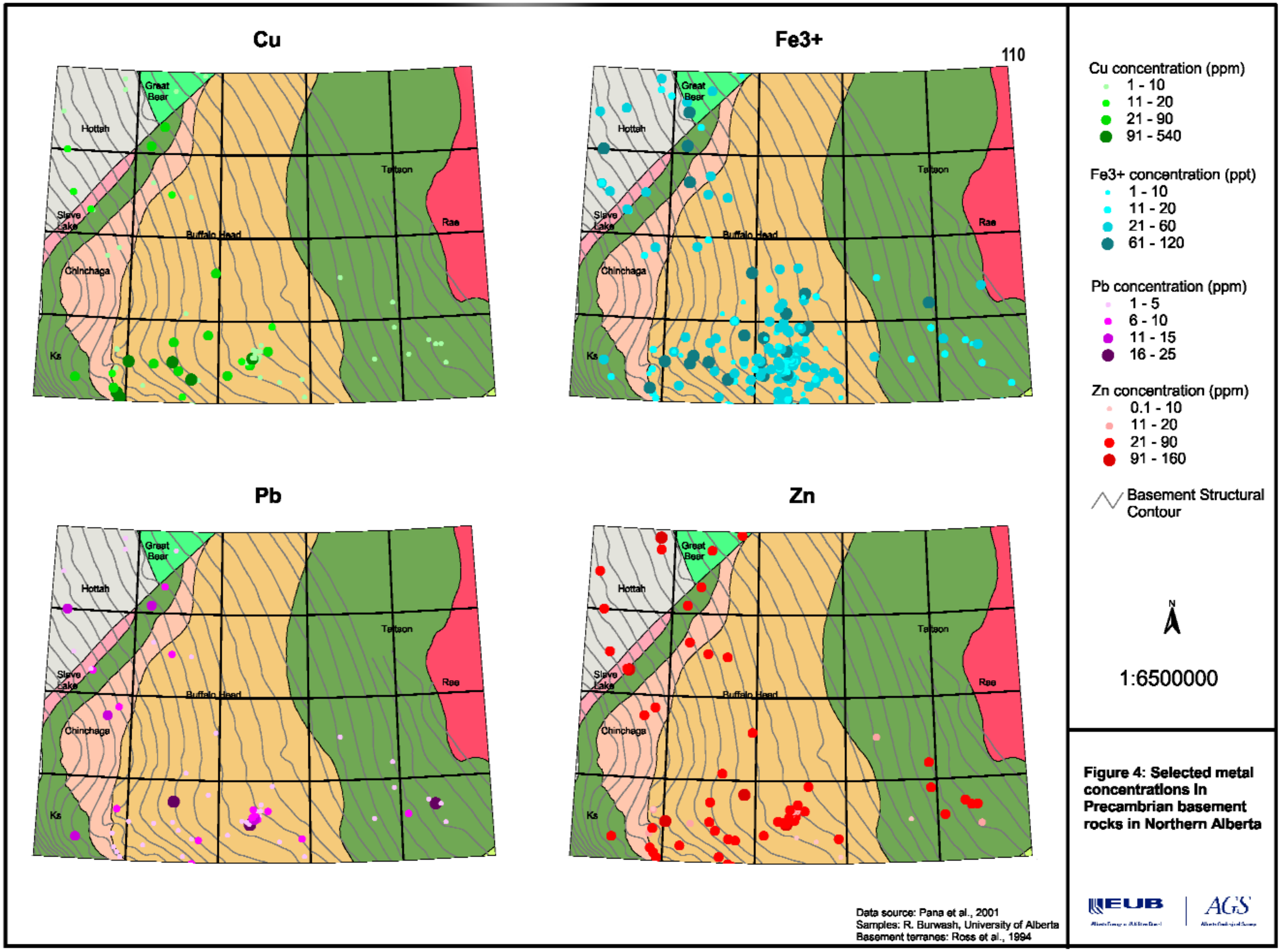

Figure 4: Selected metal concentrations In Precambrian basement rocks in Northern Alberta

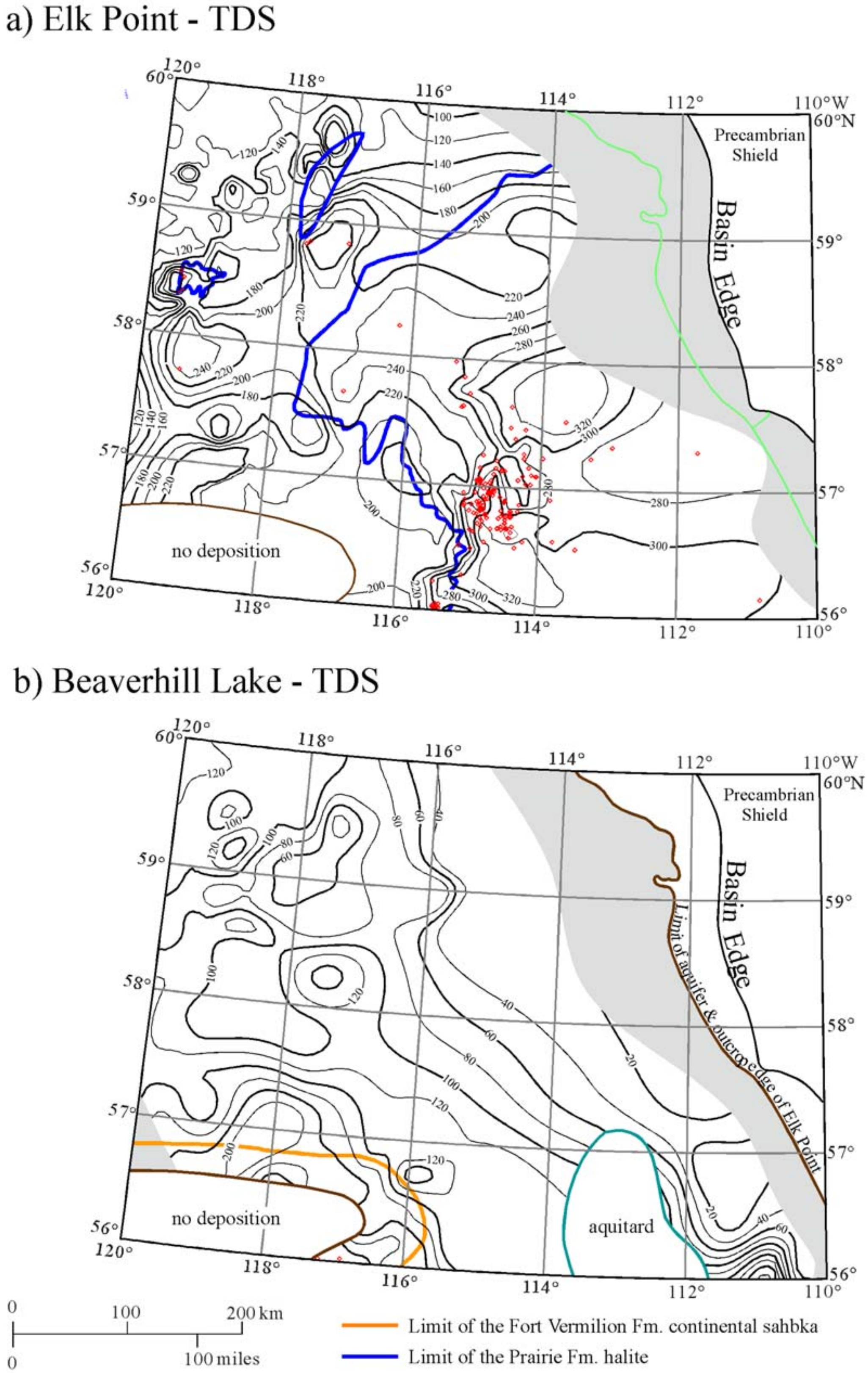

Figure 5. Present day formation water salinity in g/l TDS for a) Elk Point and b) Beaverhill Lake aquifer systems. Red diamonds represent locations of formation waters containing more than 150 g/l Cl.

The Prairie Fm. salt dissolution edge runs subparallel to the erosional edge of the basin. This suggests that much more saline water may have existed along the edge of the basin, but it has long since been flushed out.

5 Potential Exploration Areas

The formation of a MVT ore district requires a highly permeable carbonate host rock, a large source of saline brine to mobilize Pb and Zn, a source of reduced sulphur and a robust fluid flow driving force to focus fluids into the ore district. The location of the ore district and individual deposits is controlled by local-scale hydraulic heterogeneities, such as, basement highs, enhanced permeability zones, and faults.

In northern Alberta, investigation of hydraulic heterogeneities, formation water salinity and metal sources has provided several potential target areas for MVT exploration. They are reviewed below without consideration as to the depth to target stratigraphic units:

1) Around the Peace River Arch:
- Highly saline fluids, with Cl > 150 g/l
- Collection of faults active throughout the Phanerozoic
- Coincident Pb (~16-25 ppm) and Zn (>20 ppm) anomalies east of the PRA
- Suite of aquifers flank the arch, i.e., Granite Wash Fm., Gilwood Fm., Keg River Fm., and Beaverhill Lake Group

2) Along the GSLSZ, between 118° and 116°W:
- Major structural fault zone, which acts as a permeable conduit for fluids
- Coincident Pb (~11-15 ppm) and Zn (~21-90 ppm) anomalies
- Small basement high and other local highs and lows in Paleozoic strata
- Within the Presqu'ile barrier carbonates, which funnels fluids to the basin margins

3) At the margin of the basin, between 56.5° and 57.5°N:
- Highs in the Keg River Fm. and McMurray Fm.
- Adjacent to the Grosmont Fm., which is a highly permeable and narrow conduit for fluids
- Good source of Zn (~21-90 ppm) and one concentrated source of Pb (16-25 ppm)
- Adjacent to the Prairie Fm. halite dissolution edge, where highly saline water may have existed during dissolution
- Coincident sets of pre-Carboniferous faults in area of local highs (Pana et al., 2001)
- Both high salinity and high chlorinity formation waters exist in the Elk Point aquifer system

Of the three target areas reviewed, the last one, which is near the margin of the basin, would provide the shallowest mining depths and is therefore the favoured target area for exploration for at or relatively near-surface MVT Pb-Zn deposits.

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Appendix A – Surface Representation Grid Images for the Northeastern and Northwestern MVT Study Areas, Alberta

by D. Roy Eccles

1 Introduction

Devonian rocks are only known to crop out in the northeastern part of the plains of Alberta and in thrusted and folded belts associated with the Rocky Mountains. In northeastern Alberta, Devonian rocks occur between Cretaceous rocks, which cover much of north-central and northwestern Alberta, and the Precambrian Shield, with its exposure contained to the most northeastern corner of the province. This study excludes the Wood Buffalo National Park, where current regulations prohibit development, and thus focuses on two areas in northern Alberta:

1) northeastern Alberta bounded by latitudes 56.5º to 58ºN and longitudes 110º to 112ºW; and

2) northwestern Alberta bounded by latitudes 58º to 60ºN and longitudes 114ºN to 120ºW.

In northeastern Alberta, fossiliferous Devonian limestone and minor dolomite rocks are exposed along the banks of the Clearwater and Athabasca Rivers and their associated tributaries (e.g., Christina, MacKay and Muskeg Rivers). Devonian rocks in the northwestern study area are completely overlain by Cretaceous rocks and surficial deposits. Isopach maps, which portray the depth to the Devonian surface, shows that the Cretaceous and glacial cover varies between 0 m and 686 m in northeastern Alberta (Figure A.1) and between 15 m and 1,778 m in northwestern Alberta (Figure A.2). From known well logs, 74% of the northeastern study area and only 13% of the northwestern study area contain wells that penetrate Devonian rocks at a depth of <250 m from the surface.

As such, modellers are forced to rely on the well log data to provide knowledge about the subsurface physiography of the Devonian rocks. This section presents the surface representation grid images for individual formations, based on the available data, for northeastern and northwestern Alberta. The images are then used to model subsurface units in an attempt to show any trends in the data that may be attributed to structural deformation or potential pathways for the migration of metal-bearing fluids. These interpretations are presented and discussed in Section 3.3.3.

2 Surface Representation Maps

2.1 Formation Selection

Well data from International Datashare Corporation (iDc) were used to model the subsurface in the current study areas. Due to time limitations, the over 85 000 formation picks used as part of this study were not verified as being ‘true picks’. In contrast, this section recognizes that the use of raw, uncontrolled data may be useful for tectonic modeling in comparison to a ‘culled dataset’, in which all abnormalities are discarded. Where possible, controlled picks were used, such as Alberta Geological Survey picks on the top of the Waterways Group in the Fort McMurray/oil sands area. In addition to the Devonian picks, surface representation maps for the Precambrian basement and Cretaceous formations (e.g., Bluesky Formation) were used to expand our model vertically through the entire basin.

Tables A.1 and A.2 show the number of picks by formation that are recorded in the iDc database from wells in the northeastern and northwestern study areas, respectively. The surface representation maps were somewhat limited by the abundance of formation picks, particularly in the northeastern map area. Nevertheless, surface representation images were created for formations where there were >900 picks

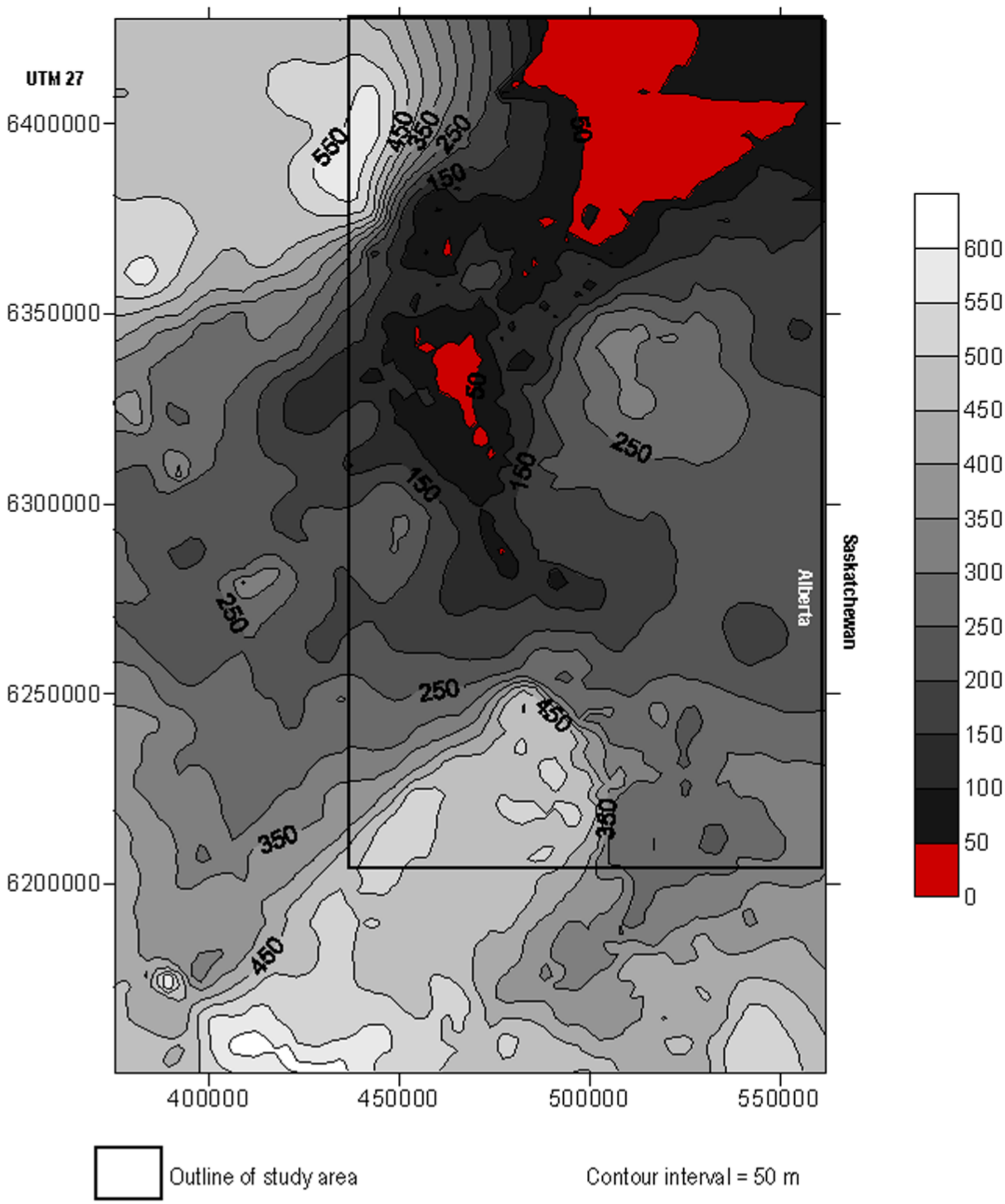


Figure A.1. Isopach map showing the depth to the Devonian surface in northeastern Alberta.

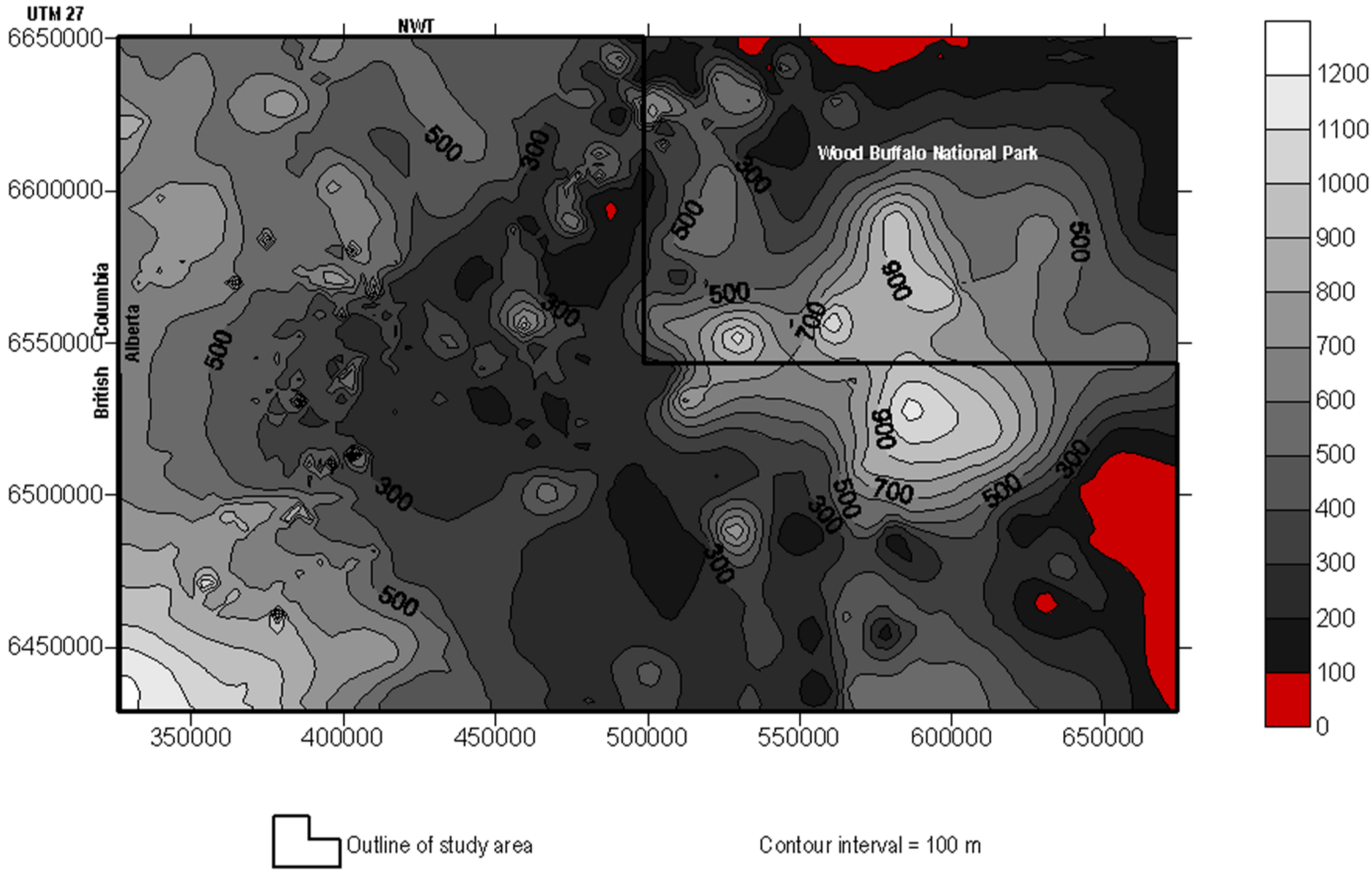


Figure A.2. Isopach map showing the depth to the Devonian surface in northwestern Alberta.

Table A.1. List of formations with number of picks used in surface representation maps for the northeastern study area.

Fm. ID No.	Formation name	Number of Fm. picks	Fm. ID No.	Formation name	Number of Fm. picks	Fm. ID No.	Formation name	Number of Fm. picks
1600	COLORADO GRP	9	7167	GROSMONT C	36	16960	NISKU FM	9
1860	SECOND WHITE SPECKLED S	133	7168	GROSMONT B	50	17100	IRETON FM	88
2060	BASE FISH SCALES ZONE	683	7169	GROSMONT A	80	17104	UPPER IRETON	6
2120	BOW ISLAND FM	2	7170	LOWER IRETON	137	17160	GROSMONT FM	184
2140	VIKING FM	264	7200	LEDUC FM	81	17166	UPPER GROSMONT 3	32
2180	VIKING SANDSTONE	1546	7280	DUVERNAY FM	1	17167	UPPER GROSMONT 2	45
2280	PEACE RIVER FM	40	7320	COOKING LAKE FM	32	17168	UPPER GROSMONT 1	49
2301	PADDY-CADOTTE	2	7400	MAJEAU LAKE FM	1	17169	LOWER GROSMONT	52
2340	PELICAN FM	60	7440	BEAVERHILL LAKE GRP	9418	17170	LOWER IRETON	107
2360	JOLI FOU FM	1427	7460	MILDRED MBR	17	17200	LEDUC FM	65
2380	HARMON MBR	14	7480	MOBERLY MBR	24	17320	COOKING LAKE FM	132
2480	MANNVILLE GRP	4	7500	CHRISTINA MBR	28	17460	MILDRED MBR	154
2560	COLONY MBR	4	7520	CALUMET MBR	30	17461	MILDRED 10	20
2620	GRAND RAPIDS FM	3010	7540	FIREBAG MBR	33	17462	MILDRED 20	120
2640	SPIRIT RIVER FM	50	7580	SLAVE POINT FM	41	17480	MOBERLY MBR	1718
2750	LOWER GRAND RAPIDS	23	7600	LIVOCK FM	1	17482	MOBERLY 20	36
2760	SPARKY MBR	3	7620	FORT VERMILION MBR	28	17483	MOBERLY 30	1074
2780	WAINWRIGHT SD	2	7700	ELK POINT GRP	52	17500	CHRISTINA MBR	431
2800	CLEARWATER FM	4930	7720	WATT MTN FM	43	17520	CALUMET MBR	797
2810	CLEARWATER SD	977	7730	DAWSON BAY FM	1	17521	CALUMET 10	665
3000	GLAUCONITIC SS	9	7810	SULPHUR POINT FM	1	17540	FIREBAG MBR	869
3006	GLAUCONITIC-WABAMUN	1	7820	MUSKEG FM	8	17541	FIREBAG 10	680
3040	BLUESKY FM	4	7860	PRAIRIE EVAPORITE FM	44	17580	SLAVE POINT FM	14
3060	WABISKAW MBR	6744	7870	FIRST SALT	1	17620	FORT VERMILION MBR	8
3062	WABISKAW-MCMURRAY	46	7880	KEG RIVER FM	14	17700	ELK POINT GRP	69
3170	BANTRY SHALE	1	7890	KEG RIVER SS	2	17720	WATT MTN FM	64
3260	GETHING FM	7	7900	METHY FM	11	17860	PRAIRIE EVAPORITE FM	67
3280	MCMURRAY FM	12220	7920	WINNIPEGOSIS FM	36	17900	METHY FM	81
3300	MOULTON SD	2	7940	CHINCHAGA FM	5	17960	CONTACT RAPIDS FM	78
3360	ELLERSLIE MBR	2	7960	CONTACT RAPIDS FM	37	19760	GRANITE WASH	7
3500	DETRITAL =CRET=	20	7980	RED BEDS	27	19763	LA LOCHE	6
6500	DEVONIAN SYSTEM	12	8000	COLD LAKE FM	14	19800	PRECAMBRIAN SYSTEM	59
6700	WINTERBURN GRP	29	8020	ERNESTINA LK FM	21			
6960	NISKU FM	96	8040	LOTSBERG FM	10			
7040	WOODBEND GRP	623	8045	THIRD SALT	1			
7100	IRETON FM	59	8060	BASAL RED BEDS	10			
7104	UPPER IRETON	21	9000	CAMBRIAN SYSTEM	3			
7160	GROSMONT FM	375	9760	GRANITE WASH	24			
7166	GROSMONT D	33	9800	PRECAMBRIAN SYSTEM	64			

Shaded column identifies formations selected for gridding

Table A.2. List of formations with number of picks used in surface representation maps for the northwestern study area.

No.	Formation name	Fm. picks
1920	DUNVEGAN FM	5
1940	FORT ST JOHN GRP	1
1960	SHAFTESBURY FM	1
2060	BASE FISH SCALES ZONE	67
2640	SPIRIT RIVER FM	3
2800	CLEARWATER FM	1
2900	WILRICH MBR	1
3000	GLAUCONITIC SS	12
3040	BLUESKY FM	1946
3060	WABISKAW MBR	80
3260	GETHING FM	306
3280	MCMURRAY FM	1
3500	DETRITAL =CRET=	8
3508	DETRITAL-DEBOLT	9
6000	MISSISSIPPIAN SYSTEM	6
6120	DEBOLT FM	40
6220	SALTER MBR	1
6380	ELKTON MBR	1
6400	SHUNDA FM	128
6420	PEKISKO FM	233
6440	BANFF FM	2850
6460	BAKKEN FM	4
6480	EXSHAW FM	40
6500	DEVONIAN SYSTEM	6
6580	WABAMUN GRP	3843
6600	BIG VALLEY FM	1
6612	UPPER KOTCHO	2
6614	MIDDLE KOTCHO SHALE	2
6616	LOWER KOTCHO	2
6650	TETCHO FM	2
6700	WINTERBURN GRP	93
6720	ALEXO FM	2
6740	TROUT RIVER FM	3130
6780	GRAMINIA FM	1
6810	WINTERBURN SHALE	6
6820	KAKISA FM	2931
6840	RED KNIFE FM	1865
6860	CALMAR FM	48
6880	FAIRHOLME GRP	1
6960	NISKU FM	26
7020	JEAN MARIE FM	3687
7040	WOODBEND GRP	62
7100	IRETON FM	66
7120	FORT SIMPSON FM	3720
7130	TATHLINA FM	8
	Shaded column identifies formations selected for gridding	
7160	GROSMONT FM	47
7165	TWIN FALLS FM	19
7170	LOWER IRETON	33
7220	HAY RIVER FM	32
7240	HAY RIVER LS	5
7320	COOKING LAKE FM	2
7340	PERDRIX FM	1
7400	MAJEAU LAKE FM	3
7430	MUSKWA FM	3355
7440	BEAVERHILL LAKE GRP	3663
7460	MILDRED MBR	2
7500	CHRISTINA MBR	5
7520	CALUMET MBR	15
7560	SWAN HILLS MBR	14
7580	SLAVE POINT FM	4233
7620	FORT VERMILION MBR	691
7700	ELK POINT GRP	28
7720	WATT MTN FM	4172
7780	GILWOOD MBR	4
7800	MANNING SD	1
7810	SULPHUR POINT FM	3983
7815	PRESQUILE FM	35
7820	MUSKEG FM	4106
7825	HORN RIVER FM	1
7830	PINE POINT FM	12
7850	ZAMA MBR	668
7855	ZAMA & KEG RIVER	468
7860	PRAIRIE EVAPORITE FM	1
7865	BLACK CREEK MBR	76
7870	FIRST SALT	11
7880	KEG RIVER FM	3378
7885	RAINBOW MBR	3
7890	KEG RIVER SS	8
7930	LOWER KEG RIVER	996
7940	CHINCHAGA FM	1249
7960	CONTACT RAPIDS FM	1
7980	RED BEDS	264
8000	COLD LAKE FM	204
8010	SECOND SALT	1
8020	ERNESTINA LK FM	167
8040	LOTSBERG FM	3
8060	BASAL RED BEDS	125
9000	CAMBRIAN SYSTEM	1
9760	GRANITE WASH	57
9800	PRECAMBRIAN SYSTEM	427

and/or where formation lithologies define clear marker units within the basin. For example, the Watt Mountain shale defines a clear lithological break between the overlying Fort Vermillion and underlying Prairie evaporites.

Formation surfaces used in the northeastern Alberta study area are highlighted on the table of formations legend for the area (Table A.3), and include

- Figure A.3. McMurray Formation
- Figure A.4. Waterways Group from IDC picks
- Figure A.5. Waterways Group from AGS picks

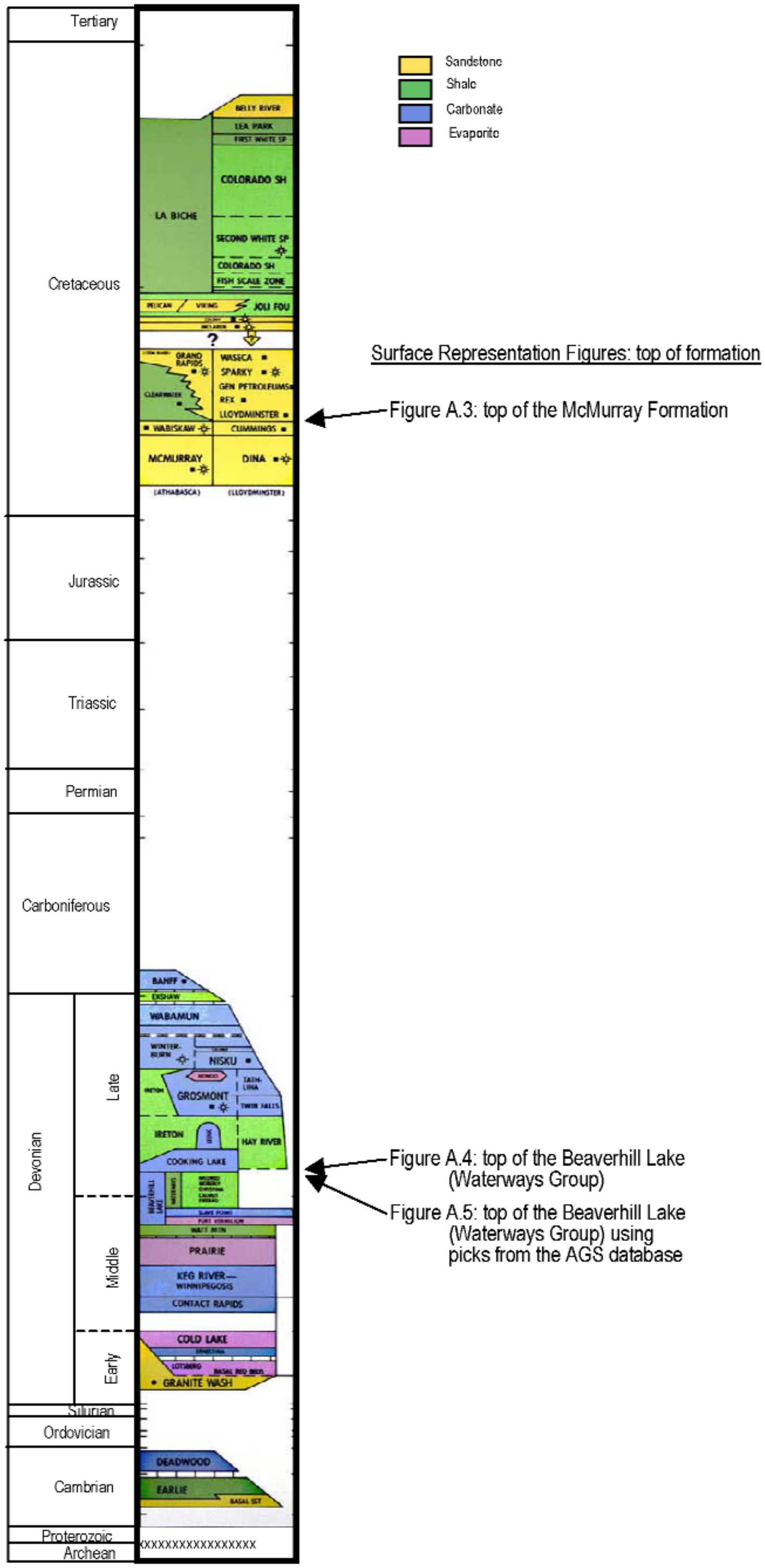
Formation surfaces used in the northwestern Alberta study area are highlighted on the table of formations legend for the area (Table A.4), and include

- Figure A.6. Bluesky Formation (equivalent to bullhead Fm. Top in Figure 2)
- Figure A.7. Banff Formation
- Figure A.8. Wabamun Group
- Figure A.9. Winterburn Group
- Figure A.10. Woodbend Group
- Figure A.11. Beaverhill Lake Group (Waterways Group)
- Figure A.12. Slave Point Formation
- Figure A.13. Watt Mountain Formation
- Figure A.14. Sulphur Point Formation
- Figure A.15. Muskeg Formation
- Figure A.16. Keg River Formation
- Figure A.17. Lower Keg River Formation
- Figure A.18. Chinchaga Formation
- Figure A.19. Precambrian basement

Because there is better subsurface data in the northwestern Alberta area, a number of isopach maps were included to portray the thickness between major formation horizons. These figures are also highlighted on the table of formations legend for the area (Table A.4), and include

- Figure A.20. Wabamun Group top to Winterburn Group top
- Figure A.21. Winterburn Group top to Woodbend Group top
- Figure A.22. Woodbend Group top to Beaverhill Lake Group (Waterways Group) top
- Figure A.23. Waterways Group top to Slave Point Formation top
- Figure A.24. Slave Point Formation top to Watt Mountain Formation top
- Figure A.25. Watt Mountain Formation top to Sulphur Point Formation top
- Figure A.26. Sulphur Point Formation top to Chinchaga Formation top
- Figure A.27. Keg River Formation top to Lower Keg River Formation top

Table A.3. Table of formations for northeastern Alberta with legend for the location of surface representation figures.



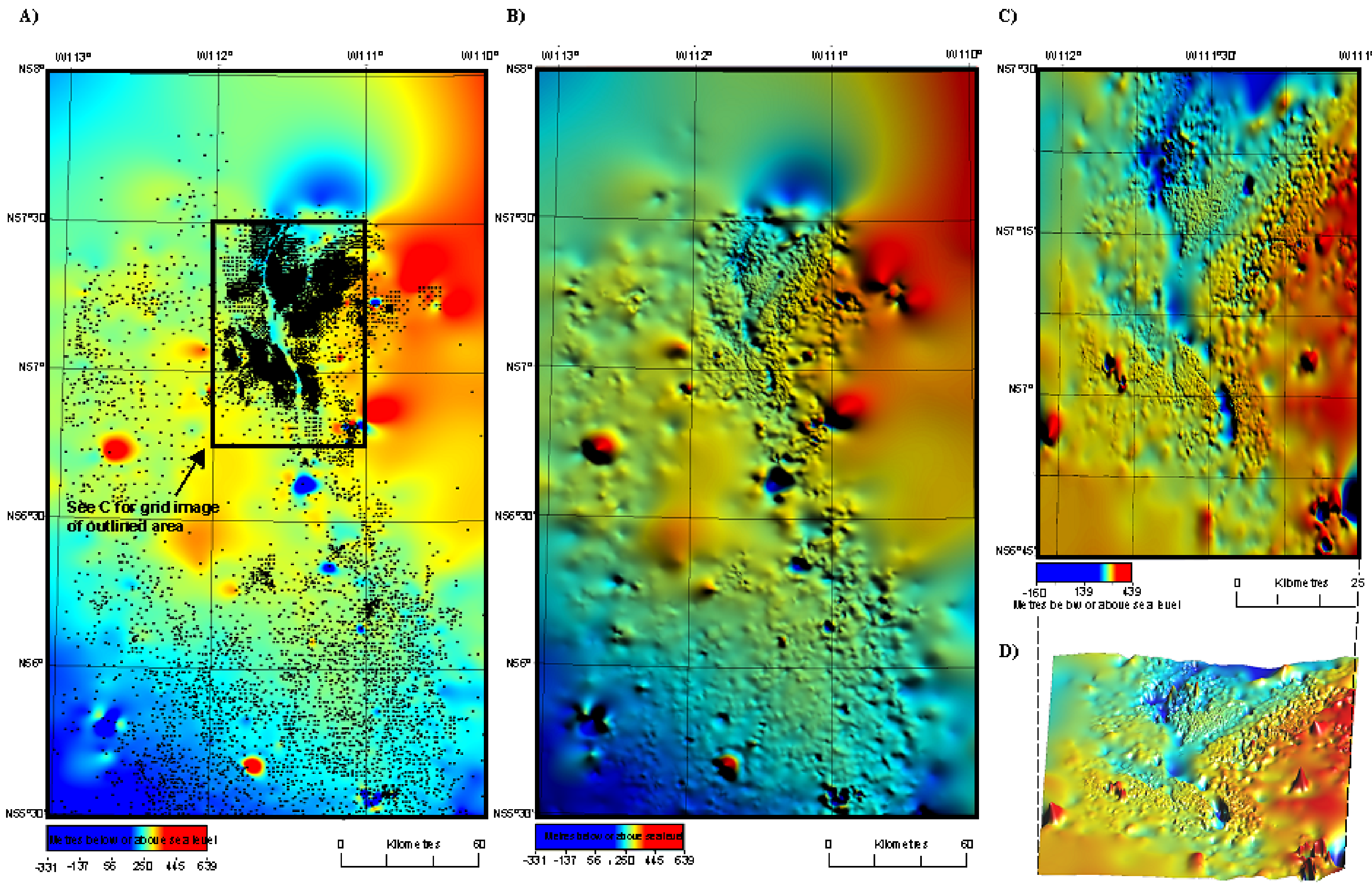


Figure A.3. Surface representation maps for the tip of the McMurray Formation. A) surface grid map with the location of wells used to create the minimum curvature grid; B) shaded-relief surface grid map with sun-angle from the north; C) shaded-relief surface grid map using only the well data from the detailed area outlined in A; and D) tilted 3D-view of the image in C with view from the south; scale 1:1 000 000.

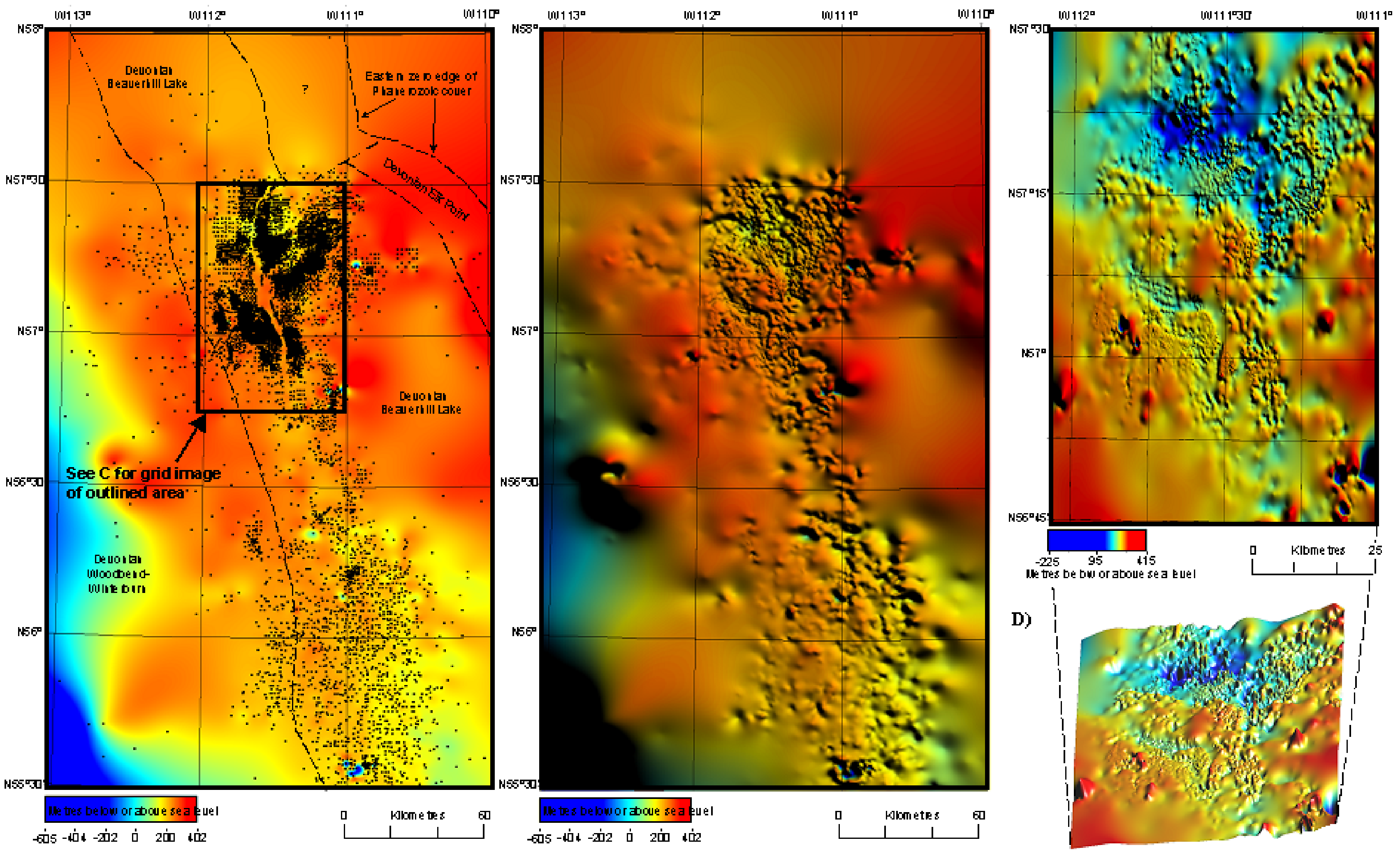


Figure A.4. Surface representation maps for the top of the Waterways Group using the IDC database. A) surface grid map with the location of wells used to create the minimum curvature grid with subcrop paleogeology from Hayes et al. (1994); B) shaded-relief surface grid map with sun-angle from the north; C) shaded-relief surface grid map using only the well data from the detailed area outlined in A; and d) tilted 3D-view of the image in C with view from the south; scale 1:1000 000.

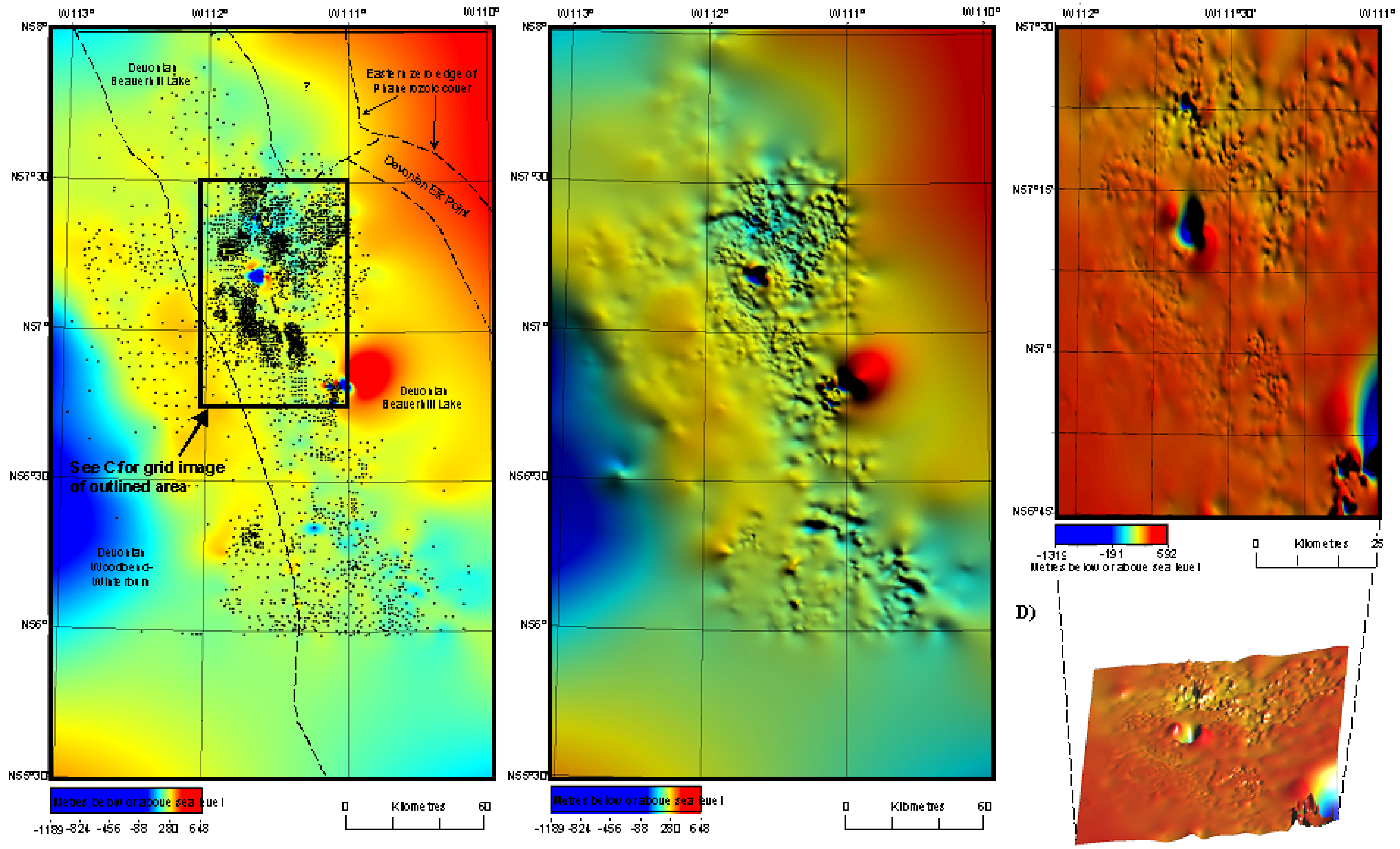
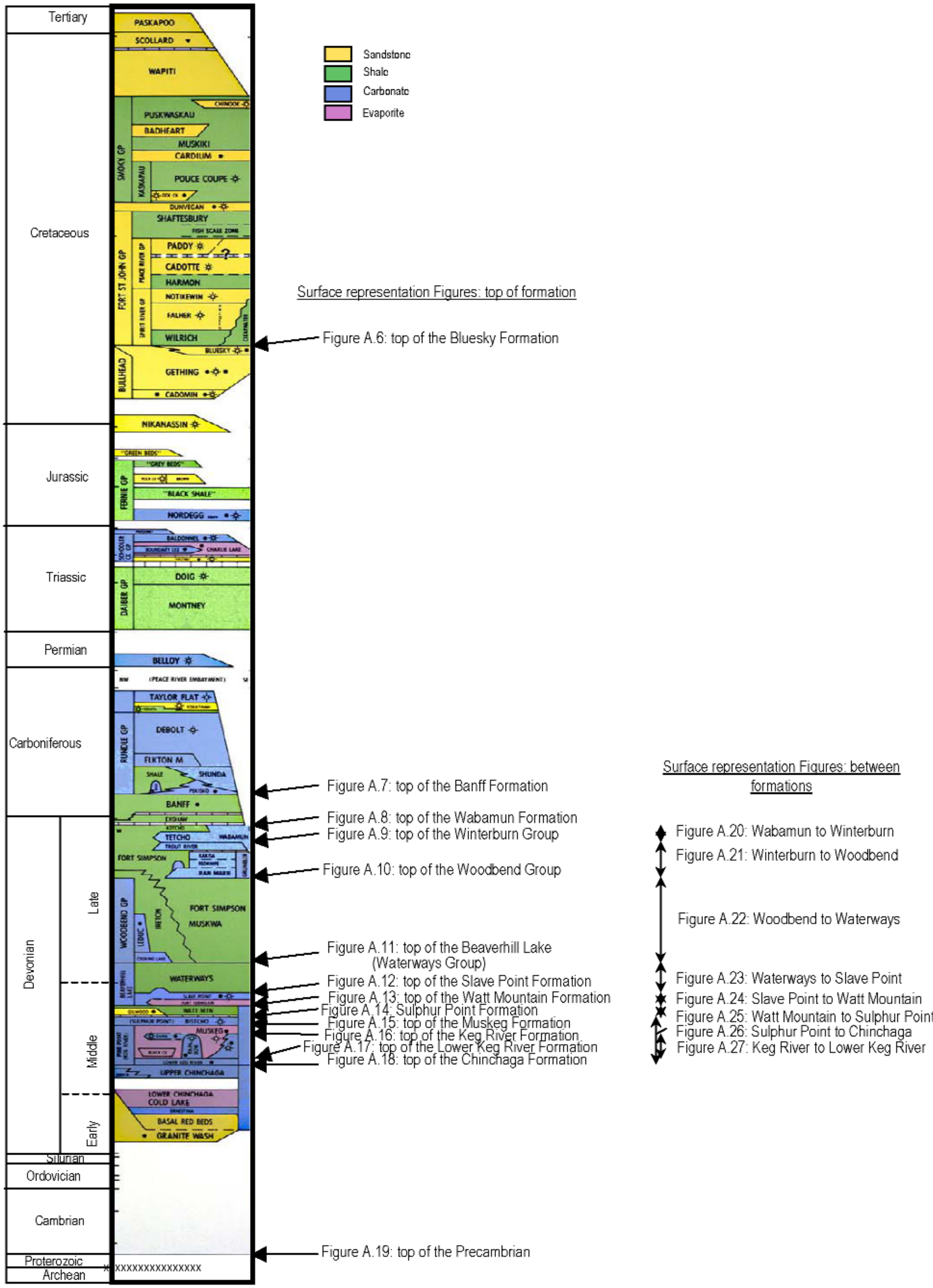


Figure A.5. Surface representation maps for the top of the Waterways Group using the AGS database. A) surface grid map with the location of wells used to create the minimum curvature grid with subcrop paleogeology from Hayes et al. (1994); B) shaded-relief surface grid map with sun-angle from the north; C) shaded-relief surface grid map using only the well data from the detailed area outlined in A; and D) tilted 3D-view of the image in C with view from the south; scale 1:100 000.

Table A4. Table of formations for northwestern Alberta with legend for the location of surface representation figures.



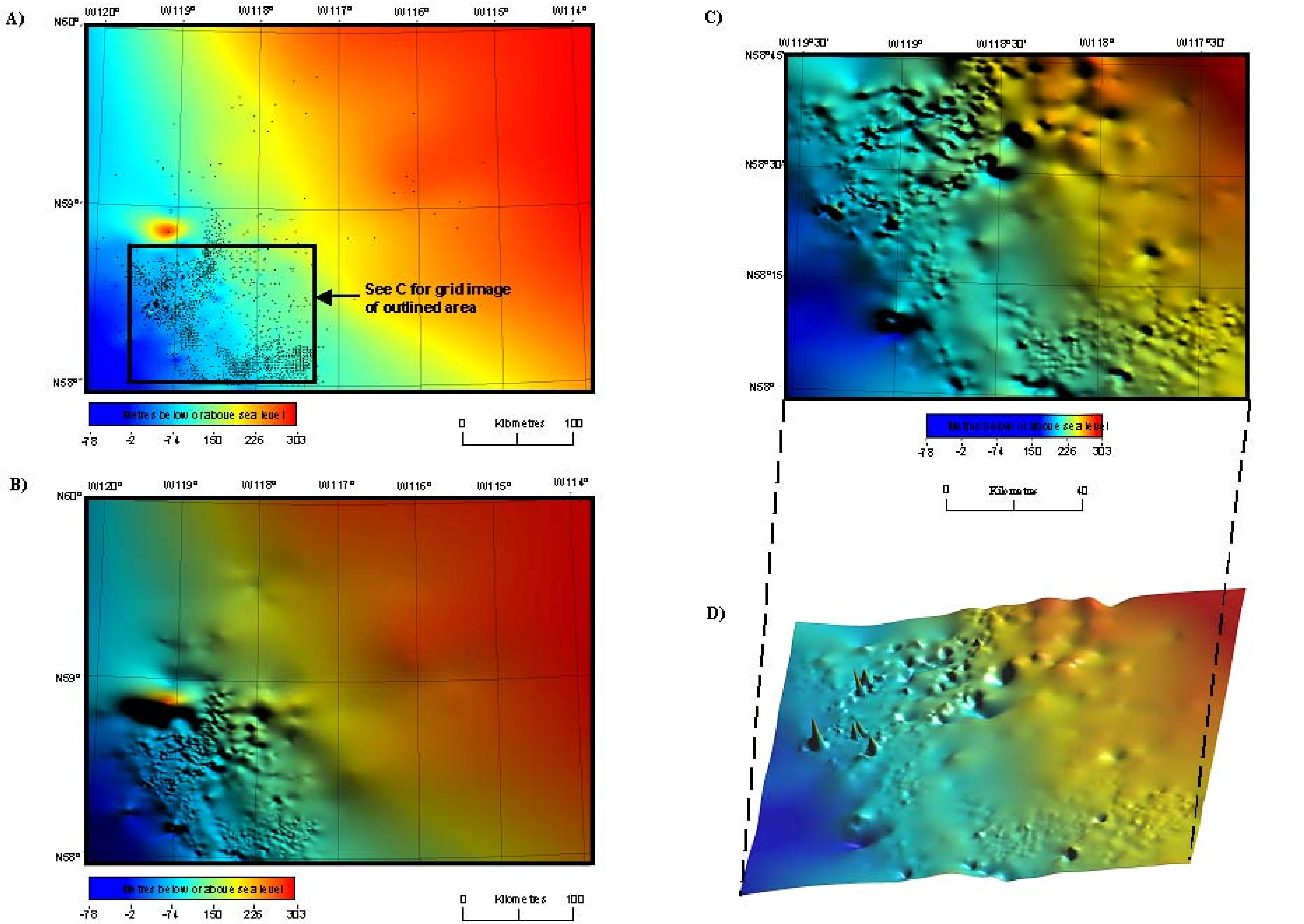


Figure A.6. Surface representation maps for the top of the Bluesky Formation. A) surface grid map with the location of wells used to create the minimum curvature grid; B) shaded-relief surface grid map with sun-angle from the north; C) shaded-relief surface grid map using only the well data from the detailed area outlined in A; and D) tilted 3D-view of the image in C with view from thw south; scale 1:100 000.

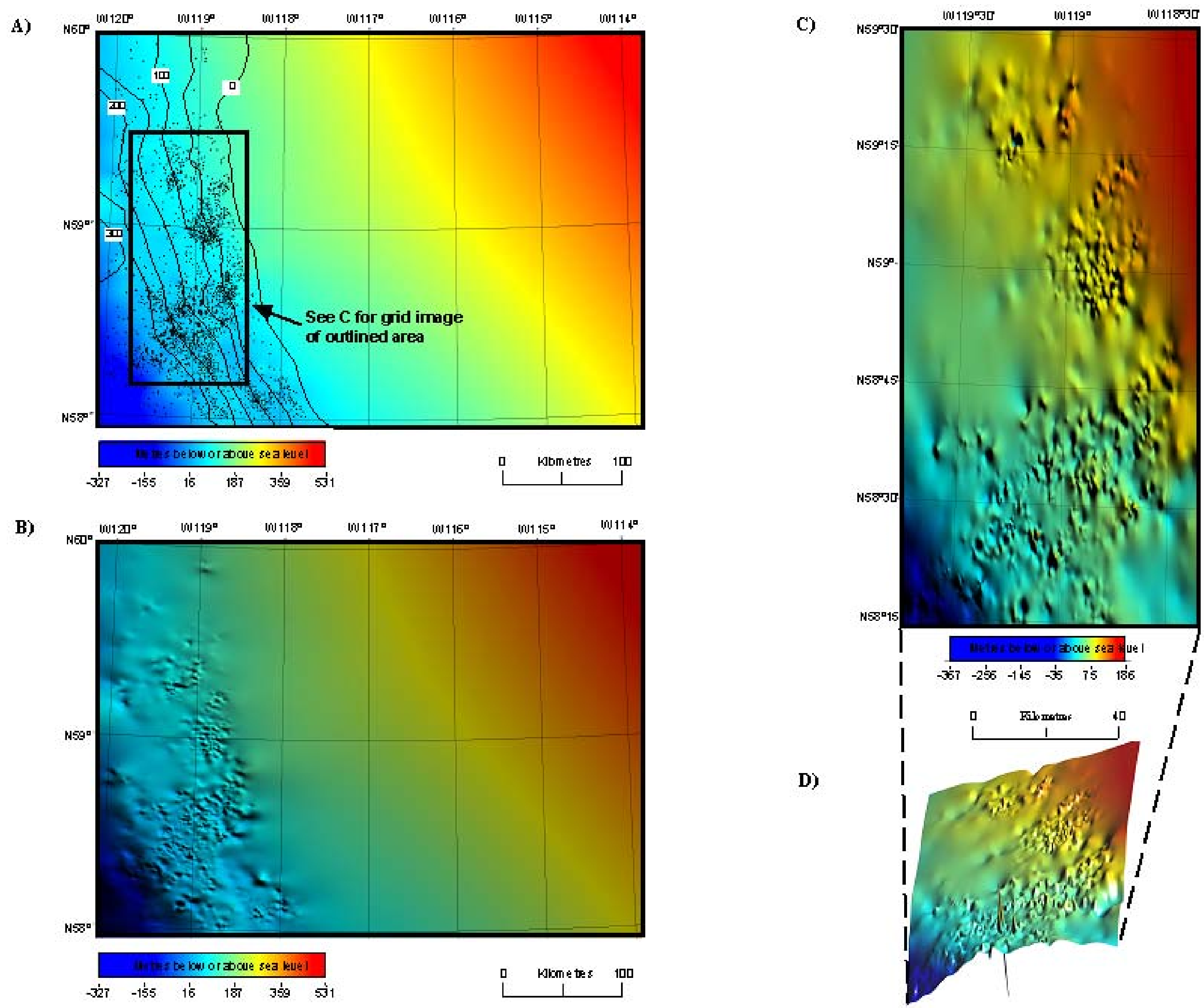


Figure A.7. Surface representation maps for the top of the Banff Formation. A) surface grid map with the location of wells used to create the minimum curvature grid and approximate isopach contours (interval=50 m) from Richards et al. (1994); B) shaded-relief surface grid map with sun-angle from the north; C) shaded-relief surface grid map using only the well data from the detailed area outlined in A; and D) tilted 3D-view of the image in C with view from the south; scale 1:100 000.

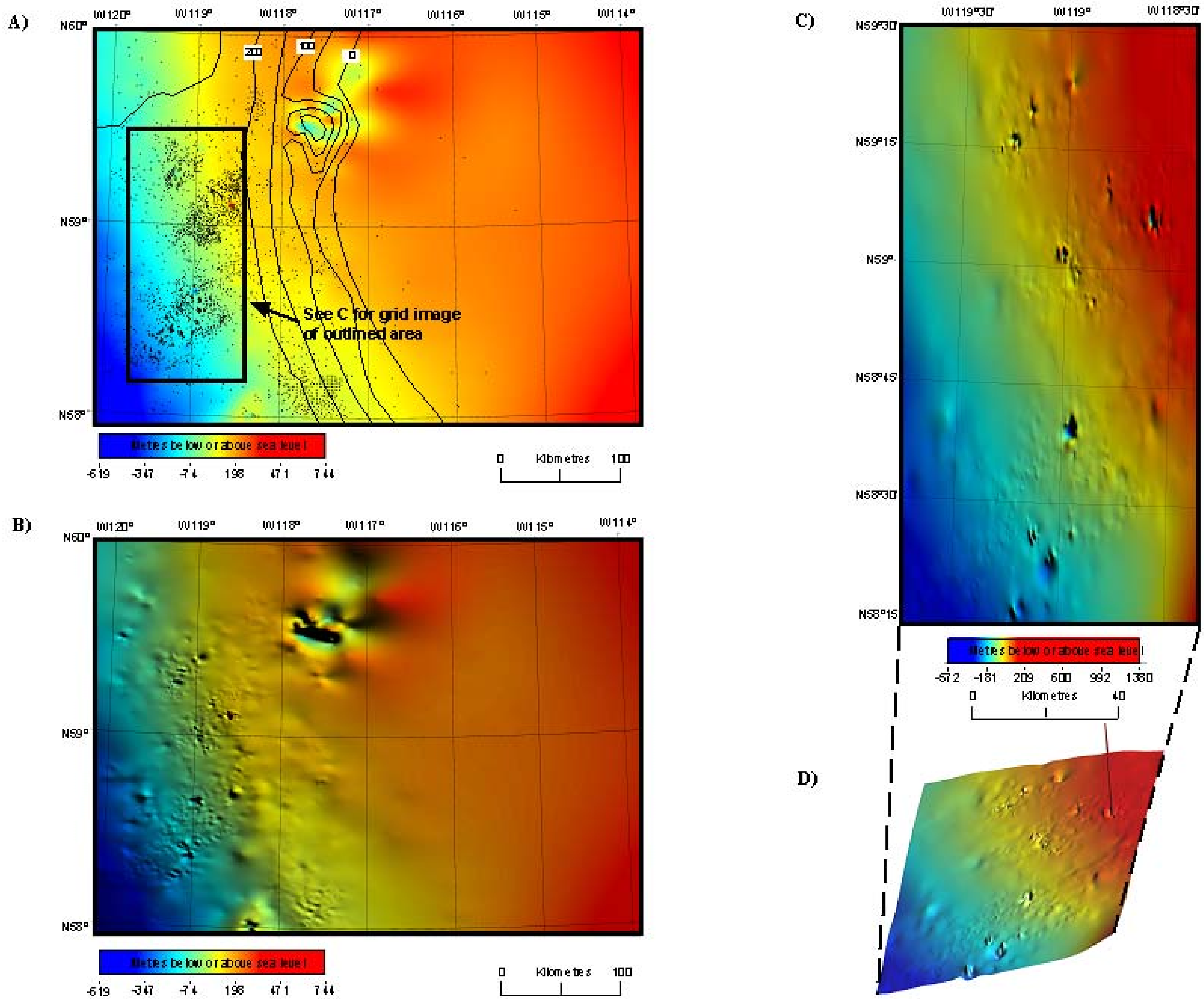


Figure A.8. Surface representation maps for the top of the Wabamun Group. A) surface grid map with the location of wells used to create the minimum curvature grid and approximate isopach contours (interval=50 m) from Halbertsma (1994); B) shaded-releif surface grid map with sun-angle from the north; C) shaded-relief surface grid map using only the well data from the detailed area outlined in A; and D) tilted 3D-view of the image in C with view from the south; scale 1:100 000.

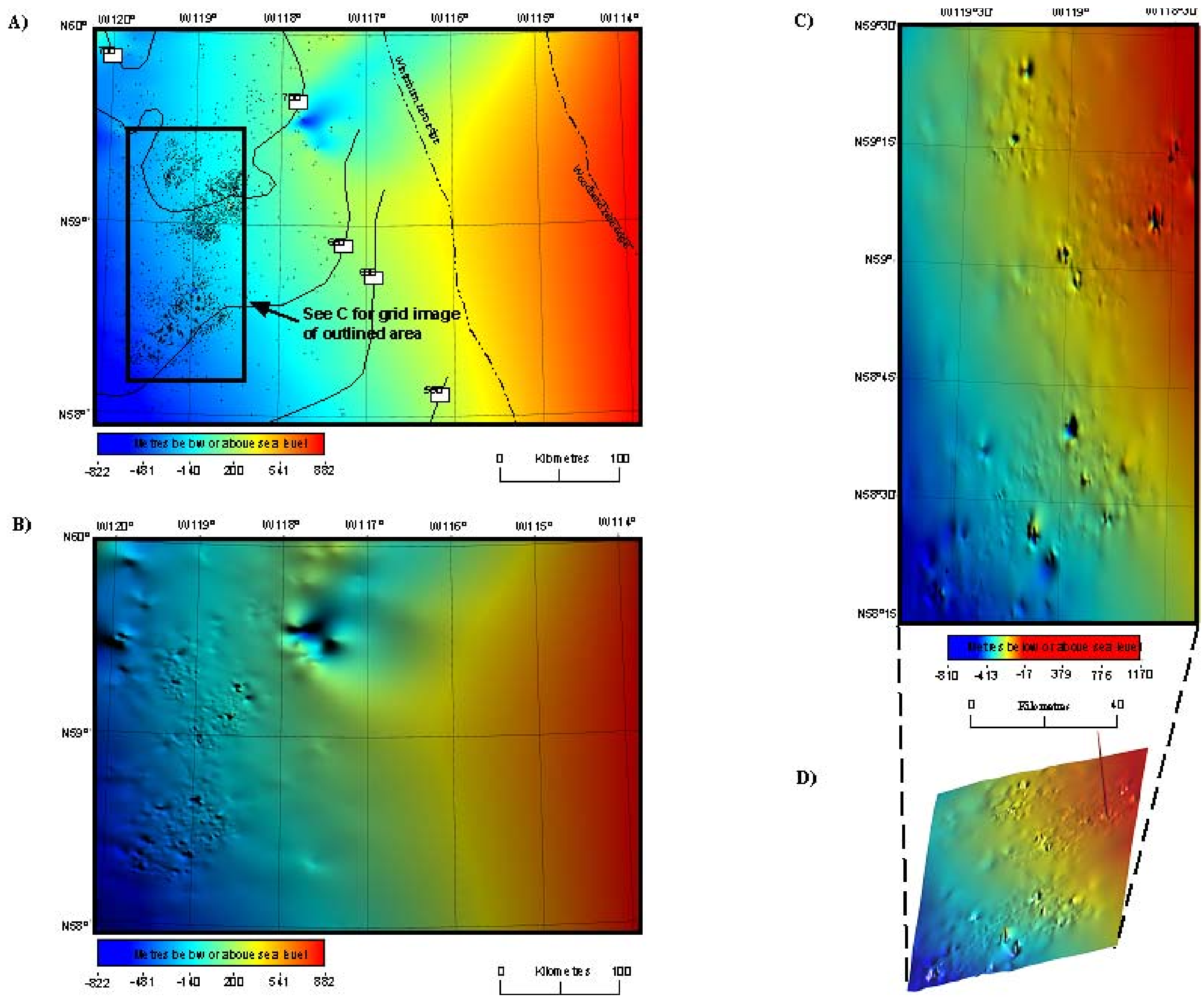


Figure A.9. Surface representation maps for the top of the Winterburn Group. A) surface grid map with the location of wells used to create the minimum curvature grid and approximate isopach contours (interval=50 m) for the combined Woodbend and Winterburn intervals from Switzer et al. (1994); B) shaded-relief surface grid map with sun-angle from the north; C) shade-relief surface grid map using only the well data from the detailed area outlined in A; and D) tilted 3D-view of the image in C with view from the south; scale 1:100 000.

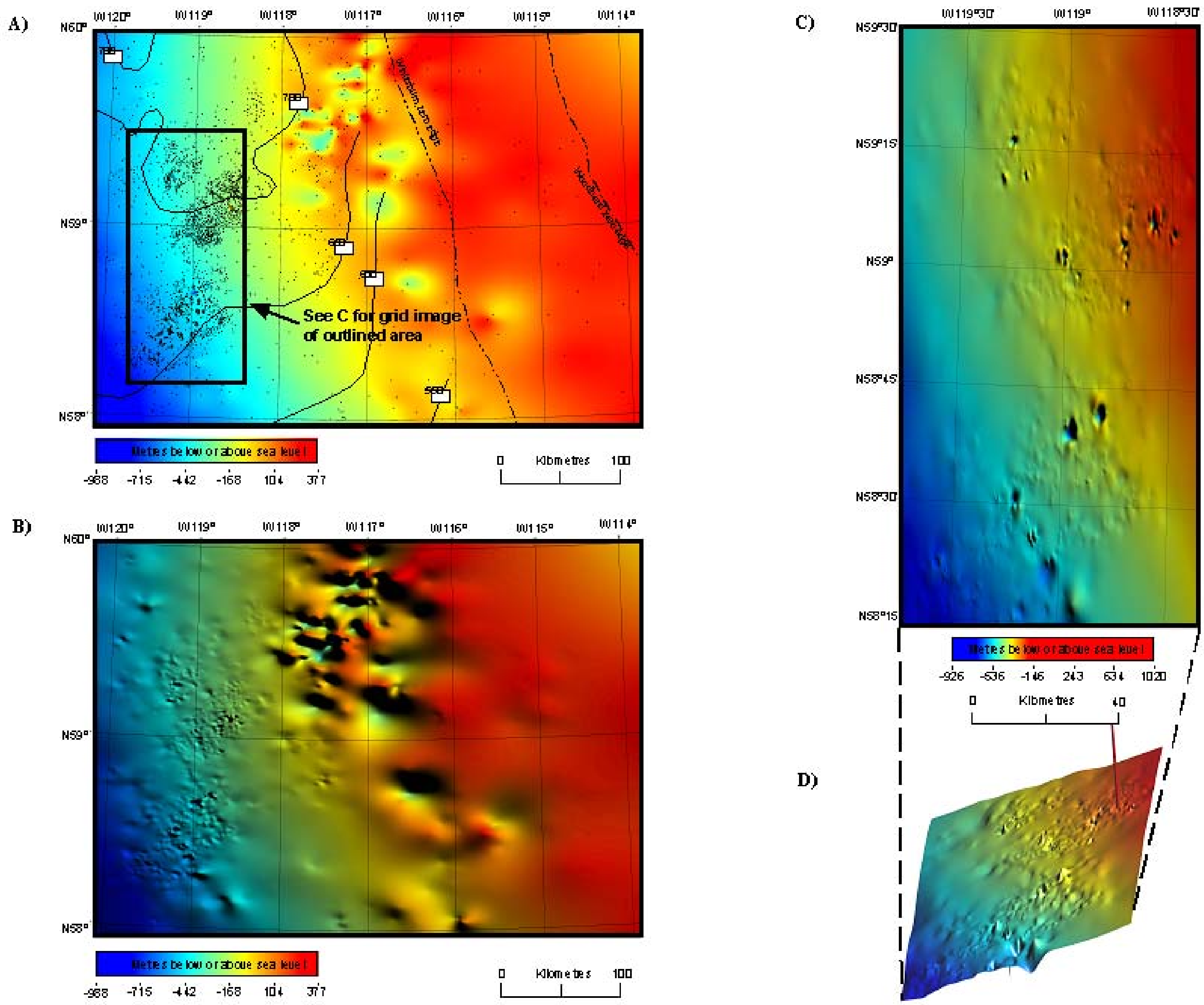


Figure A.10. Surface representation maps for the top of the Woodbend Group. A) surface grid map with the location of wells used to create the minimum curvature grid and approximate isopach contours (interval=50 m) for the combined Woodbend and Winterburn intervals from Switzer et al. (1994); B) shaded-relief surface grid map with sun-angle from the north; C) shade-relief suvface grid map using only the well data from the detailed area outlined in A; and D) tilted 3D-view of the image in C with view from the south; scale 1:100 000.

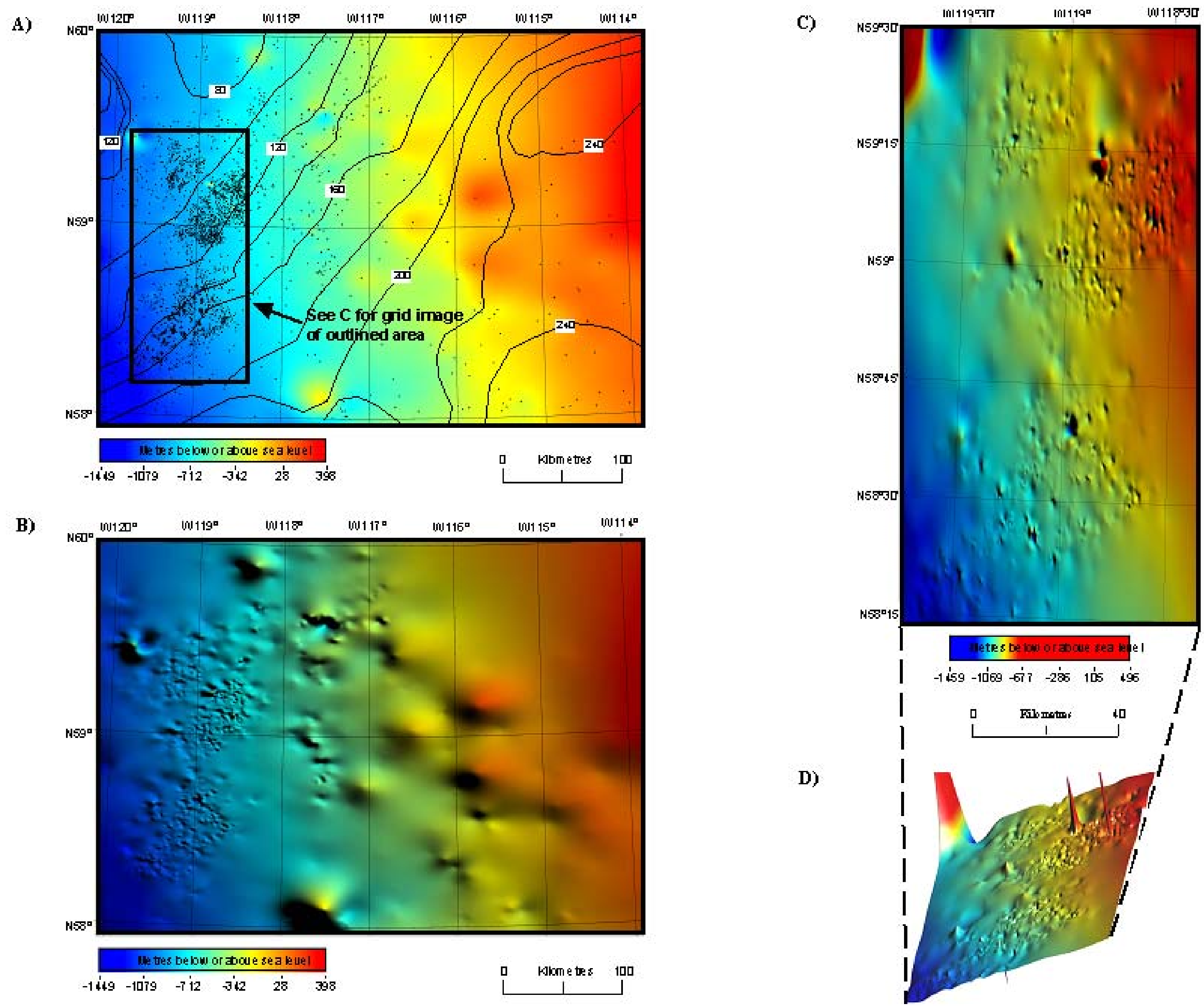


Figure A.11. Surface representation maps for the top of the Beaverhill Lake Group or top of the Waterways Group. A) surface grid map with the location of wells used to create the minimum curvature grid and approximate isopach contours (interval=20 m) from Oldale and Munday (1994); B) shaded-relief surface grid map with sun-angle from the north; C) shaded-relief surface grid map using only the well data from the detailed area outlined in A; and D) tilted 3D-view of the image in C with view from the south; scale 1:100 000.

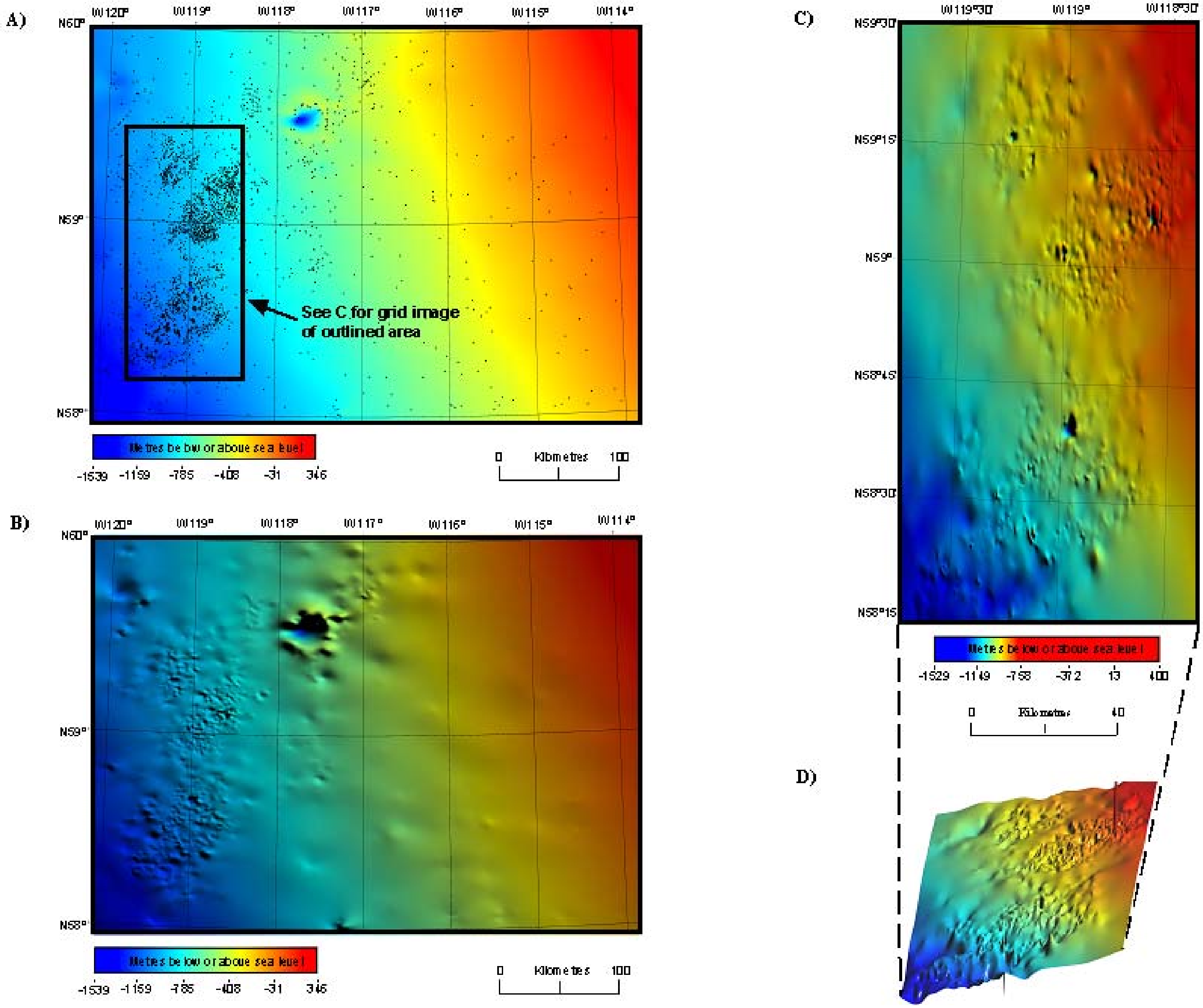


Figure A.12. Surface representation maps for the top of the Slave Point Formation. A) surface grid map with the location of wells used to create the minimum curvature grid; B) shade-relief surface grid map with sun-angle from the north; C) shade-relief surface grid map of detailed area outlined in A; and D) tilted 3D-view of the image in C with view from the south; scale 1:00 000.

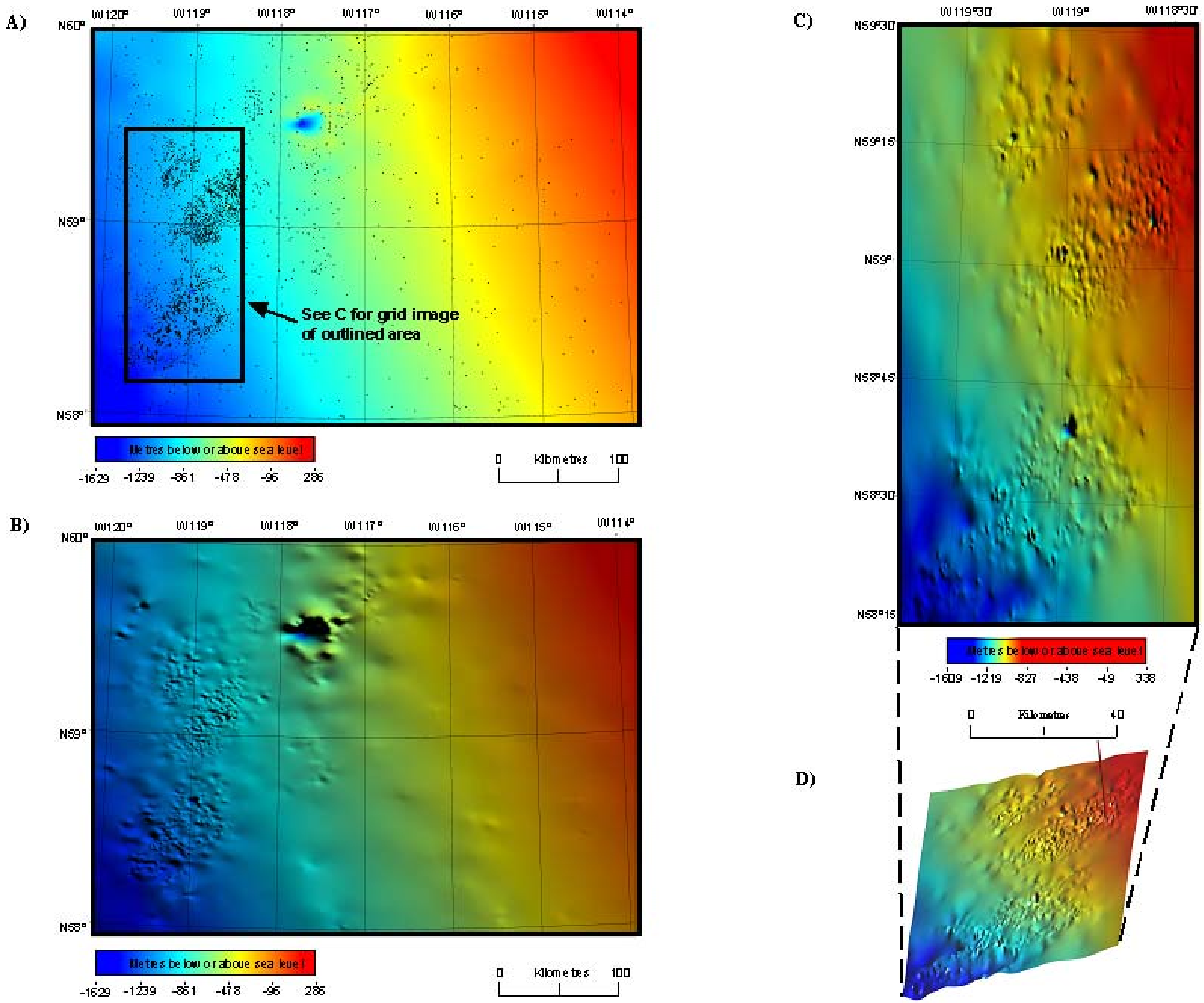


Figure A.13. Surface representation maps for the top of the Watt Mountain Formation. A) surface grid map with the location of wells used to create the minimum curvature grid; B) shade-relief surface grid map with sun-angle from the north; C) shaded-relief surface grid map using only the well data from the detailed area outlined in A; and D) tilted 3D-view of the image in C with view from the south; scale 1:100 000.

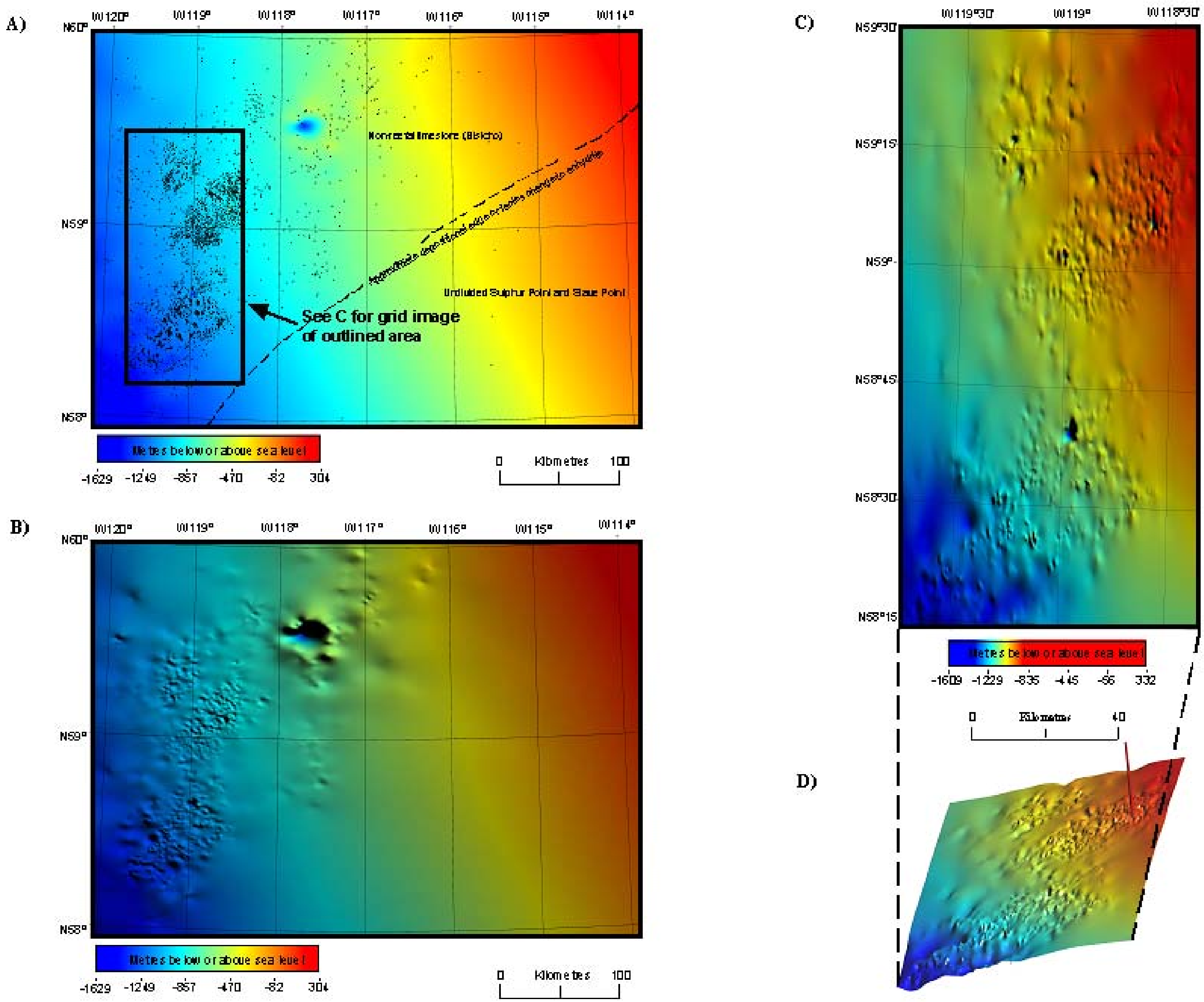


Figure A.14. Surface representation maps for the top of the Sulphur Point Formation. A) surface grid map with the location of wells used to create the minimum curvature grid and epositional edge of the Sulphur Point from Jeijer Drees (1994); B) shaded-relief surface grid map with sun-angle from the north; C) shaded-relief surface grid map using only the well data from the detailed area outlined in A; and D) tilted 3D-view of the image in C with view from the south; scale 1:100 000.

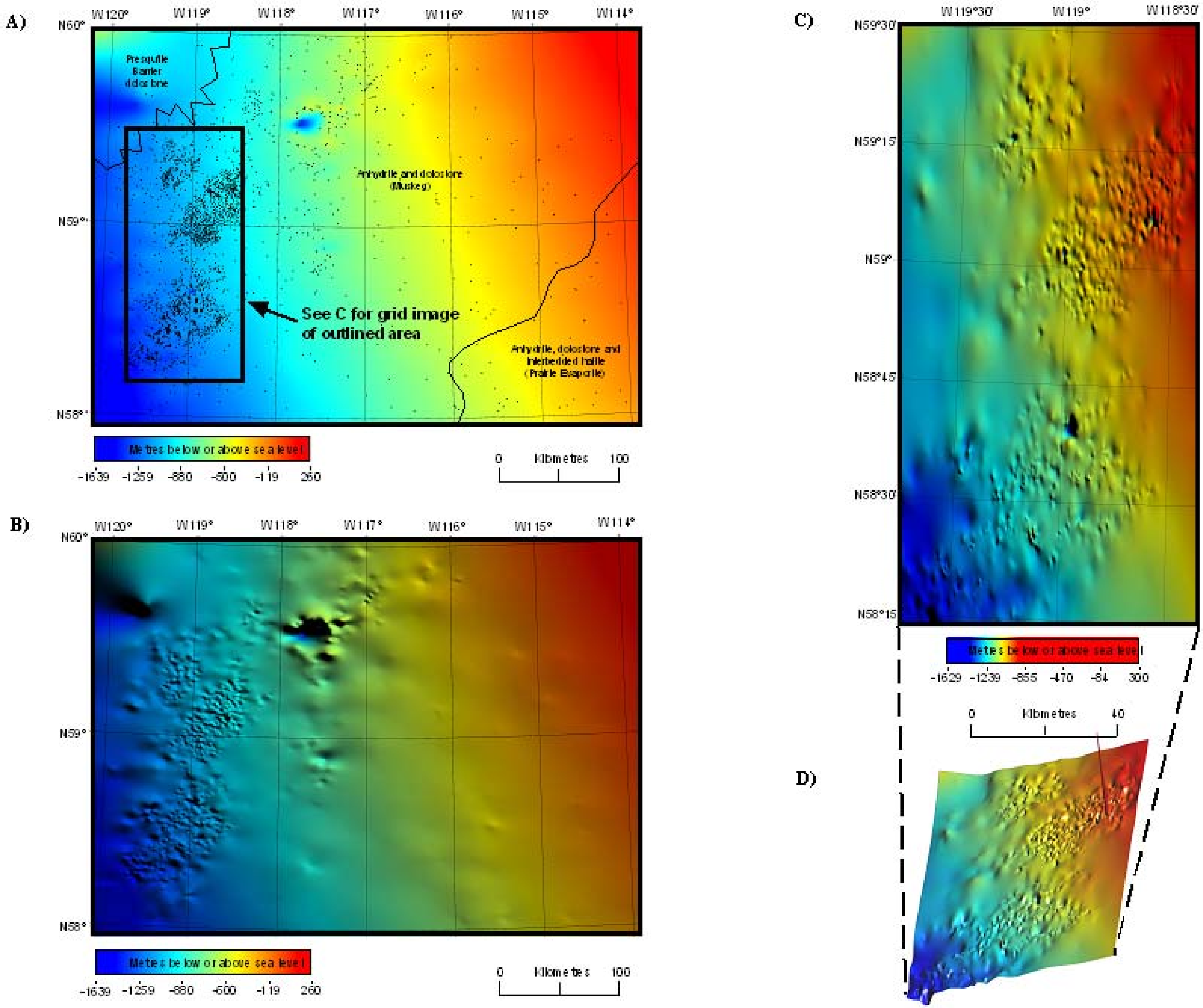


Figure A.15. Surface representation maps for the top of the Muskeg Formation. A) surface grid map with the location of wells used to create the minimum curvature grid and distribution of Muskeg from Meijer Drees (1994); B) shaded-relief surface grid map with sun-angle from the north; C) shaded-relief surface grid map using only the well data from the detailed area outlined in A; and D) tilted 3D-view of the image in C with view from the south; scale 1:100 000.

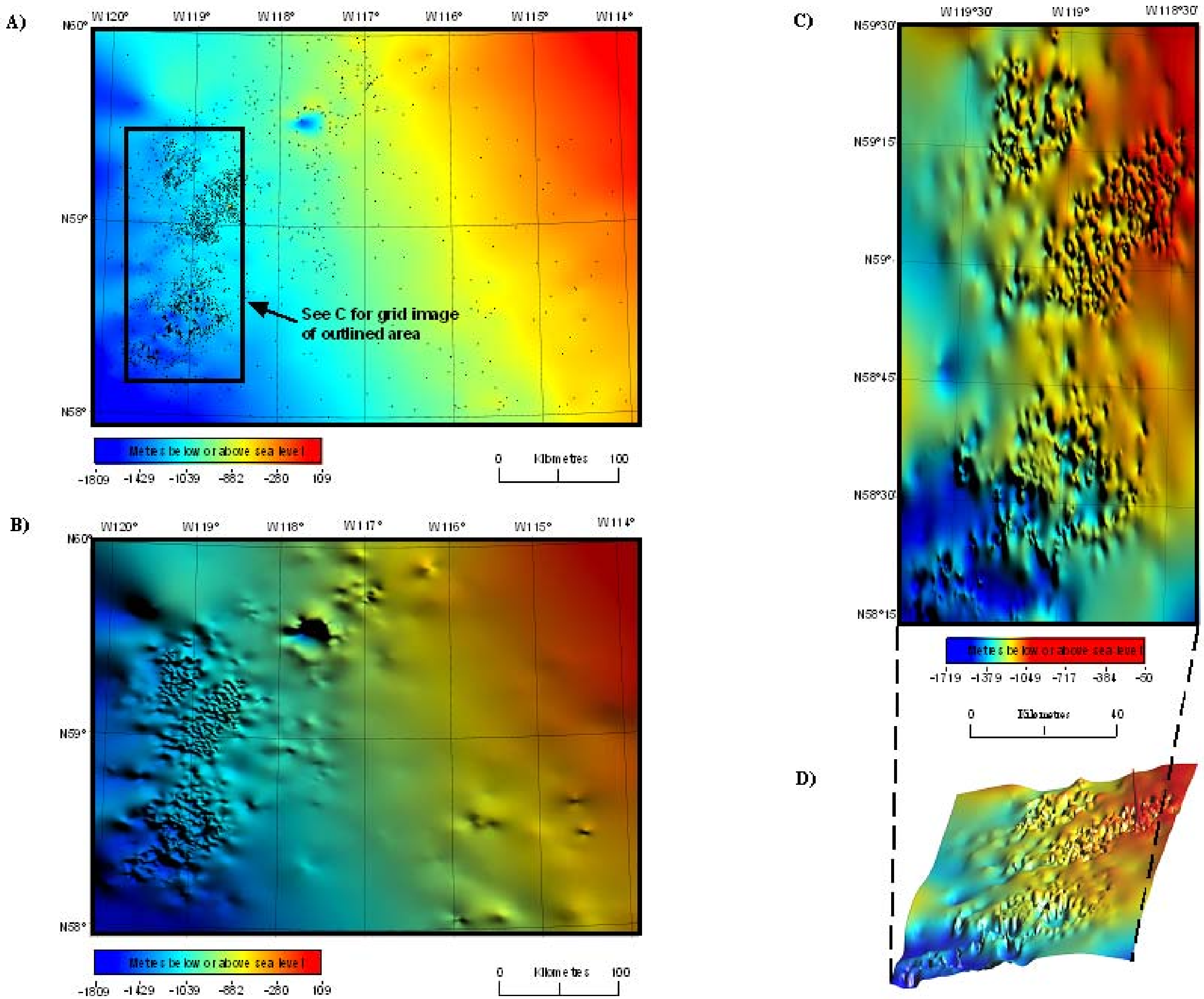


Figure A.16. Surface representation maps for the top of the Keg River Formation. A) surface grid map with the location of wells used to create the minimum curvature grid; B) shaded-relief surface grid map with sun-angle from the north; C) shaded-relief surface grid map using only the well data from the detailed area outlined in A; and D) tilted 3D-view of the image in C with view from the south; scale 1:100 000.

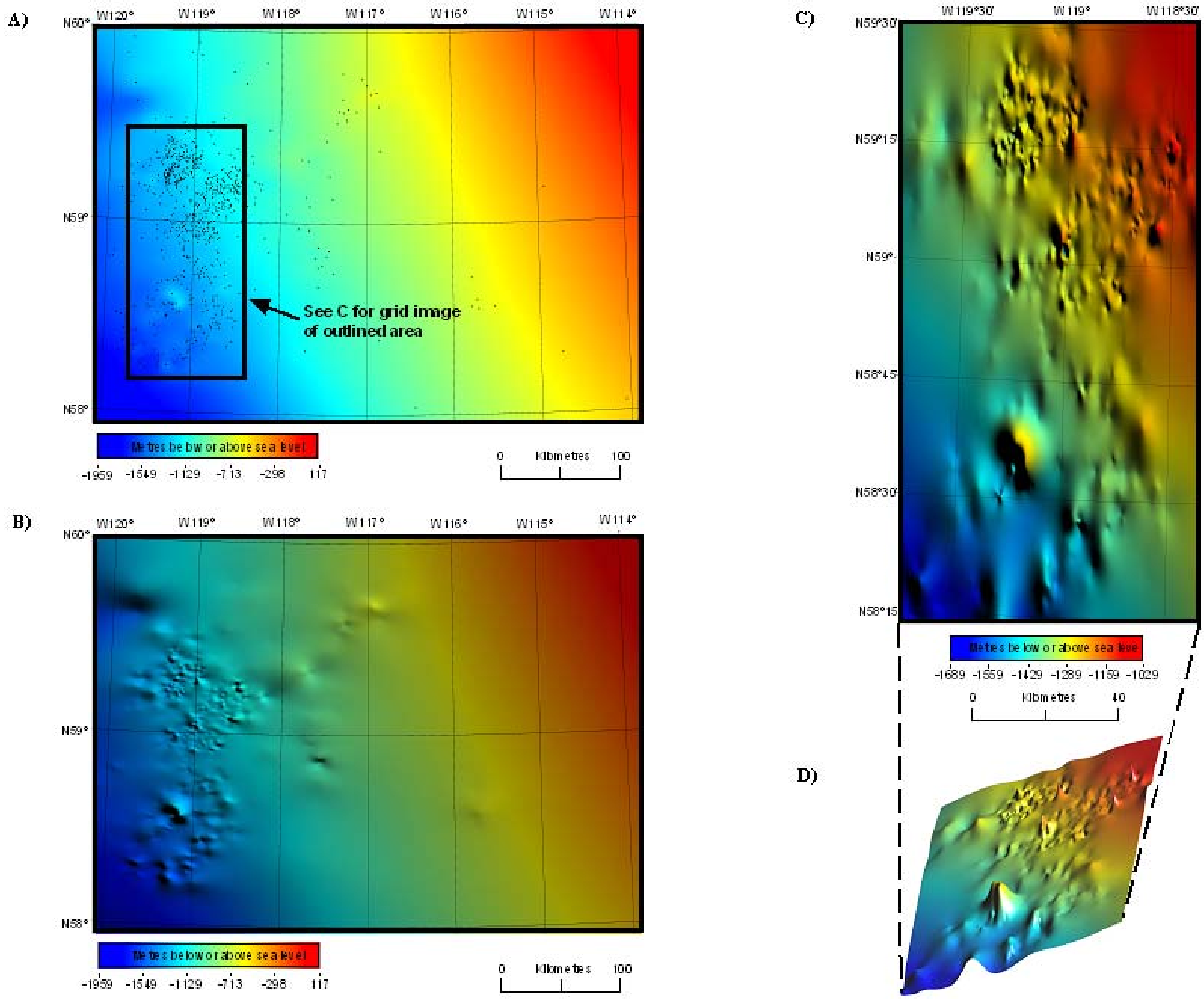


Figure A.17. Surface representation maps for the top of the Lower Keg River Formation. A) surface grid map with the location of wells used to create the minimum curvature grid; B) shaded-relief surface grid map with sun-angle from the north; C) shaded-relief surface grid map using only the well data from the detailed area outlined in A; and D) tilted 3D-view of the image in C with view from the south; scale 1:100 000.

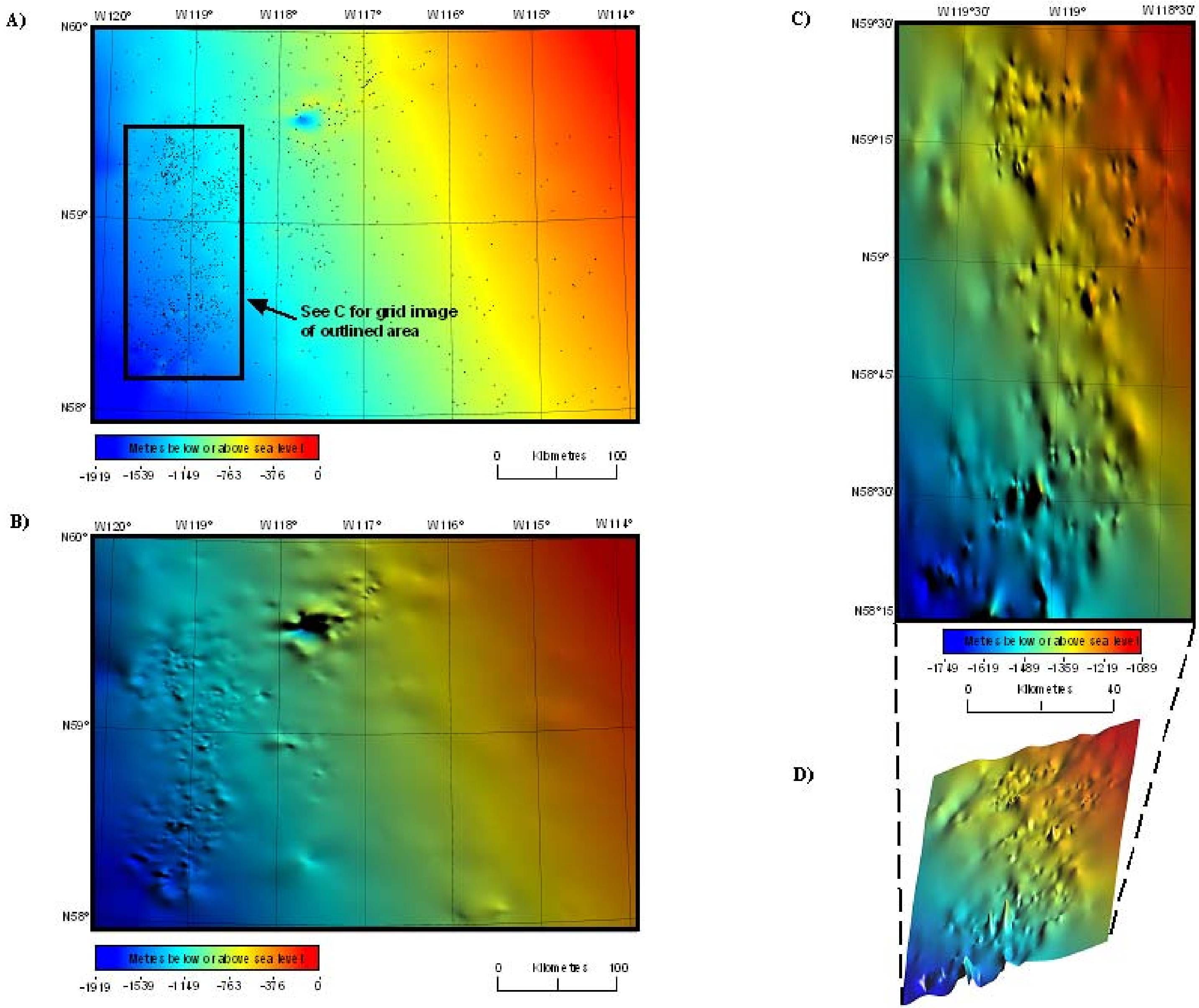
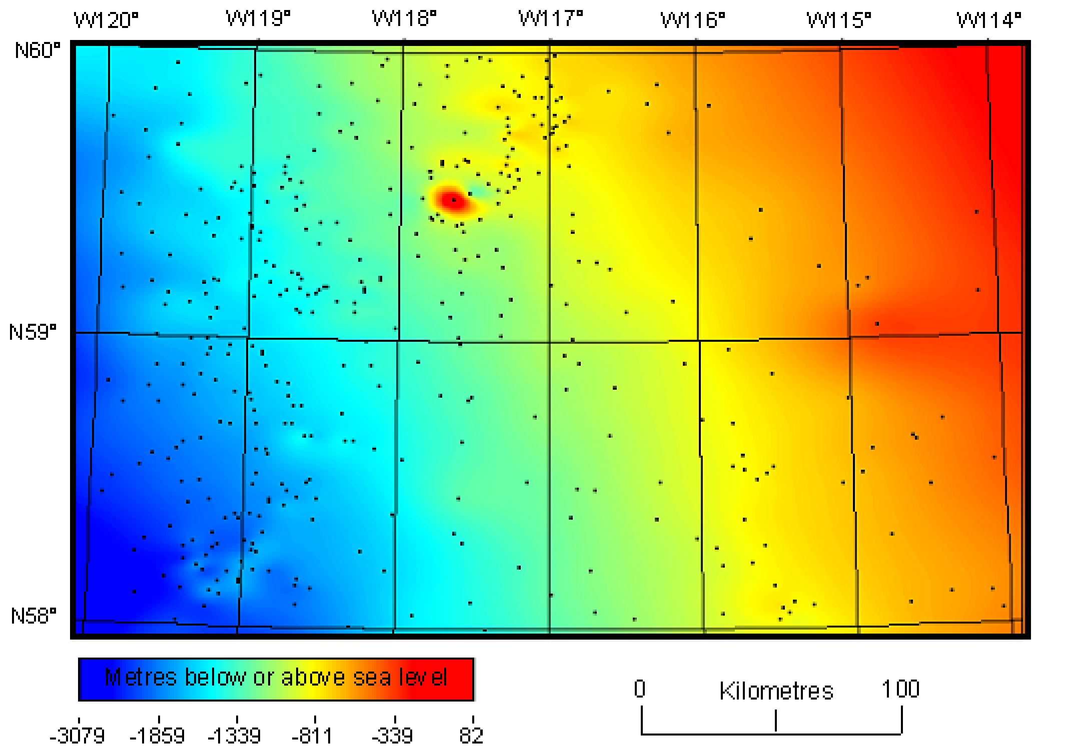


Figure A.18. Surface representation maps for the top of the Chinchaga Formation. A) surface grid map with the location of wells used to create the minimum curvature grid; B) shaded-relief surface grid map with sun-angle from the north; C) shaded-relief surface grid map using only the well data from the detailed area outlined in A; and D) tilted 3D-view of the image in C with view from the south; scale 1:100 000.

A)



B)

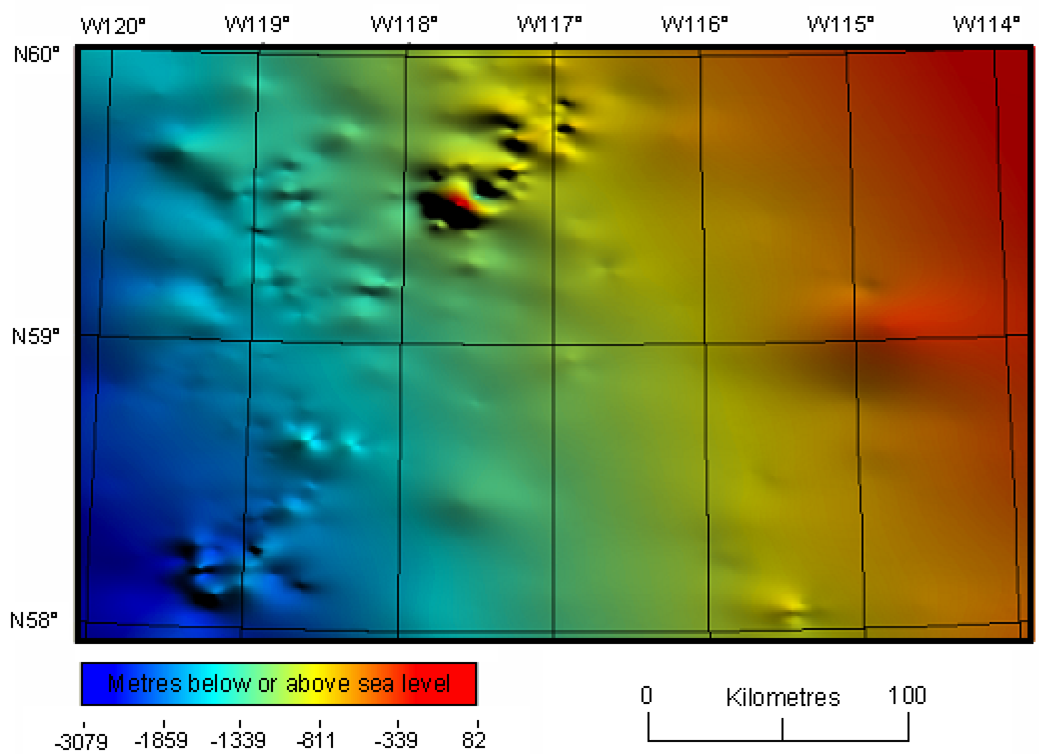


Figure A.19. Surface representation grid maps for the top of the Precambrian basement. A) surface grid with the location of the wells used to create the minimum curvature grid; and B) shaded-relief surface grid with sun-angle from the northeast.

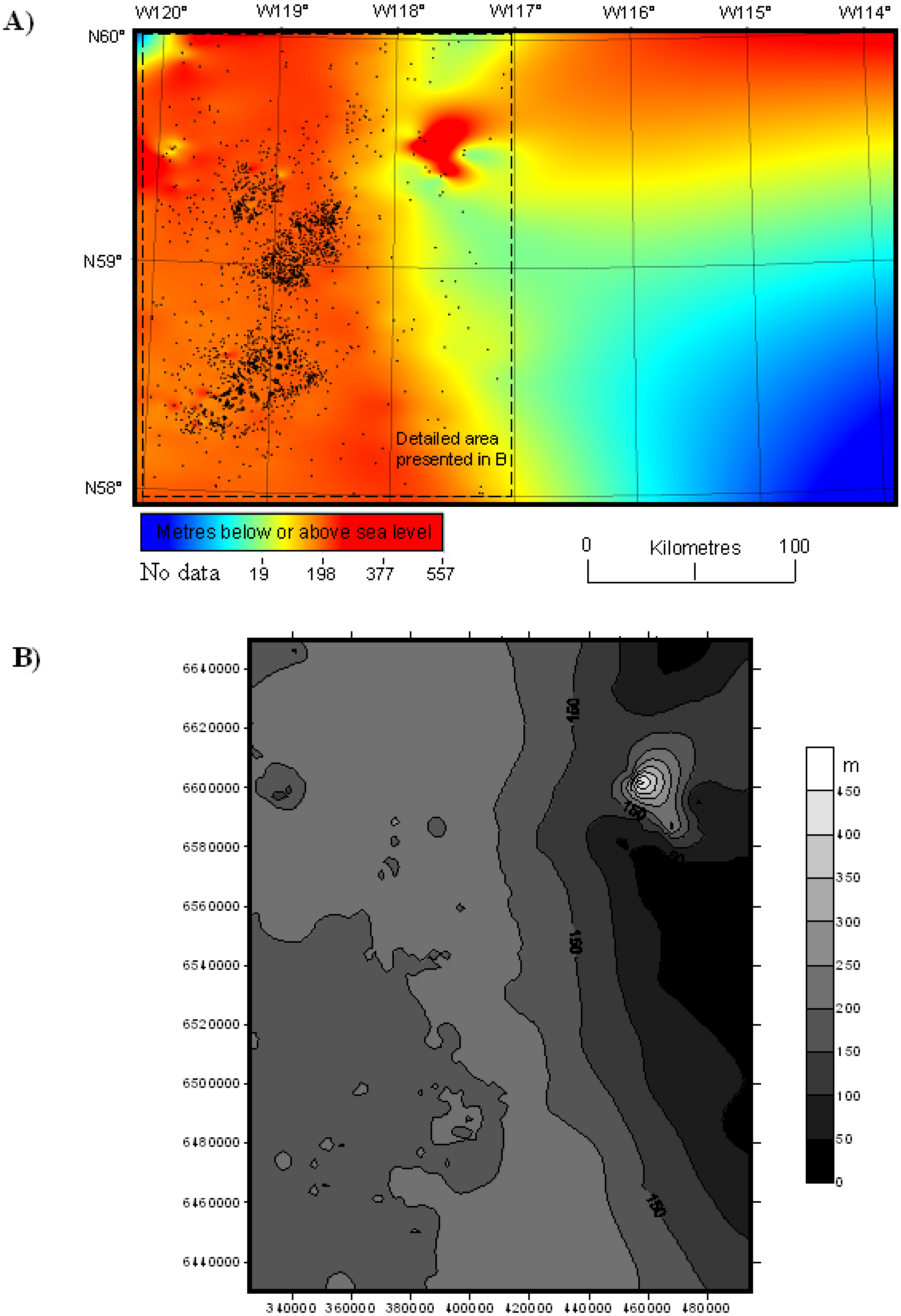
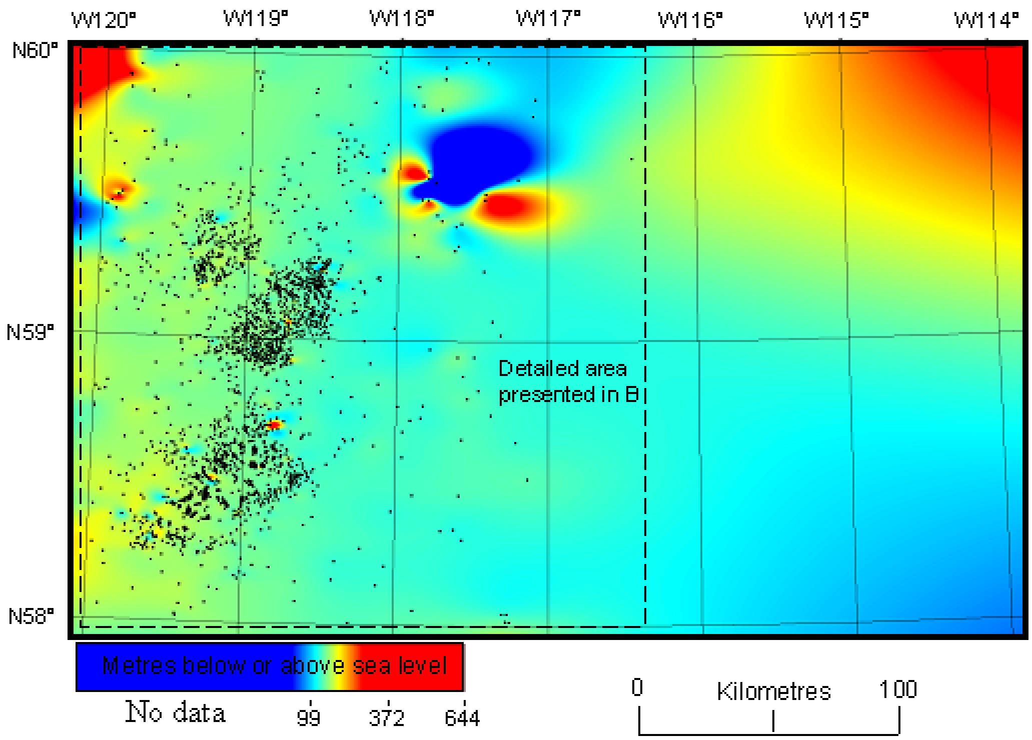


Figure A.20. Surface representation isopach maps from the top of the Wabamun Group to the top of the Winterburn Group. A) surface grid with the location of the wells used to create the minimum curvature grid; and B) contour map (see A for location of area).

A)



B)

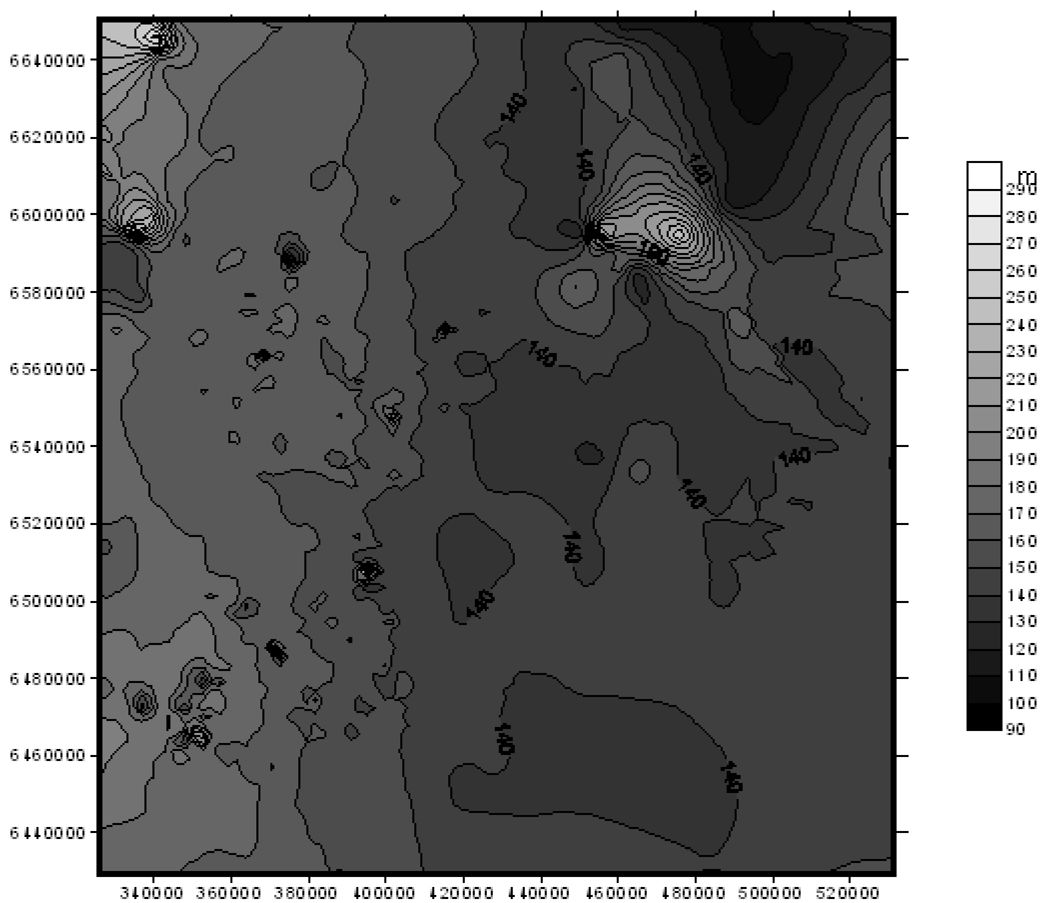
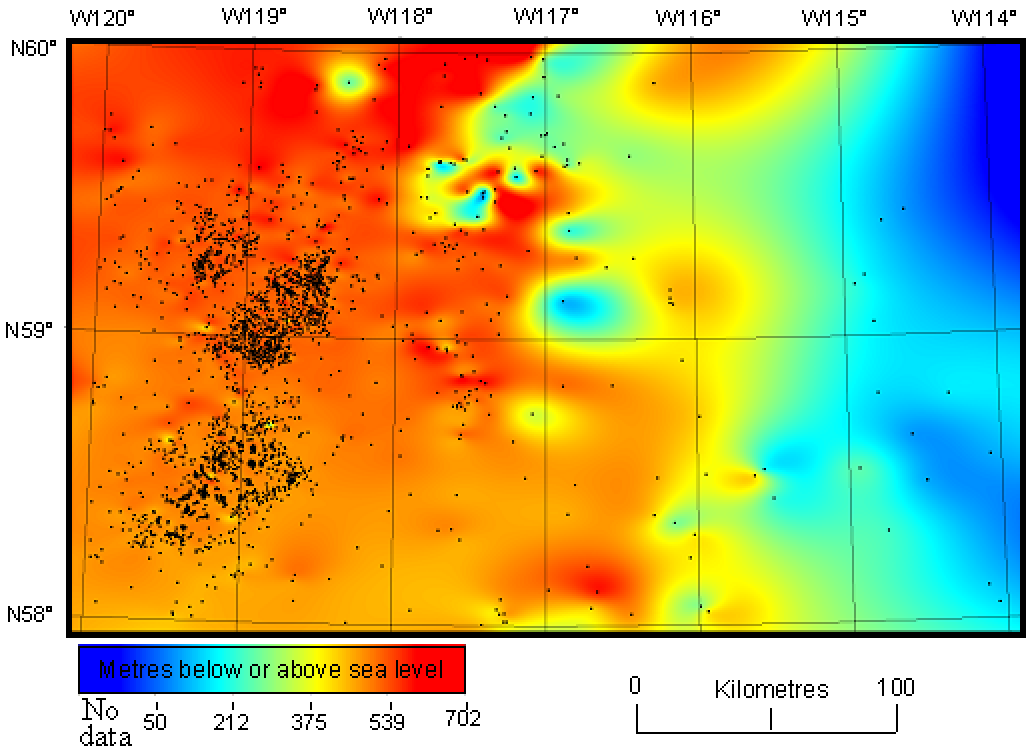


Figure A.21. Surface representation isopach maps from the top of the Winterburn Group to the top of the Woodbend Group. A) surface grid with the location of the wells used to create the minimum curvature grid; and B) contour map (see A for location of area).

A)



B)

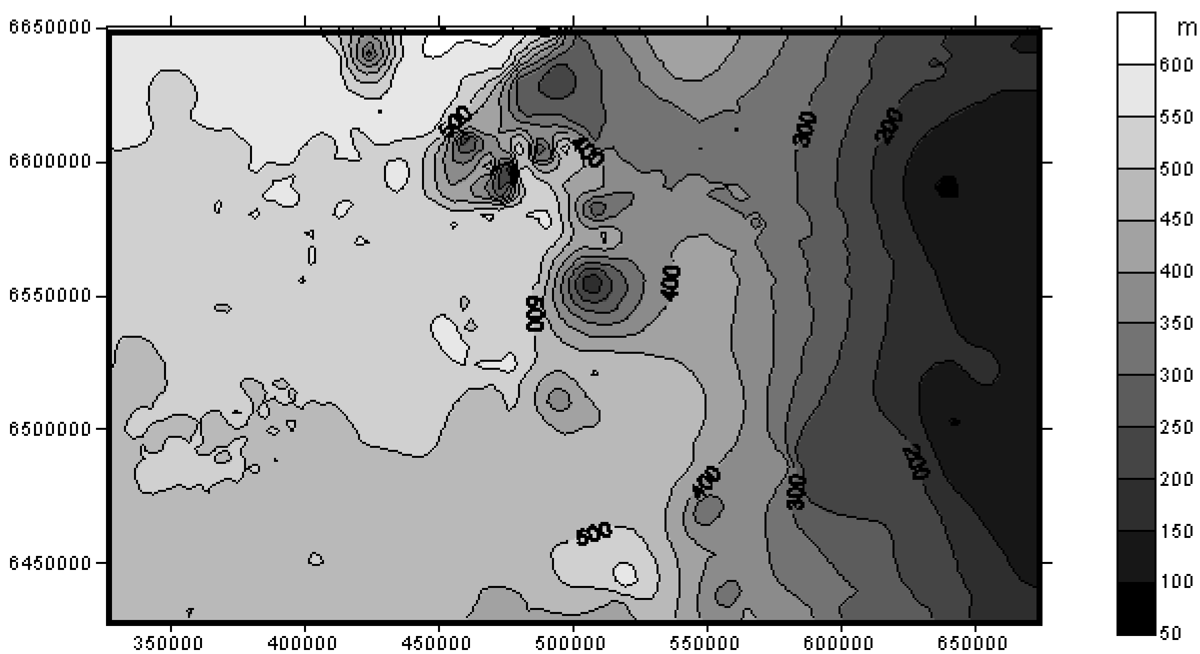
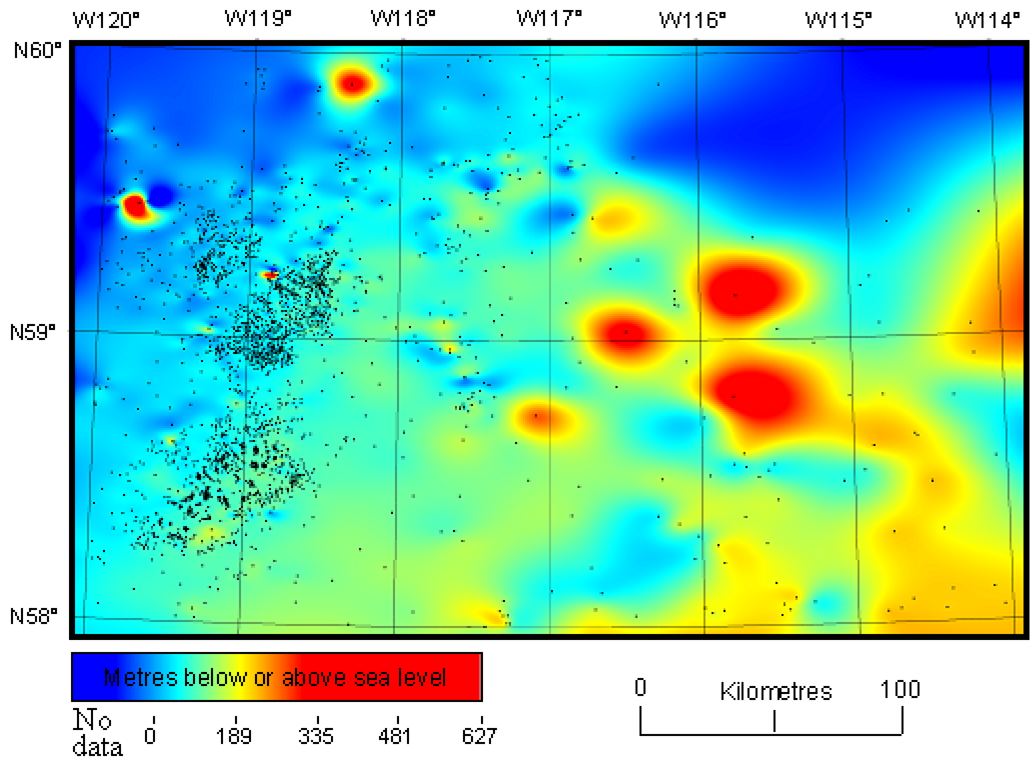


Figure A.22. Surface representation isopach maps from the top of the Woodbend Group to the top of the Beaverhill Lake Group (Waterways Group). A) surface grid with the location of the wells used to create the minimum curvature grid; and B) contour map.

A)



B)

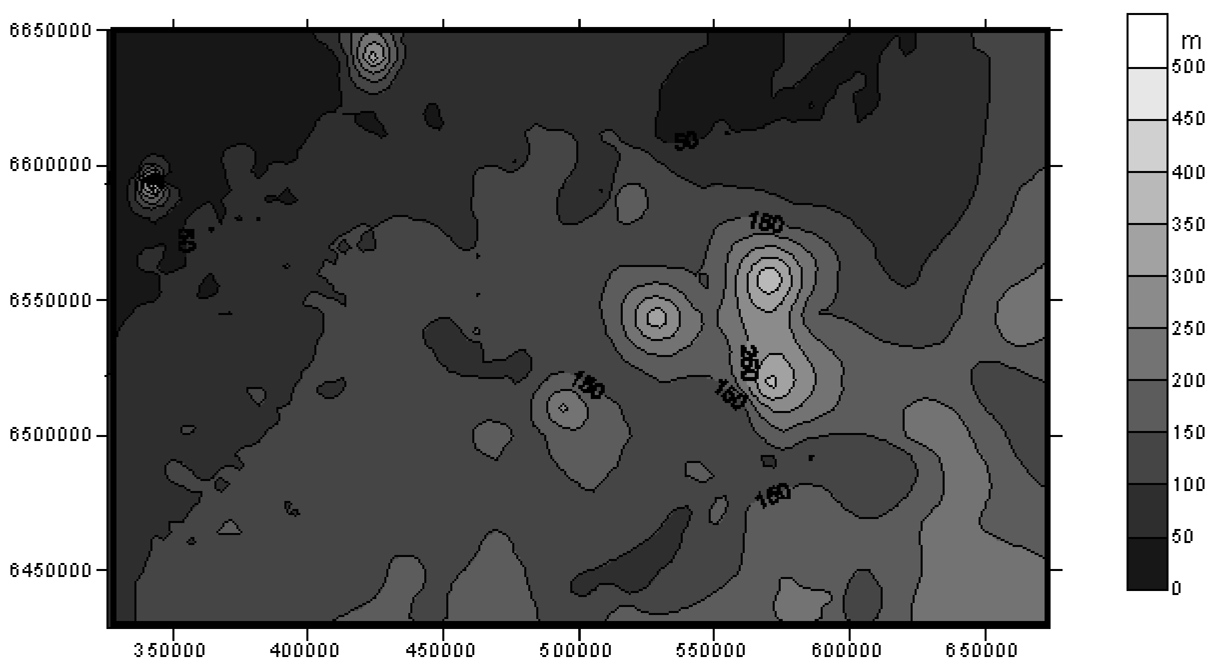


Figure A.23. Surface representation isopach maps from the top of the Beaverhill Lake Group (or top of the Waterways Group) to the top of the Slave Point Formation. A) surface grid with the location of the wells used to create the minimum curvature grid; and B) contour map.

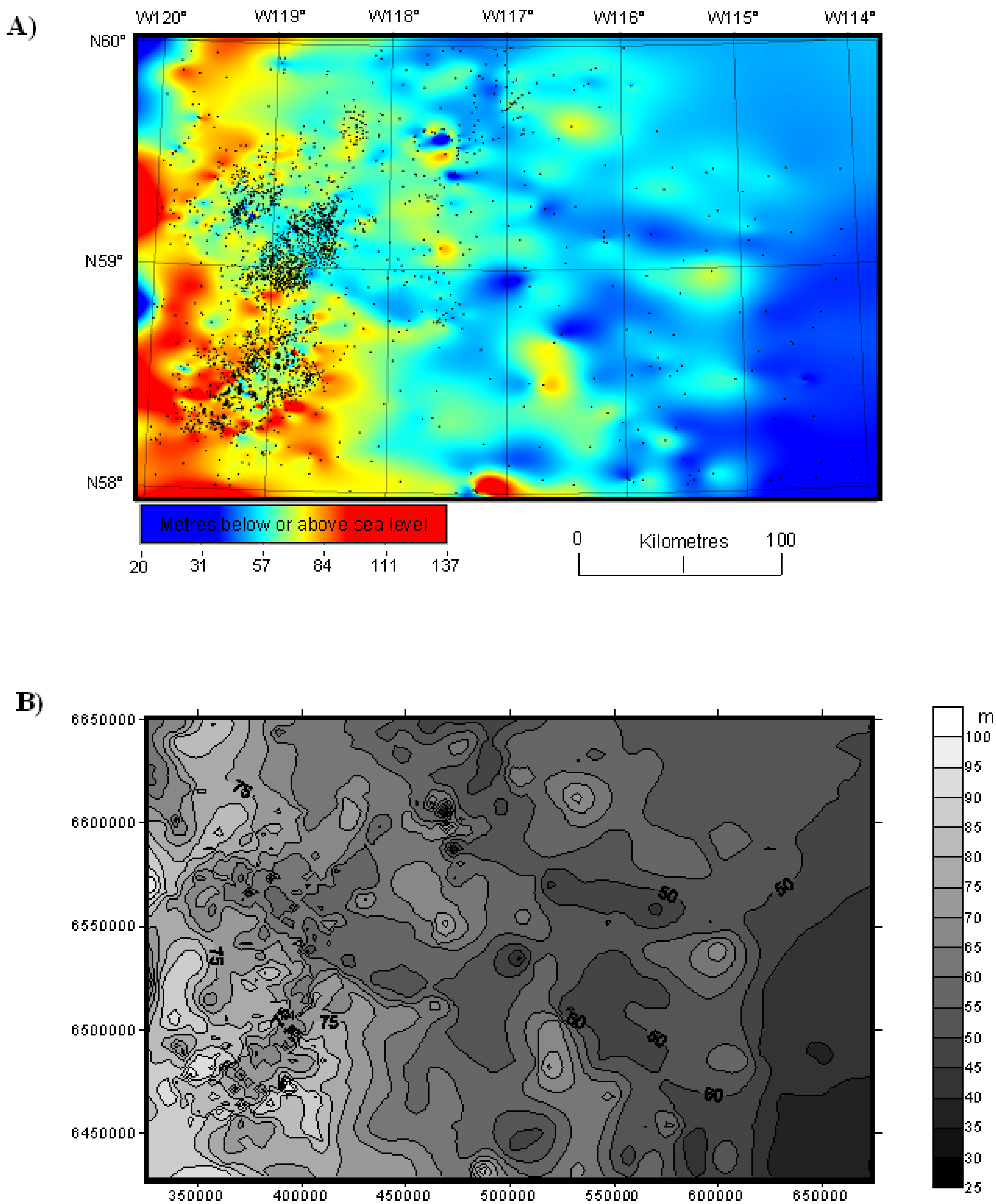


Figure A. 24. Surface representation isopach maps from the top of the Slave Point Formation to the top of the Watt Mountain Formation. A) surface grid with the location of the wells used to create the minimum curvature grid; and B) contour map.

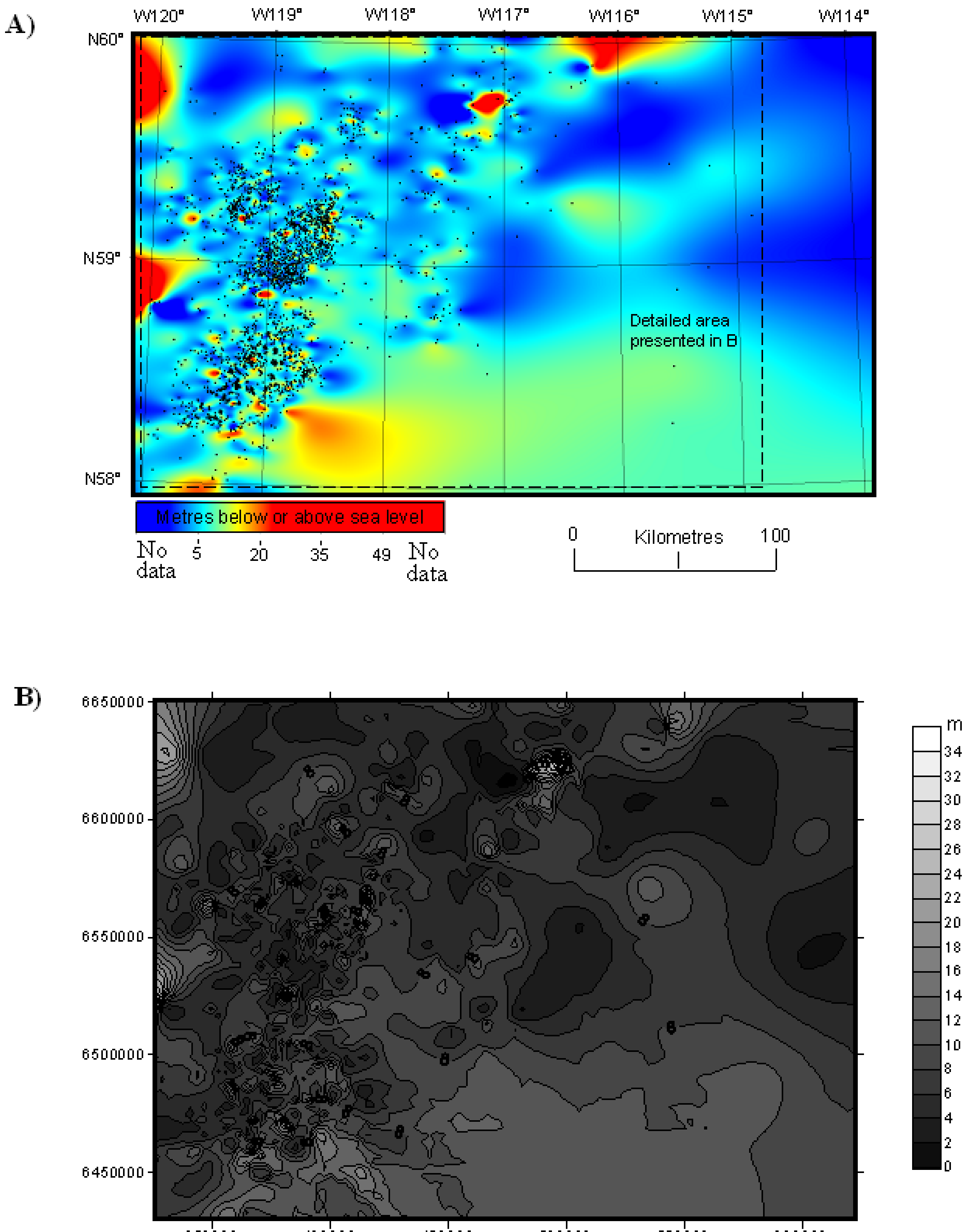


Figure A.25. Surface representation isopach maps from the top of the Watt Mountain Formation to the top of the Sulphur Point Formation. A) surface grid with the location of the wells used to create the minimum curvature grid; and B) contour map (see A for location of area).

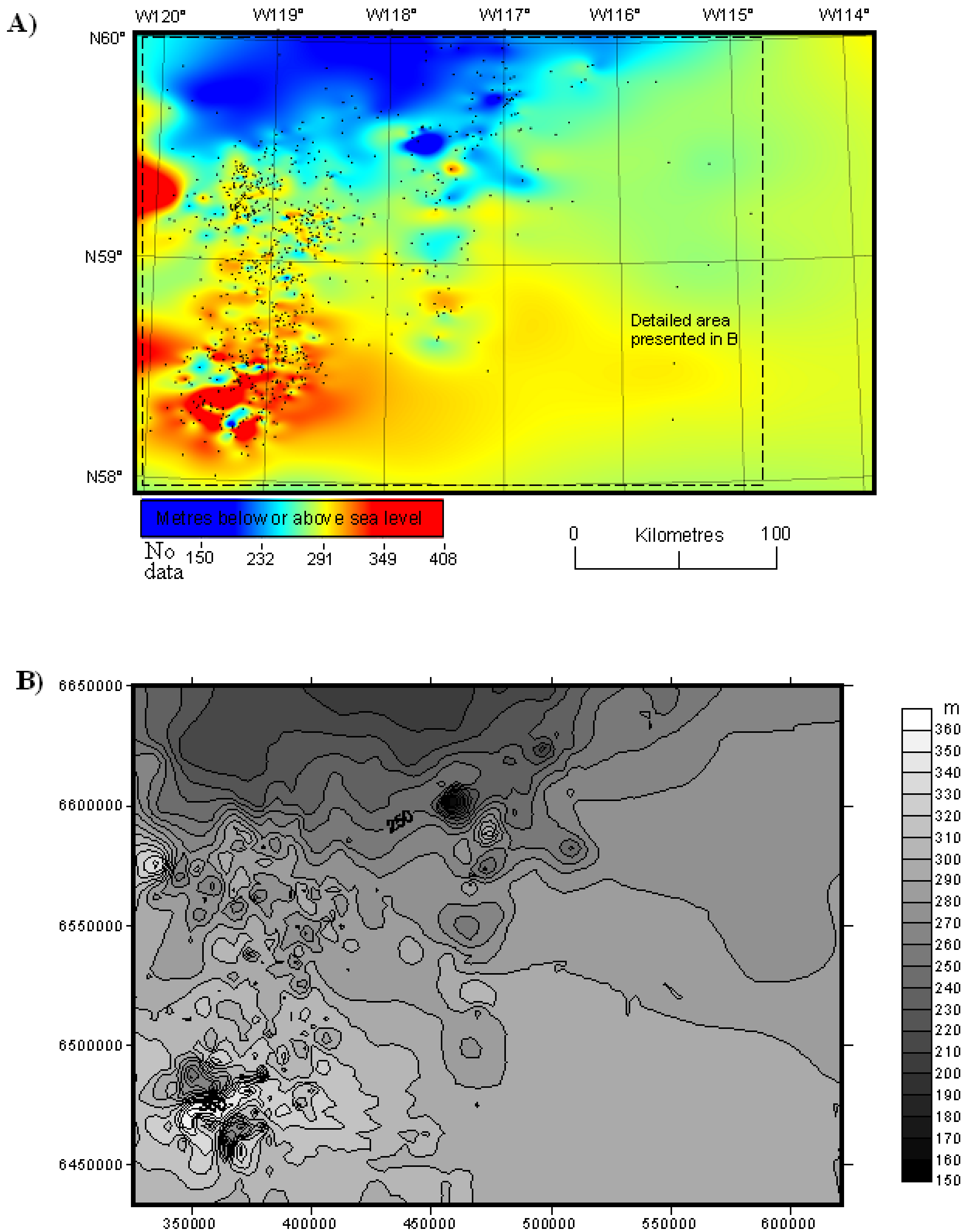


Figure A.26. Surface representation isopach maps from the top of the Sulphur Point Formation to the top of the Chinchaga Formation. A) surface grid with the location of the wells used to create the minimum curvature grid; and B) contour map (see A for location of area).

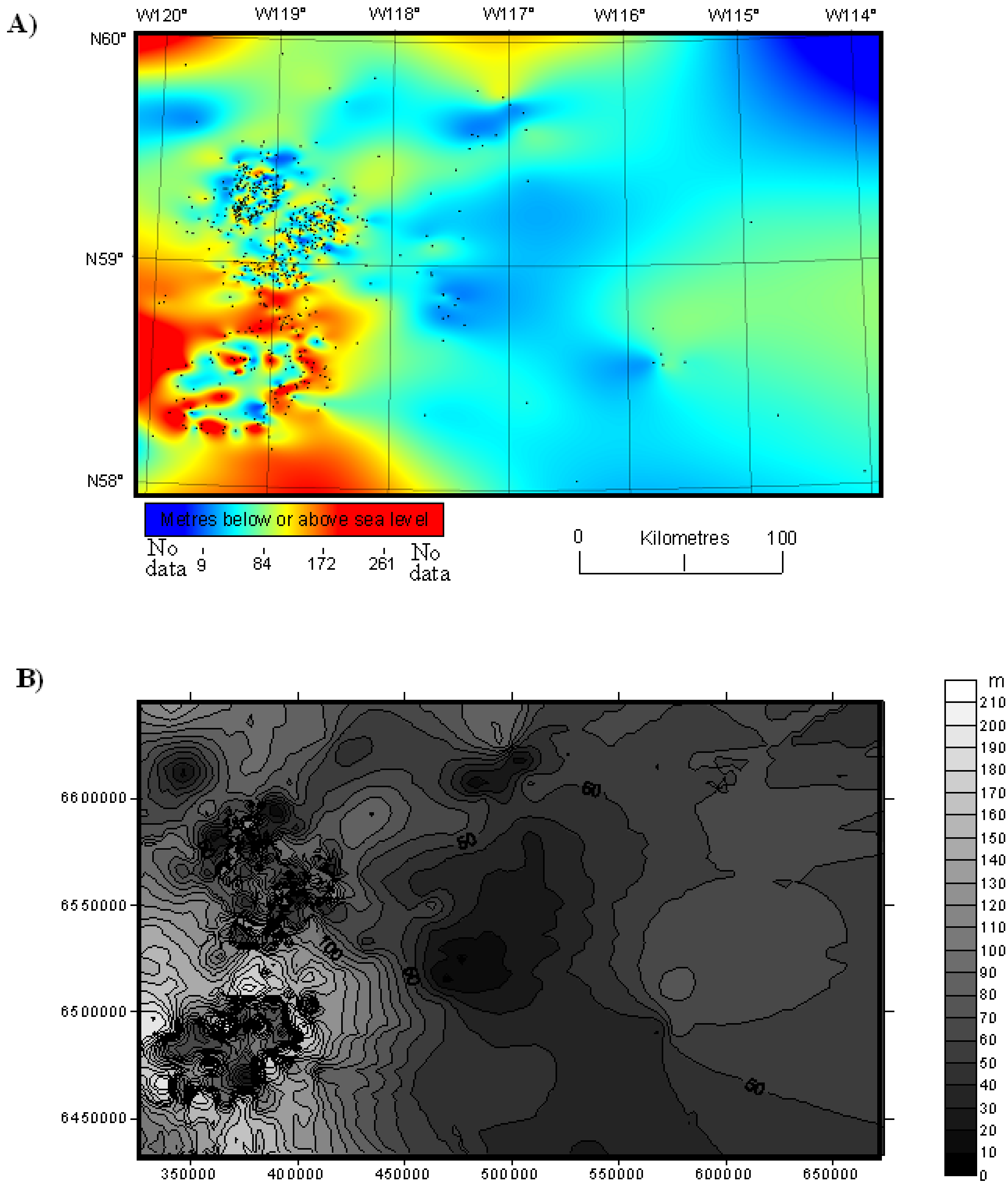


Figure A.27. Surface representation isopach maps from the top of the Keg River Formation to the top of the Lower Keg River Formation. A) surface grid with the location of the wells used to create the minimum curvature grid; and B) contour map.

2.2 Methodology

The data were retrieved from iDc using GeoSoft v3.4 and the well locations were transformed to Universal Transverse Mercator projection (UTM Zones 11 and 12; map datum NAD83). A gridded raster image was created using the minimum curvature interpolation method (set to standard parameters) using ERMapper image processing software (Earth Resources Mapping Pty. Ltd., 1998). The boundary extent of each 'formation grid' was set to identical parameters in order to allow for a visual comparison. Two X, Y cell sizes were used to grid the data: 500 x 500 m for the larger surface representation maps that cover the entire study area, and 200 x 200 m for detailed images.

Each surface representation figure includes

1) a 1:500 000 (500 x 500 m cell size) image with the location of the wells used in the gridding process (e.g., Figure A.3.A);
2) a 1:500 000 (500 x 500 m cell size) shaded relief image with a sun-angle from the north (e.g., Figure A.3.B);
3) a 1:100 000 (200 x 200 m cell size) shaded relief image, which was regridding using only the data from an area of detail, which focuses on the area with the densest proportion of well data (e.g., Figure A.3.C); and
4) a rotated, three-dimensional view of the area of detail (e.g., Figure A.3.D).

Additional information, where possible, was added to the grid images from the Geological Atlas of the Western Canada Sedimentary Basin (Mossop and Shetsen, 1994).