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Alberta Energy Regulator

Modelling of the Sub-Cretaceous Unconformity: Elevation, Subcrop Mapping, and Paleotopography in the Peace River and Slave Lake Regions, Alberta (NTS 83N, 83O, 84C, 84B)

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Modelling of the Sub-Cretaceous Unconformity: Elevation, Subcrop Mapping, and Paleotopography in the Peace River and Slave Lake Regions, Alberta (NTS 83N, 83O, 84C, 84B)

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Abstract

This report provides documentation on the scientific approach that was used to pick, map, and model the sub-Cretaceous unconformity surface in the Peace River and Slave Lake regions and provides supporting documentation to accompany *Map 578: Paleotopography of the Sub-Cretaceous Unconformity, Peace River – Slave Lake Region, Alberta (NTS 83N, 83O, 84C, 84B)* (Peterson and MacCormack, 2015).

The sub-Cretaceous unconformity is an important regional surface across the Alberta Basin. It represents a significant period of nondeposition and erosion initiated after the deposition of Upper Jurassic / lowermost Cretaceous sediments of the first foreland basin clastic wedge. The variable paleotopography developed on the sub-Cretaceous unconformity surface was an important control on sedimentation and preservation of major petroleum-bearing Cretaceous formations in areas such as the Athabasca, Peace River, and Cold Lake oil sands areas. Previous modelling of the sub-Cretaceous unconformity surface was completed using datasets from multiple sources, resulting in a variable-quality surface due to inconsistent picking criteria between sources, colocated data, and clustered data distribution. To ensure consistency and increase our confidence in models of this important surface, the sub-Cretaceous unconformity was mapped across the study area by reviewing the well logs for 4175 wells, identifying subcropping formations, and determining the elevation of the unconformity surface. Additional modelling was then performed to generate a paleotopographic surface representing the topography of the unconformity surface prior to the onset of Cretaceous sedimentation in the study area.

1 Introduction

This report is intended to provide further information on the creation of *Map 578* (Peterson and MacCormack, 2015). The study area is located in the Peace River and Slave Lake regions and covers NTS sheets 83N, 83O, 84C, and 84B. It extends over most of the Peace River Oil Sands Area and a small western portion of the Athabasca Oil Sands Area (Figure 1). The study area is directly north of that depicted in *Map 573: Paleotopography of the sub-Cretaceous unconformity, west-central Alberta (NTS 83F, 83G, 83J and 83K)* and is a continuation of that work (Peterson and MacCormack, 2014a, b).

The sub-Cretaceous unconformity is an important regional surface across the Alberta Basin, which represents a significant period of nondeposition and erosion initiated after the deposition of Upper Jurassic / lowermost Cretaceous sediments of the first foreland basin clastic wedge. Although the application of the term 'sub-Cretaceous unconformity' is technically incorrect in the spatially limited areas where lowermost Cretaceous sediments are present below the unconformity, it is widely used in the literature and is adopted here, because of its common use and applicability over most of the area of the Alberta Basin. In the investigated area, with the exception of the Upper Jurassic Fernie strata, this major unconformity surface separates the basin stratigraphy into sequences assigned to two distinct depositional settings: an early passive margin basin and a subsequent foreland basin.

This unconformity surface formed a major control on the accommodation space and subsequent deposition of the overlying Lower Cretaceous Mannville Group and equivalent strata in the Athabasca,

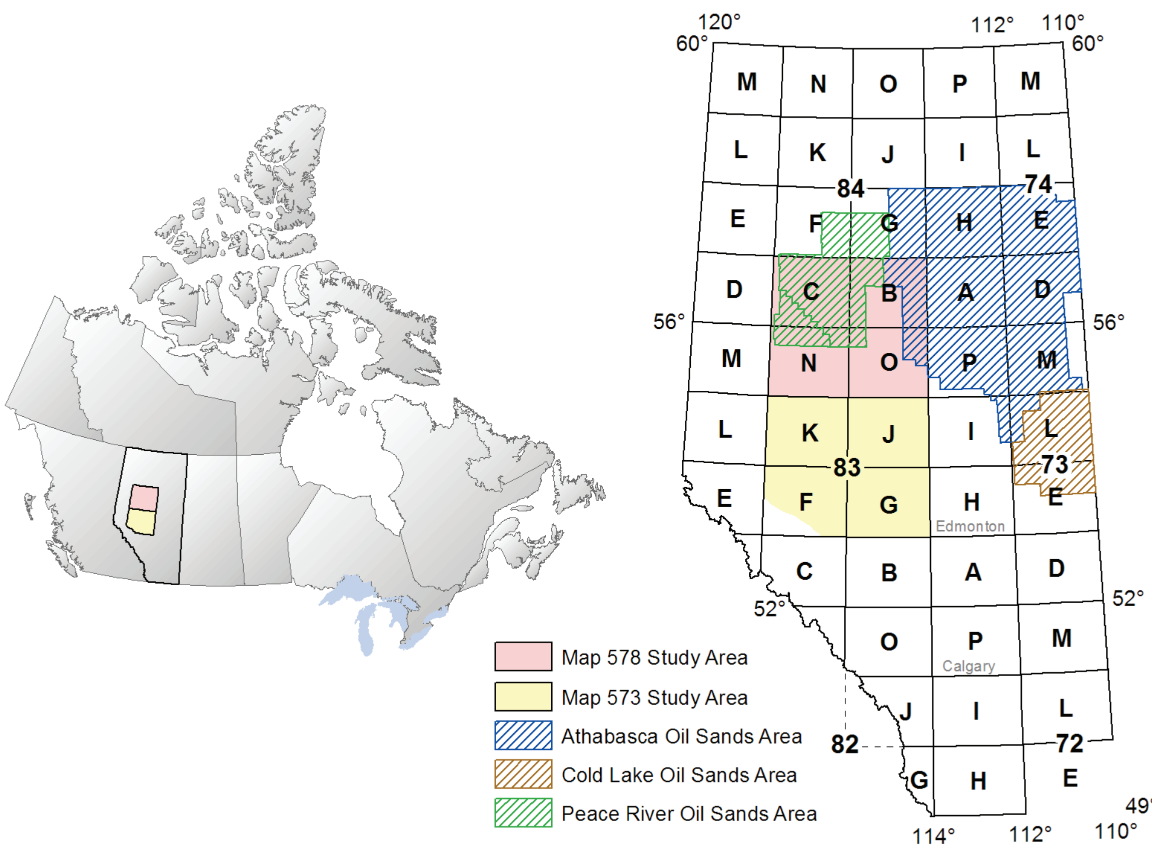


Figure 1. Location map highlighting the current (pink) and previous (yellow) study areas, with oil sands regions (hatched blue, orange, and green) of Alberta.

Peace River, and Cold Lake oil sands areas due to varying and complex topography generated on the angular unconformity. The sub-Cretaceous unconformity surface also provided a pathway for hydrocarbons to migrate from their source rock location below the unconformity, upwards through subcropping formations and across the sub-Cretaceous unconformity surface, into the overlying Cretaceous rocks.

Modelling of the sub-Cretaceous unconformity surface and zero-edge delineation of subcropping formations are an integral part of a larger project at the Alberta Geological Survey (AGS) to create a provincial-scale three-dimensional (3D) geological framework model of Alberta's subsurface. Previous modelling of the sub-Cretaceous unconformity surface was completed using datasets from multiple sources, resulting in a variable-quality surface due to inconsistent picking criteria between sources, colocated data, and clustered data distribution. In order to increase our confidence in this important surface model, a dataset based on spatial distribution and log quality of unconformity picks made prior to this study were evaluated and adjusted where necessary to ensure consistency. Additional picks were made based on newer logs to optimize the spatial distribution for modelling in areas of increased geological complexity. Unconformity picks were used to determine the extent of formation boundaries and complex erosional features along the unconformity surface.

2 Methodology

2.1 Picking Criteria

Geophysical wireline log correlation was the primary method for mapping the sub-Cretaceous unconformity surface. Cross-sections and well picks were made using IHS Petra software.

Geophysical wireline logs for 4175 wells in the study area were examined to identify the depth of the unconformity surface and to determine the stratigraphic unit underlying the unconformity. To account for edge effects in the modelling process, an additional 743 unconformity picks were made surrounding the outside of the study area border. An additional 7884 formation picks were made to identify the position of various stratigraphic units underlying the unconformity. Wells were picked at a minimum density of three wells per township and range block to ensure adequate spatial distribution in the modelling process. Where subcrop boundaries and complex structural or erosional features were present, additional wells were picked to aid in the delineation of these features.

Correctly identifying the sub-Cretaceous unconformity on logs and core is based on understanding the regional framework of the underlying stratigraphic units. The formations below the sub-Cretaceous unconformity vary greatly depending on the location within the province. Therefore, it was important to properly identify the underlying formations and accurately model their extents.

Logs used to identify the unconformity and underlying formations were not restricted to any particular suite, and as many logs as possible were used to make the picks. Both rasterized versions of the original paper logs (raster logs) and digital logs (LAS) were used, with digital logs being preferred. When available, the following logs were displayed in combination: gamma ray, spontaneous potential, caliper, bulk density, neutron porosity, photoelectric effect (PE), density correction, and resistivity. PE logs were extensively used in identification of the sub-Cretaceous unconformity when available. Formations found below the sub-Cretaceous unconformity are typically carbonate bearing and thus have PE readings between 3 (dolostone) and 5 (limestone). Formations above the unconformity are siliciclastic, and PE readings are typically below 3 (PE of a clean sandstone is ~1.8–2). When using digital logs, a PE flag was used to highlight any section of the well where the PE was above 2.8. This greatly aided in the visual identification of carbonate rocks on digital logs.

In wells where PE curves are not available, or where the underlying lithology is not a clean carbonate, changes to the sonic travel time, an increase in the bulk density (lower porosity), decreases in the neutron porosity, and increases in the resistivity logs could typify the unconformity surface. However, this changes greatly depending on the lithology of the units above and below the unconformity surface. In cases where Cretaceous siltstones are overlying Paleozoic shales, identifying the unconformity relied heavily on understanding the regional stratigraphic framework and being able to follow localized stratigraphic markers and their position in relation to the unconformity surface. The same difficulty occurs when there is a sand-on-sand contact, such as when Gething Formation sandstone overlies Belloy Formation sandstone. Again, using regional correlations and paying close attention to a wide variety of log signatures made it possible to make a pick or provide a reasonable estimation for the sub-Cretaceous unconformity surface.

Cross-sections were made across the study area, and digital logs were presented using a standard presentation format to ensure consistency between cross-sections. For wells that did not have LAS files, or there were only a minimum number of curves available, raster logs were used. Neutron-density and resistivity raster logs were displayed together when available. If neutron-density logs were not available, sonic travel time was used. If no open-hole logs were available and well control was sparse, cased-hole logs were used if present, such as gamma-ray and neutron logs.

Cross-sections were displayed both in structural and stratigraphic settings, using multiple stratigraphic datums. Hanging the section on a datum below the unconformity and correlating or visually following localized markers allows the user to see how the unconformity has eroded down into the underlying stratigraphic units. Using a datum above the unconformity highlights the relatively planar stratigraphy of the Cretaceous strata and the angular relationship of the underlying strata at the unconformity.

2.2 Representative Wells and General Stratigraphy

Within the study area, Lower Cretaceous sedimentary strata of the Bullhead Group and the equivalent Mannville Group unconformably overlie stratigraphic units ranging from the upper Fernie Formation to the Upper Devonian Winterburn Group, separated by the sub-Cretaceous unconformity (Figure 2) (Alberta Geological Survey, 2015). However, not all of the strata within this succession have been eroded by the sub-Cretaceous unconformity, namely the Carboniferous-aged Stoddart Group and the Triassic Montney Formation. The extents of these unaffected units are controlled by depositional boundaries and other unconformities and were therefore not correlated in detail within the study area.

2.2.1 Fernie Formation

Within the study area, the Jurassic-aged Fernie Formation is the uppermost stratigraphic unit eroded by the sub-Cretaceous unconformity. The Fernie Formation consists of the Gordondale Member overlain by undifferentiated Fernie shales and sandstones. The Gordondale Member is a highly radioactive, organic-rich, phosphatic, fine-grained unit (Figure 3) that has previously been identified as the lower Fernie Formation, lower Fernie shelf limestone and clastic unit, the Nordegg Member, or the "Nordegg Member" (Asgar-Deen et al., 2004). The overlying undifferentiated shales and sandstones likely comprise the Poker Chip Shale Member and, in the southern portion of the study area, upper Fernie shales. No differentiation of these two units was made in this study. The Gordondale Member was correlated and mapped due to its easily identifiable log signature and significance as a source rock (Asgar-Deen et al., 2004).

Cretaceous sedimentary strata overlying the Fernie Formation are commonly interbedded sandstones and shales identified by a serrated gamma-ray log signature (Figure 3), and the succession typically contains thin coal beds. Coal beds are identified by high neutron-density porosity and sonic travel time spikes, low

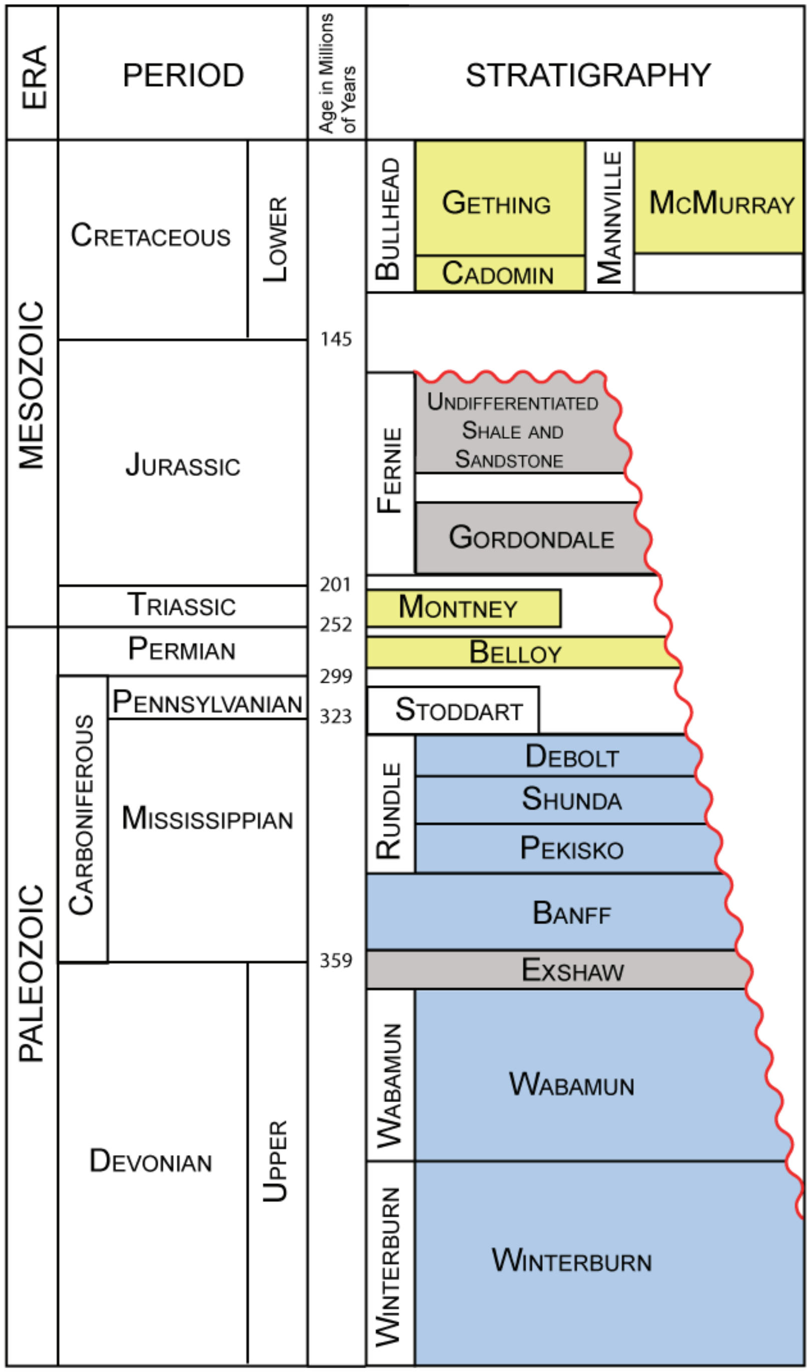


Figure 2. Generalized stratigraphy of the Peace River – Slave Lake area highlighting stratigraphic units found above and below the sub-Cretaceous unconformity, adapted from the *Alberta Table of Formations* (Alberta Geological Survey, 2015).

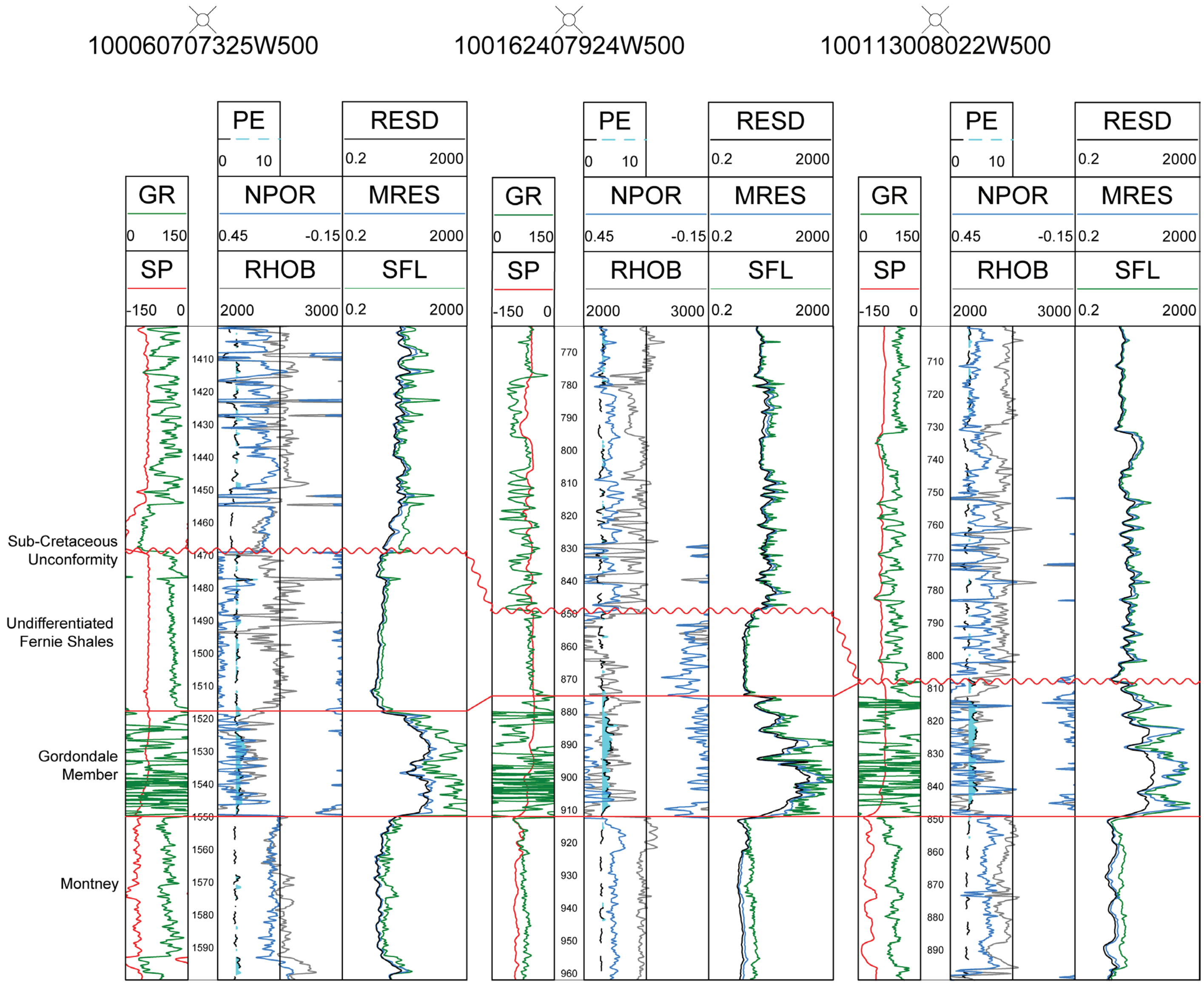


Figure 3. Stratigraphic cross-section (datum=top Montney Formation) with log examples of the Fernie Formation and the sub-Cretaceous unconformity. Log mnemonics are as follows: GR=gamma ray, SP=spontaneous potential, PE=photoelectric effect, NPOR=neutron porosity, RHOB=bulk density, RESD=deep resistivity, MRES=medium resistivity, SFL=shallow resistivity.

PE readings, typically low gamma-ray readings, and commonly by resistivity increases. It is common to find clean sandstones at the base of the Cretaceous succession, such as the Cadomin Formation in the west, or Gething Formation sandstones within the central to eastern limit of the Fernie Formation.

The undifferentiated shale unit of the Fernie Formation has gamma-ray readings that are typically smoother (less API variation), corresponding with lower resistivity readings that show little to no invasion profile compared to overlying Cretaceous strata. This typically corresponds with an increase in separation between the neutron and density curves, and lower readings in both porosity curves.

The Gordondale Member is typified by high radioactivity identified on the gamma-ray log, with readings wrapping past the 150 API scale. PE readings are over 3, which aids in differentiating the Gordondale Member from the overlying Fernie shales (Figure 3). Resistivity readings are significantly higher than both the overlying Fernie Formation shale unit and Cretaceous sediments.

Identifying the location of the sub-Cretaceous unconformity within the interval comprising Cretaceous shales and Fernie shales is aided with modern log suites and local correlations in the over- and underlying sediments. In the three-well cross-section in Figure 3, the sub-Cretaceous unconformity erodes through the Fernie shales and into the Gordondale Member. In well 100/06-07-073-25W5/00, Cretaceous strata consist of interbedded sandstones and shales, numerous coal beds, and a thick clean sandstone at the base of the unit sitting unconformably on the Fernie Formation shales. In well 100/11-30-080-22W5/00, the upper Fernie shales have been removed and interbedded sandstones, shales, and coal beds of the Cretaceous unconformably overlie the Gordondale Member, identified by a highly radioactive gamma-ray curve, PE readings over 3, and distinctly higher resistivity readings.

2.2.2 Belloy Formation

The Permian-aged Belloy Formation is typically identified by a clean, blocky gamma-ray profile, with variable porosity and resistivity. When available, PE readings are typically below 2, indicating a sandstone lithology. In Figure 4, the Belloy Formation has a clean gamma-ray signature with little variation in API readings, except for minor spikes. The overlying Cretaceous Gething Formation is characterized by a serrated gamma-ray character indicating interbedded sandstones and shales. In well 1AA/12-27-085-20W5/00, the Gething Formation thins over a paleotopographic high and a cleaning-upwards gamma-ray profile develops with high porosity and high resistivity readings. Regional and local correlations are important in distinguishing the Belloy sandstones at the subcrop surface from overlying Gething sandstones.

The underling Debolt Formation can be distinguished from the Belloy by PE readings between 3 and 5, indicating a carbonate lithology, increased resistivity readings, a decrease in sonic travel time, and an increase in gamma-ray readings.

2.2.3 Debolt Formation

The Mississippian-aged Debolt Formation is the uppermost unit of the Rundle Group (Figure 2) and comprises the lower Debolt member and the upper Debolt member. The Debolt Formation consists primarily of limestones and dolostones interbedded with calcareous shales. The individual stratigraphic members were correlated across much of the study area, but for the purposes of this study, the Debolt was treated as one stratigraphic unit. The base of the lower Debolt member can be identified by a clean, blocky gamma-ray signature, a PE reading of 3–5, and high resistivity readings. It is fairly uniform in thickness where uneroded by the sub-Cretaceous unconformity. Log readings for the remaining lower Debolt member are variable throughout, but regional and localized correlations can be made across the

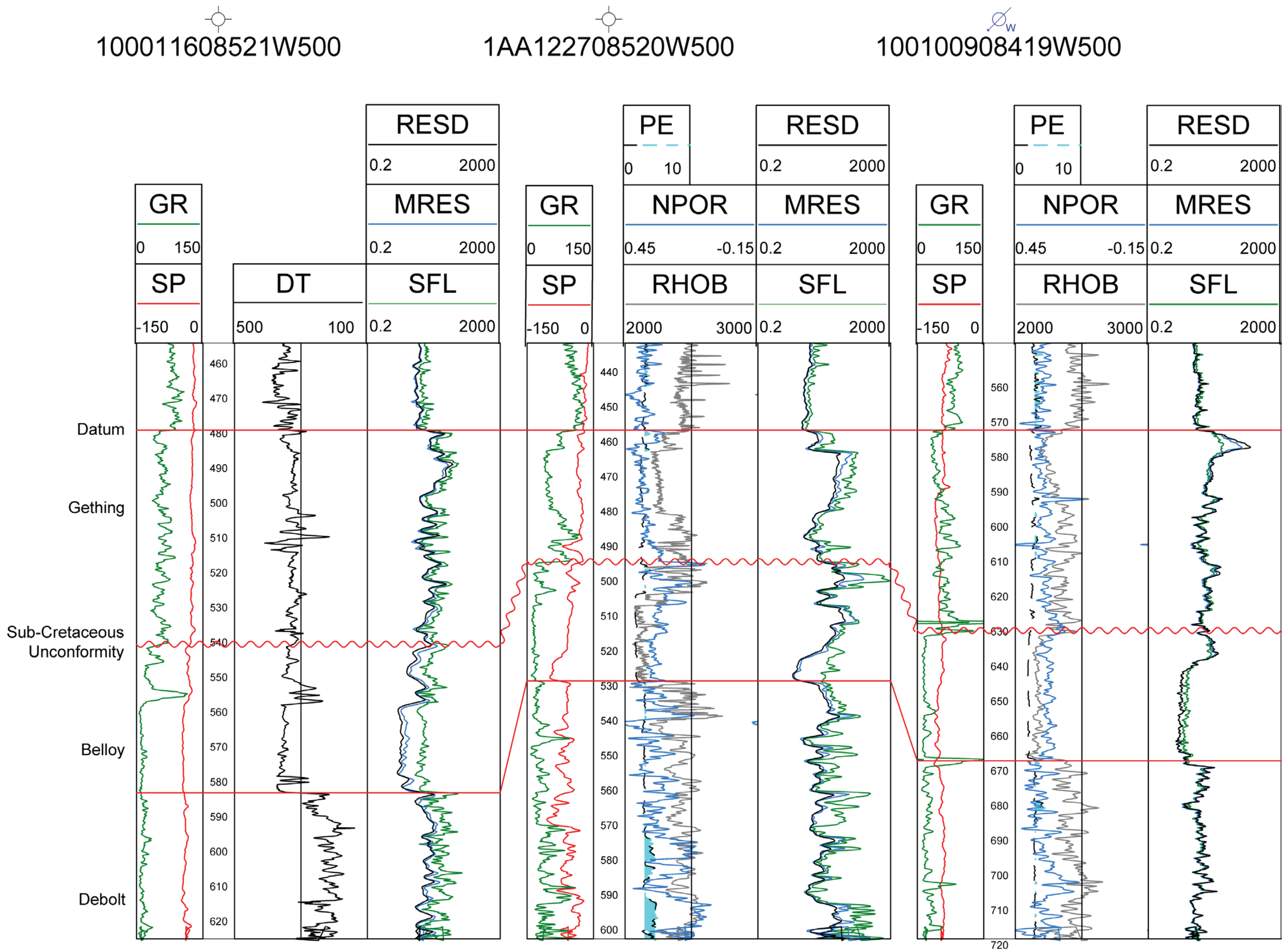


Figure 4. Stratigraphic cross-section (datum=top Gething Formation) with log examples of the Belloy Formation. Log mnemonics are as follows: GR=gamma ray, SP=spontaneous potential, DT=sonic travel time, PE=photoelectric effect, NPOR=neutron porosity, RHOB=bulk density, RESD=deep resistivity, MRES=medium resistivity, SFL=shallow resistivity.

study area. The top of the lower Debolt is easily identifiable on logs by a clean gamma-ray signature overlain by a shaly gamma-ray signature indicative of the upper Debolt member. Strata above the sub-Cretaceous unconformity surface range from Gething sandstones to lower Mannville shales. In each case, the unconformity is identified by a contrasting gamma-ray signature, an increase in PE readings, and typical increases in resistivity readings. In the stratigraphic cross-section in Figure 5, erosion at the sub-Cretaceous unconformity exposes the upper Debolt, as seen in well 1AA/06-08-088-21W5/00, and the lower Debolt in wells 100/16-22-088-21W5/00 and 100/11-19-088-19W5/00. The overlying Gething Formation also thins as it onlaps a paleotopographic high.

2.2.4 Shunda Formation

The Mississippian-aged Shunda Formation of the Rundle Group (Figure 2) consists of interbedded limestones and calcareous shales, with correlatable markers across the study area. Where the Shunda Formation does not subcrop at the unconformity, the top is easily identifiable by the presence of the overlying clean carbonate unit found at the base of the lower Debolt member (Figure 5). Where the Shunda begins to be eroded, correlation of internal markers aids in picking the sub-Cretaceous unconformity. The Shunda Formation is also carbonate rich, with PE readings over 3, and is easily distinguishable from the overlying siliciclastic lower Mannville strata. In Figure 6, lower Mannville consists of a thick sequence of shale with high gamma-ray readings, PE less than 3, and low resistivity readings. The contact with the underlying Shunda Formation is identified by a sharp decrease on the gamma-ray log, PE readings above 3, and in wells 100/16-09-086-16W5/00 and 100/10-29-086-15W5/00, a sharp increase in the resistivity curves. In well 100/13-35-087-15W5/00, the higher resistivity strata found in the uppermost Shunda has been eroded, resulting in an absence of a high resistivity contrast. However, the contact is still easily identified by a distinct change in the gamma-ray and PE curves.

2.2.5 Pekisko Formation

The Mississippian-aged Pekisko Formation is the lowermost formation of the Rundle Group and conformably overlies the Mississippian Banff Formation (Figure 2). It is identified on logs by a clean, blocky gamma-ray signature, PE readings between 3 and 5, and high resistivity readings. It is easily distinguishable on logs from the shalier overlying Shunda and underlying Banff formations, which both show higher gamma-ray readings. The sub-Cretaceous unconformity is identified in the Pekisko Formation by a sharp drop in the gamma-ray curve, an increase in the PE curve, and an increase in resistivity readings (Figure 7).

2.2.6 Banff/Exshaw

The Mississippian Banff Formation is a thick unit and ranges in lithology from calcareous shales to clean carbonates. Where modern log suites are available, particularly the PE curve, identifying the unconformity surface can be straightforward, since the overlying siliciclastic Cretaceous strata have PE readings below 3, and carbonate sediments of the Banff Formation typically have PE readings between 3 and 5. Where older wells are present and sufficient depth control is not available, correlation of regional and local markers becomes important in distinguishing the eroded Banff Formation from the overlying Cretaceous strata.

The importance of using all of the logs available when determining the sub-Cretaceous unconformity pick is highlighted in the stratigraphic cross-section in Figure 8, particularly in wells 100/10-34-086-10W5/00 (10-34) and 1AA/05-10-088-09W5/00 (AA/05-10). A relatively clean carbonate is found in well 10-34 from 480 mKB (metres below kelly bushing) to 492 mKB, identified by gamma-ray readings lower than the over- and underlying shales, a PE reading of 5, and higher resistivity readings. If stratigraphic picks

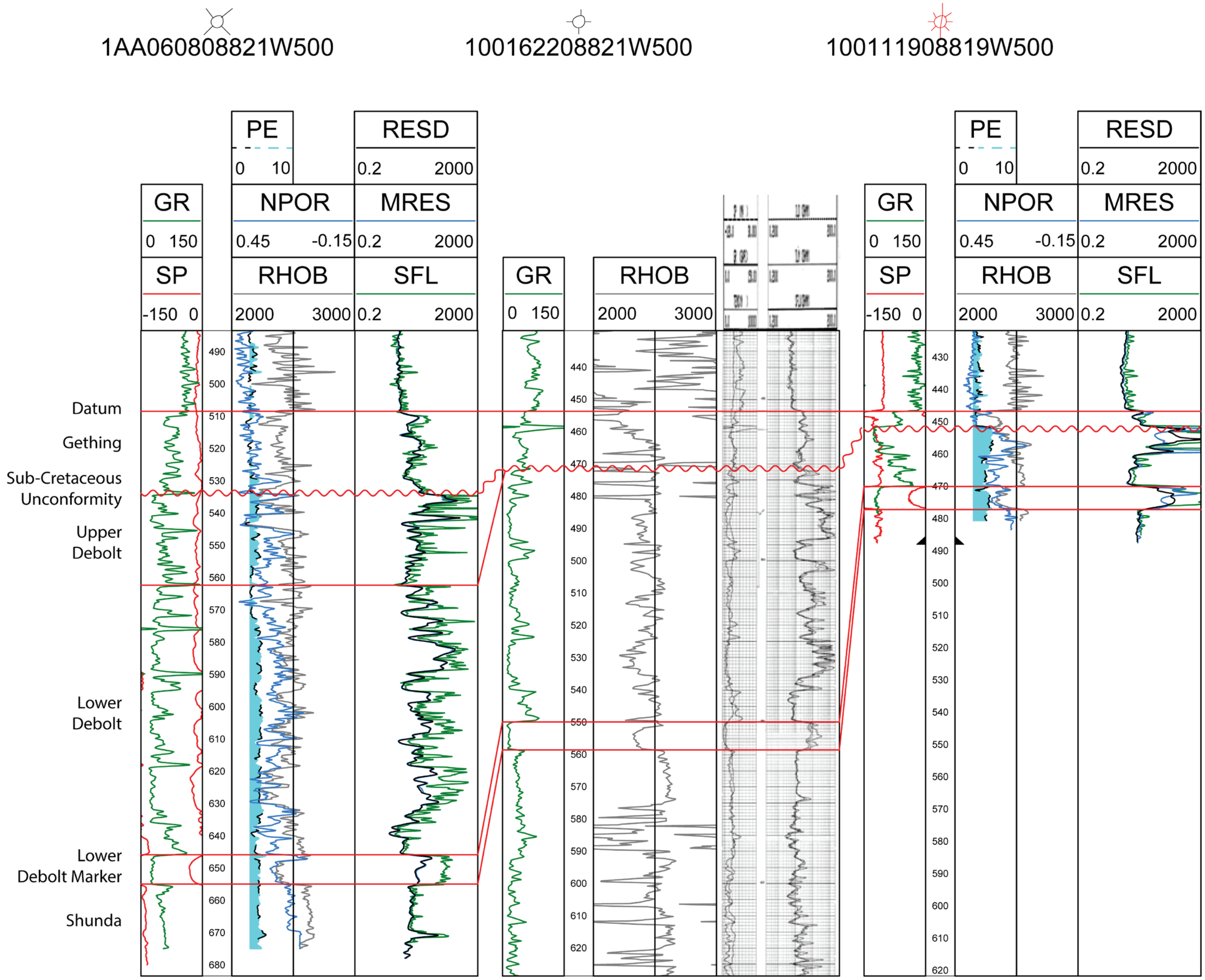


Figure 5. Stratigraphic cross-section (datum=top Gething Formation) with log examples of the Debolt Formation. Log mnemonics are as follows: GR=gamma ray, SP=spontaneous potential, PE=photoelectric effect, NPOR=neutron porosity, RHOB=bulk density, RESD=deep resistivity, MRES=medium resistivity, SFL=shallow resistivity.

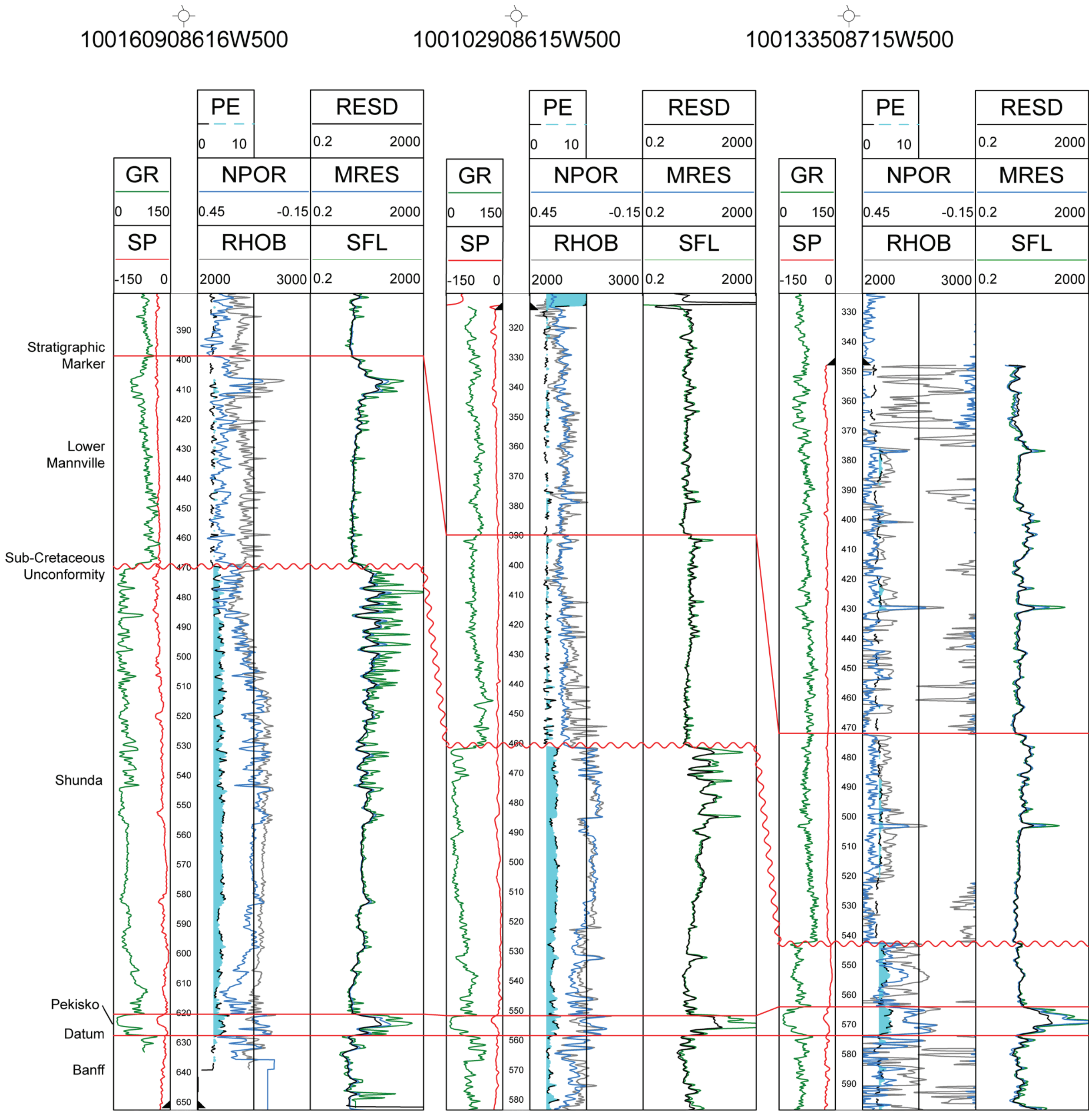


Figure 6. Stratigraphic cross-section (datum=top Banff Formation) with log examples of the Shunda Formation. Log mnemonics are as follows: GR=gamma ray, SP=spontaneous potential, PE=photoelectric effect, NPOR=neutron porosity, RHOB=bulk density, RESD=deep resistivity, MRES=medium resistivity, SFL=shallow resistivity.

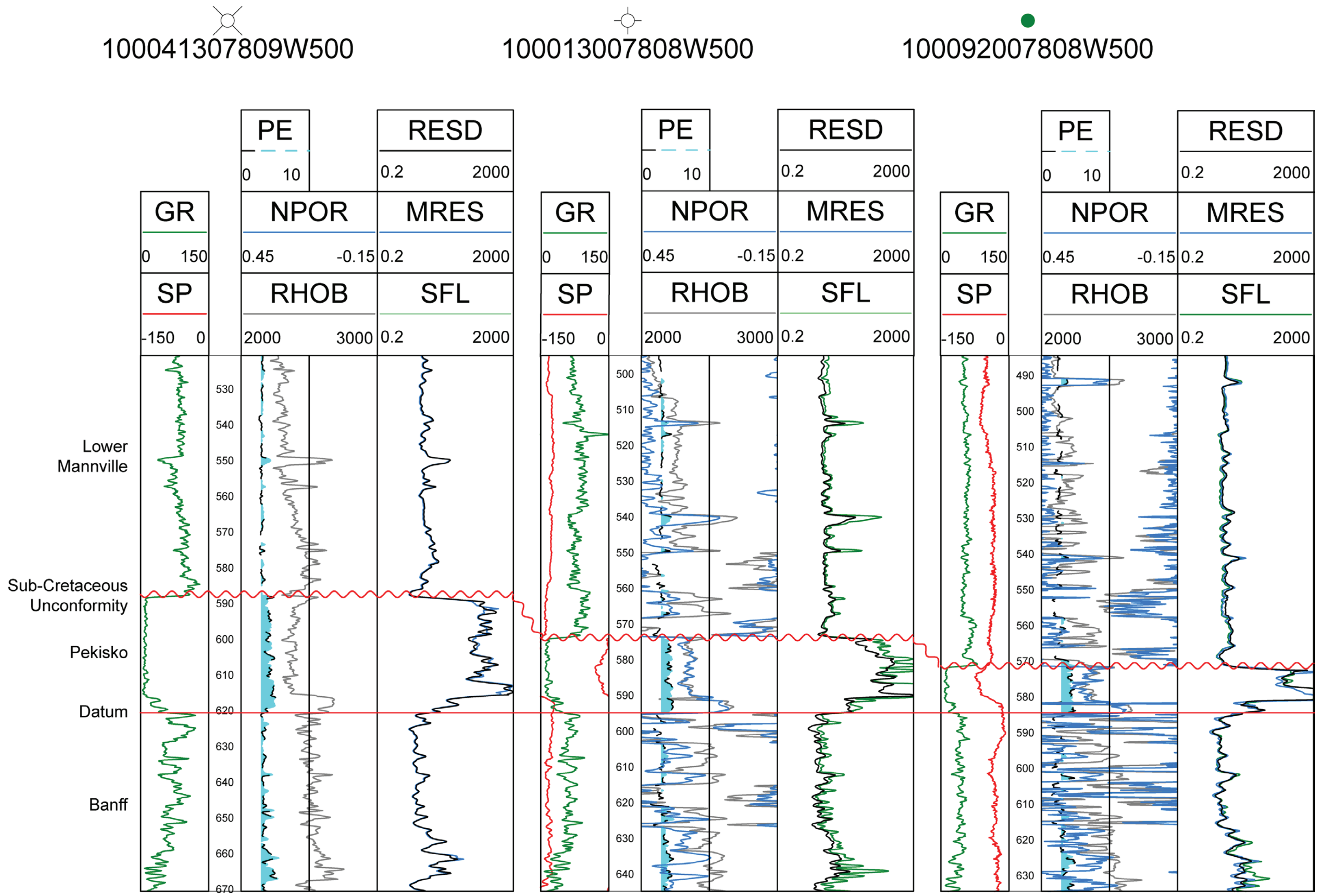


Figure 7. Stratigraphic cross-section (datum=top Banff Formation) with log examples of the Pekisko Formation. Log mnemonics are as follows: GR=gamma ray, SP=spontaneous potential, PE=photoelectric effect, NPOR=neutron porosity, RHOB=bulk density, RESD=deep resistivity, MRES=medium resistivity, SFL=shallow resistivity.

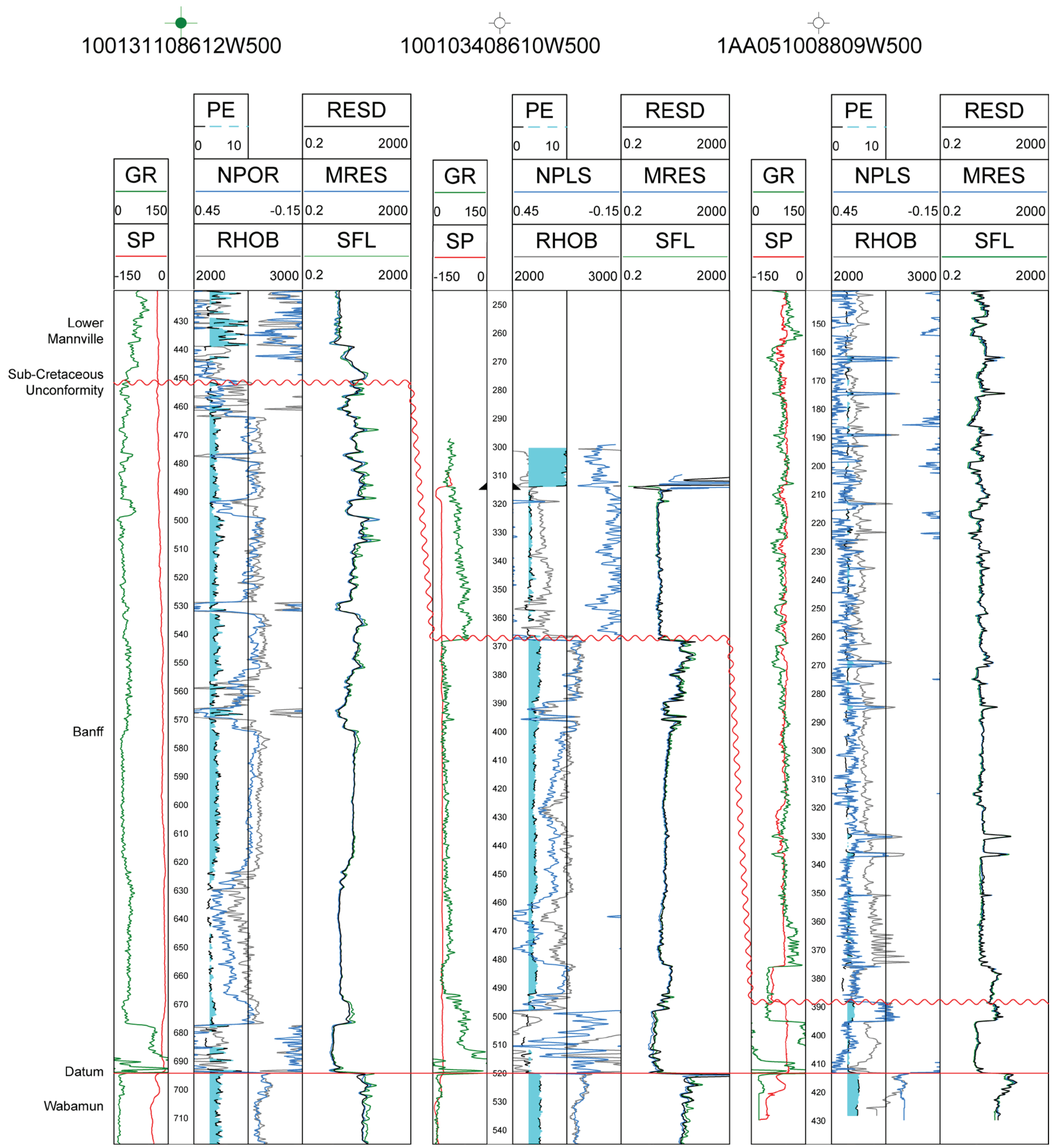


Figure 8. Stratigraphic cross-section (datum=top Wabamun Formation) with log examples of the Banff Formation. Log mnemonics are as follows: GR=gamma ray, SP=spontaneous potential, PE=photoelectric, NPOR=neutron porosity, NPLS=neutron porosity limestone, RHOB=bulk density, RESD=deep resistivity, MRES=medium resistivity, SFL=shallow resistivity.

were made using only the gamma-ray curve, the potential exists to incorrectly identify the same carbonate in well AA/05-10 from 375 mKB to 395 mKB. Or, if well AA/05-10 was reviewed without a regional context and limited log availability, there is also potential to identify the same interval in well AA/05-10 as a Gething sandstone, eroding into shales of the lower Banff Formation and placing the unconformity at 395 mKB. If fact, when using all of the logs available, it becomes apparent that a Gething sandstone with a PE reading of 2 overlies a clean carbonate present at 388 mKB, identified by a PE reading between 3 and 5 (Figure 8). See Figure 9 for a more detailed image of well AA/05-10.

The log response and the presence of the unconformity seen in Figure 9 is confirmed in core (Figure 10), with mud laminated limestone overlain by mud rich Cretaceous sandstone.

2.2.7 Wabamun Group

Within the study area, the Wabamun Group is a thick succession of limestone and dolostone and, for the purposes of this study, was treated as an undifferentiated unit. It subcrops beneath Cretaceous strata in the eastern portion of the study area. It is distinguishable from overlying Cretaceous strata by a PE reading between 3 and 5, a clean gamma-ray profile, and high resistivity readings. In the Wabamun subcrop area, there are three cases that add to the difficulty in picking the sub-Cretaceous unconformity.

First, many wells are drilled for shallower Cretaceous targets, with wells drilled to the top of the Wabamun Group or only drilling a few metres into it. This limits the amount of log data available, making it difficult to determine if the formation at the well bottom is indeed below the unconformity surface. Even if there is sufficient log coverage to determine that the well extends below the unconformity surface, there still may be difficulty in identifying the formation due to an absence of any stratigraphic markers. This is particularly troublesome at the Wabamun/Winterburn subcrop boundary, where the two units have similar lithologies and an absence of stratigraphic markers when encountered in wells that do not penetrate a significant depth into the formation.

Second, if there is casing present near the unconformity surface and there is sufficient depth below for open-hole logs, care must be taken not to confuse changes in log responses due to formation boundaries with responses due to the presence of a casing shoe. In either situation, changes to the log responses could appear as a sharp contact.

Third, numerous wells are drilled with casing set below the Wabamun Group, restricting the availability of a full open-hole log suite. In most of these instances, it is common to have gamma-ray and neutron curves logged through casing available, making the unconformity pick possible. As seen in Figure 11, casing was set at 545 mKB at the base of the Cretaceous succession in well 100/11-17-089-04W5/00. The well was then drilled to 1584 mKB, where intermediate casing was set and the remainder of the hole was drilled to a measured depth of 1602.5 mKB. In this case, only gamma-ray and neutron curves logged through casing are available for the interval of interest. However, the sub-Cretaceous unconformity pick was made with the available curves and confirmed by correlations based on local cross-sections.

In order to have sufficient data distribution for the modelling of the unconformity surface in the Wabamun subcrop area, an estimated sub-Cretaceous unconformity top was used in thirteen instances (Table 1). In twelve of these cases, the wells were assumed to have been drilled to the top of the Wabamun Group based on correlations from other wells where a definitive unconformity pick could be made. In these instances, the sub-Cretaceous unconformity pick was placed either at the base of the wellbore or just below. In nine of the thirteen cases, the reported formation at bottomhole depth on the well ticket was the Wabamun Group. Two wells were listed as terminating in the McMurray Formation, but local correlations were used to justify making a subcropping Wabamun pick at the base of the well. The remaining well

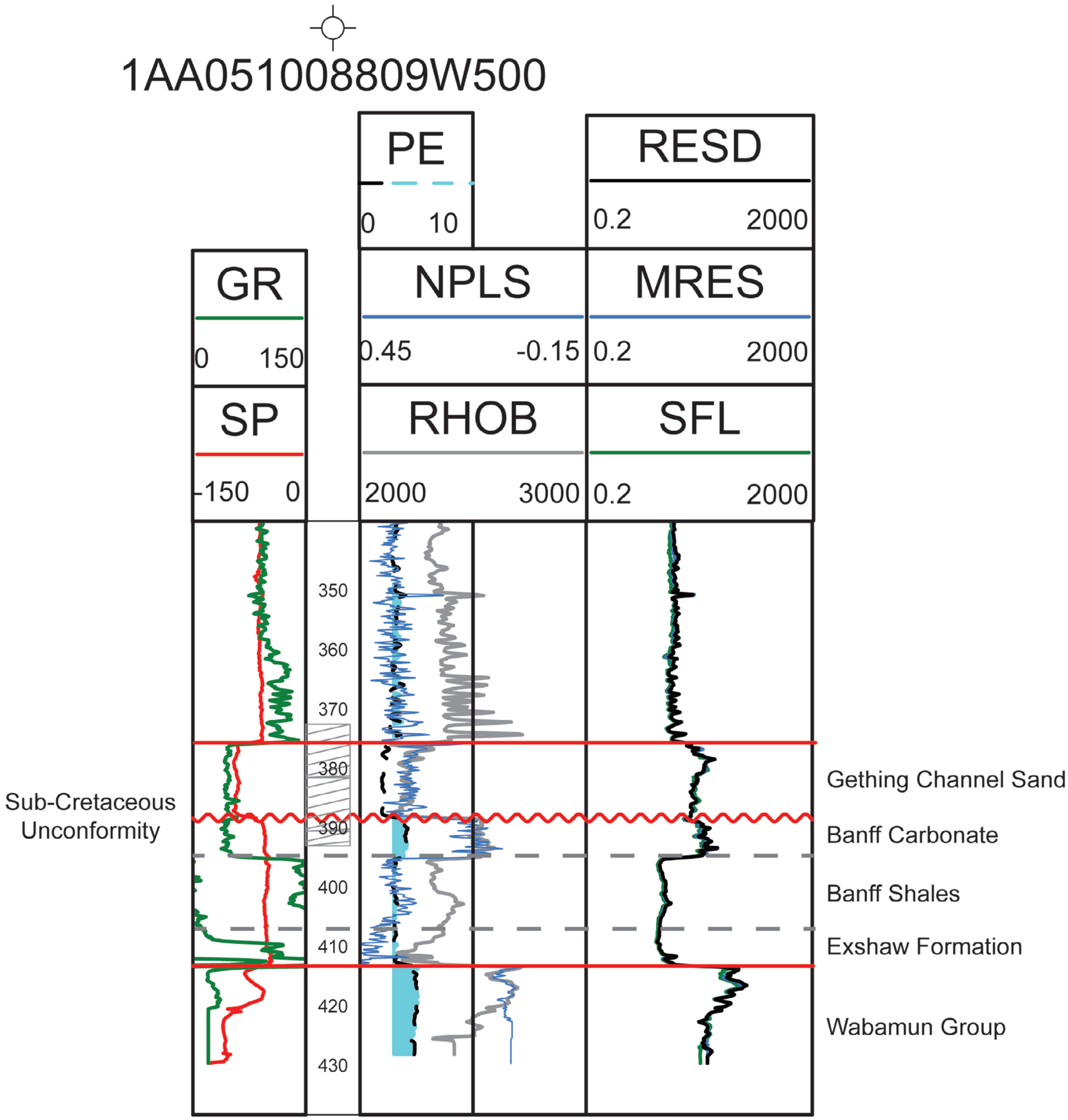


Figure 9. Digital logs of well 1AA/05-10-088-09W5/00, highlighting complexity in picking the sub-Cretaceous unconformity surface. The unconformity is placed at 388 mKB based on distinct changes in PE, RHOB, NPLS, and SP readings. Log mnemonics are as follows: GR=gamma ray, SP=spontaneous potential, PE=photoelectric effect, NPLS=neutron porosity limestone, RHOB=bulk density, RESD=deep resistivity, MRES=medium resistivity, SFL=shallow resistivity.

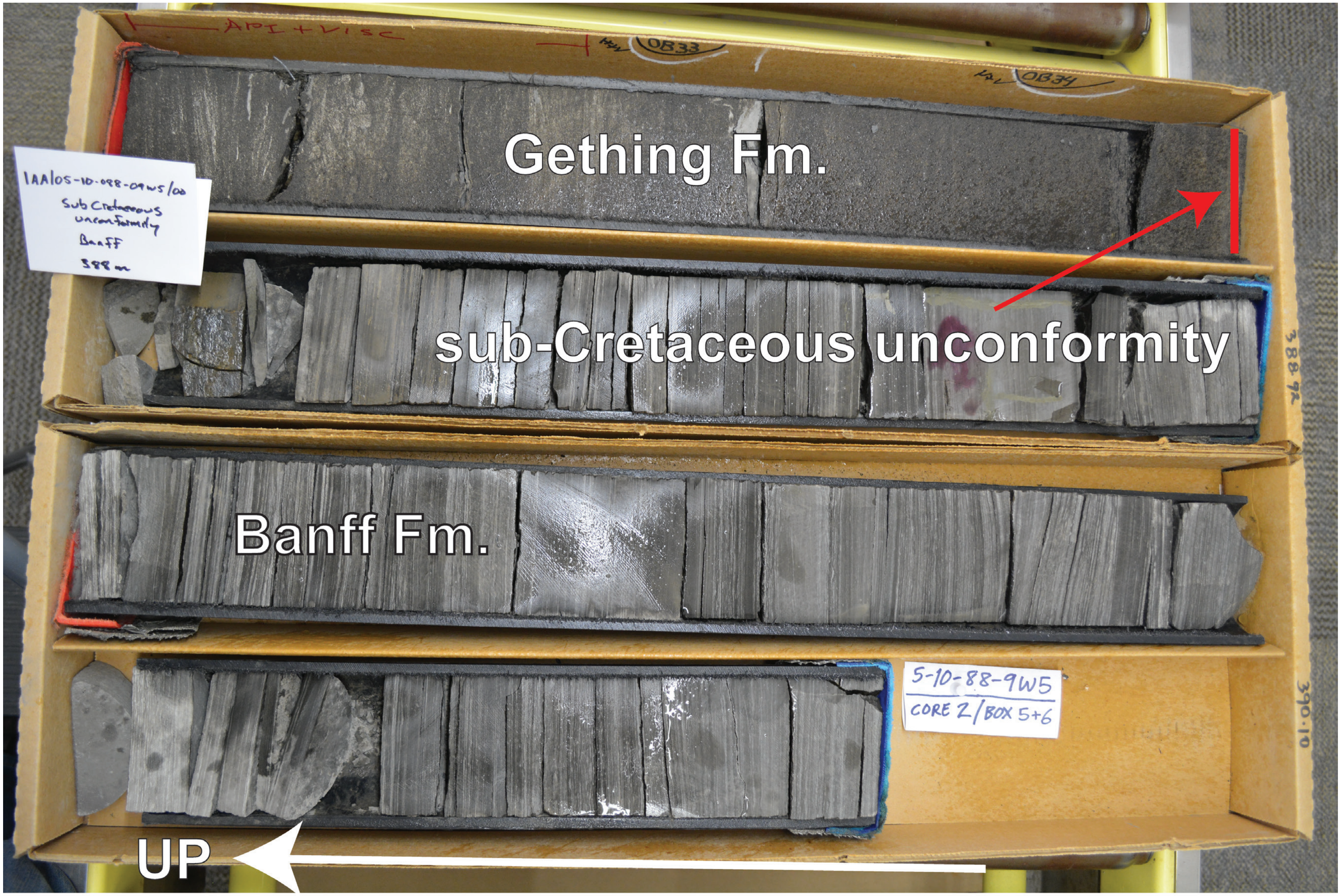


Figure 10. Core photo of well 1AA/05-10-088-09W5/00, with the sub-Cretaceous unconformity surface separating carbonate-rich Banff Formation from overlying Cretaceous Gething Formation argillaceous sandstone.

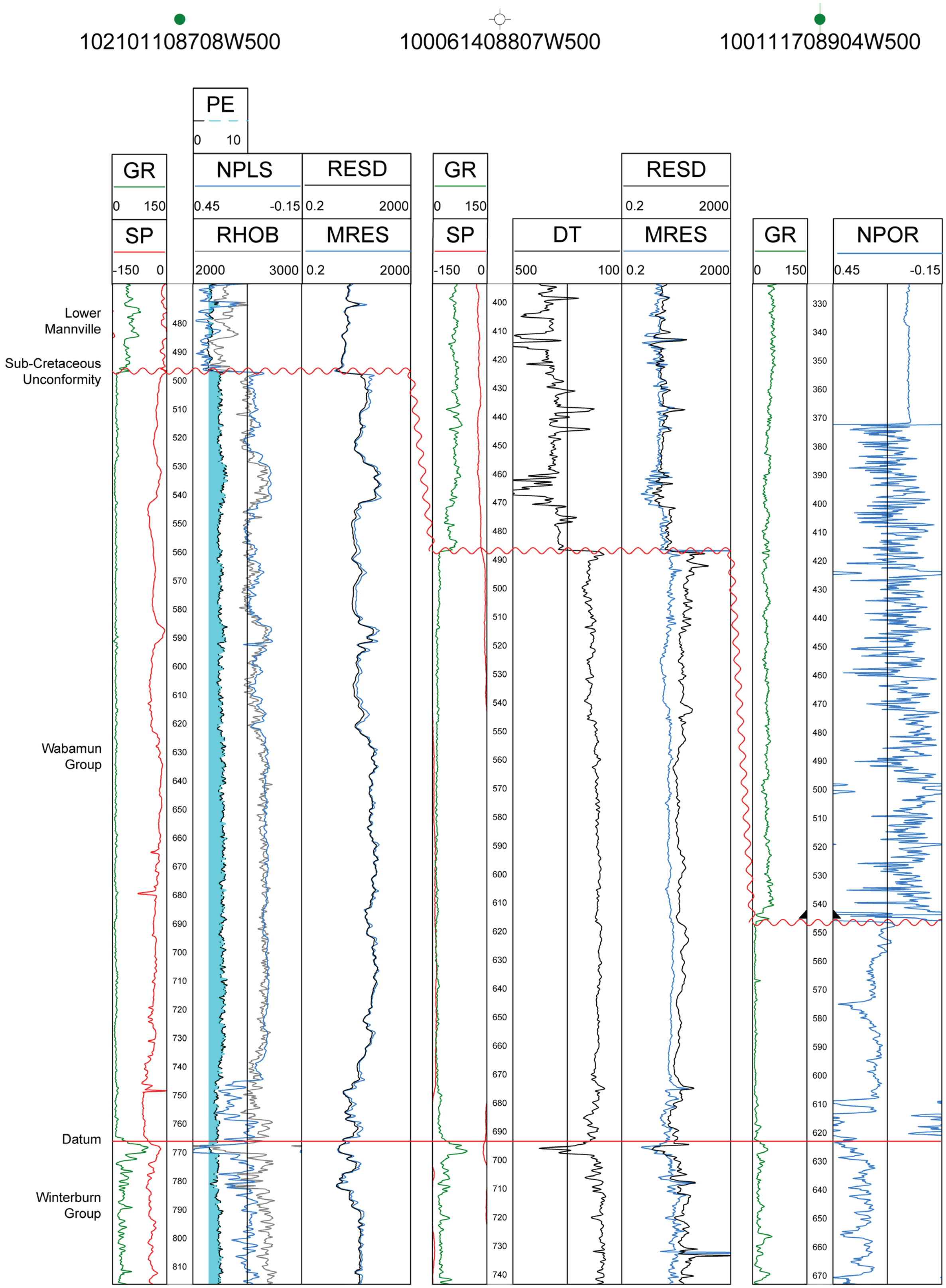


Figure 11. Stratigraphic cross-section (datum=top Winterburn Group) with log examples of the Wabamun Group. Log mnemonics are as follows: GR=gamma ray, SP=spontaneous potential, PE=photoelectric effect, NPOR=neutron porosity, NPLS=neutron porosity limestone, RHOB=bulk density, RESD=deep resistivity, MRES=medium resistivity.

was drilled to the Precambrian, but the absence of any log curves across the interval of interest due to the placement of intermediate casing made it impossible to accurately identify the position of the unconformity surface, so an estimated pick was made based on casing depth, log curves found above and below the casing, and correlations with offsetting wells.

Table 1. Wells with estimated sub-Cretaceous unconformity top and reported formation at total depth (TD) from the well ticket.

Wells with estimated unconformity top	Reported FM@TD
100/02-28-086-04W5/00	PreCambrian
100/08-24-085-01W5/00	Wabamun
100/07-21-085-01W5/00	Wabamun
100/11-32-086-01W5/00	Wabamun
100/09-31-085-04W5/00	Wabamun
100/07-03-087-02W5/00	Wabamun
100/09-27-083-03W5/00	Wabamun
100/12-12-085-02W5/00	Wabamun
100/14-18-085-01W5/00	Wabamun
100/03-29-085-03W5/00	Wabamun
100/01-35-084-03W5/00	Wabamun
100/09-29-074-26W4/00	McMurray
100/06-28-074-26W4/00	McMurray

2.2.8 Winterburn Group

The Winterburn Group is a thick carbonate succession underlying the Wabamun Group and is the lowermost stratigraphic unit affected by the sub-Cretaceous unconformity in this study area. It is only partially eroded and subcrops in the northeastern corner. The Winterburn is identified by a cleaner gamma-ray profile and lower sonic travel time than the overlying Cretaceous strata, has a PE between 3 and 5, and typically has high resistivity readings (Figure 12). Similar to the Wabamun Group, within the Winterburn subcrop area many wells are cased at the unconformity surface or below the base of the Winterburn Group, limiting the well density and the availability of good-quality open-hole logs.

2.3 Modelling

2.3.1 Elevation

The sub-Cretaceous unconformity surface was modelled using 4918 picks. These picks provided the location (x and y coordinates) of the well, and the elevation (z) at which the unconformity was identified within the well. These data were evaluated both visually and geostatistically to identify potential outliers. The first step in this process was to assess the data in 3D space to determine the presence of any data points that appeared as visual outliers. The data were then geostatistically modelled (Figure 13), and the cross-validation results were reviewed to look for outliers (Figure 14). During the first cross-validation run, 95 data points were identified as being more than 25 metres from the predicted surface. These data were further scrutinized by assessing the elevation difference between the kelly bushing (KB) and the ground level to identify any potential errors in the reported KB elevation. One well had a difference of 23.8 metres, but upon examining the well data it became apparent that an incorrect ground elevation was reported, and the KB elevation was determined to be valid based on offsetting wells and structural

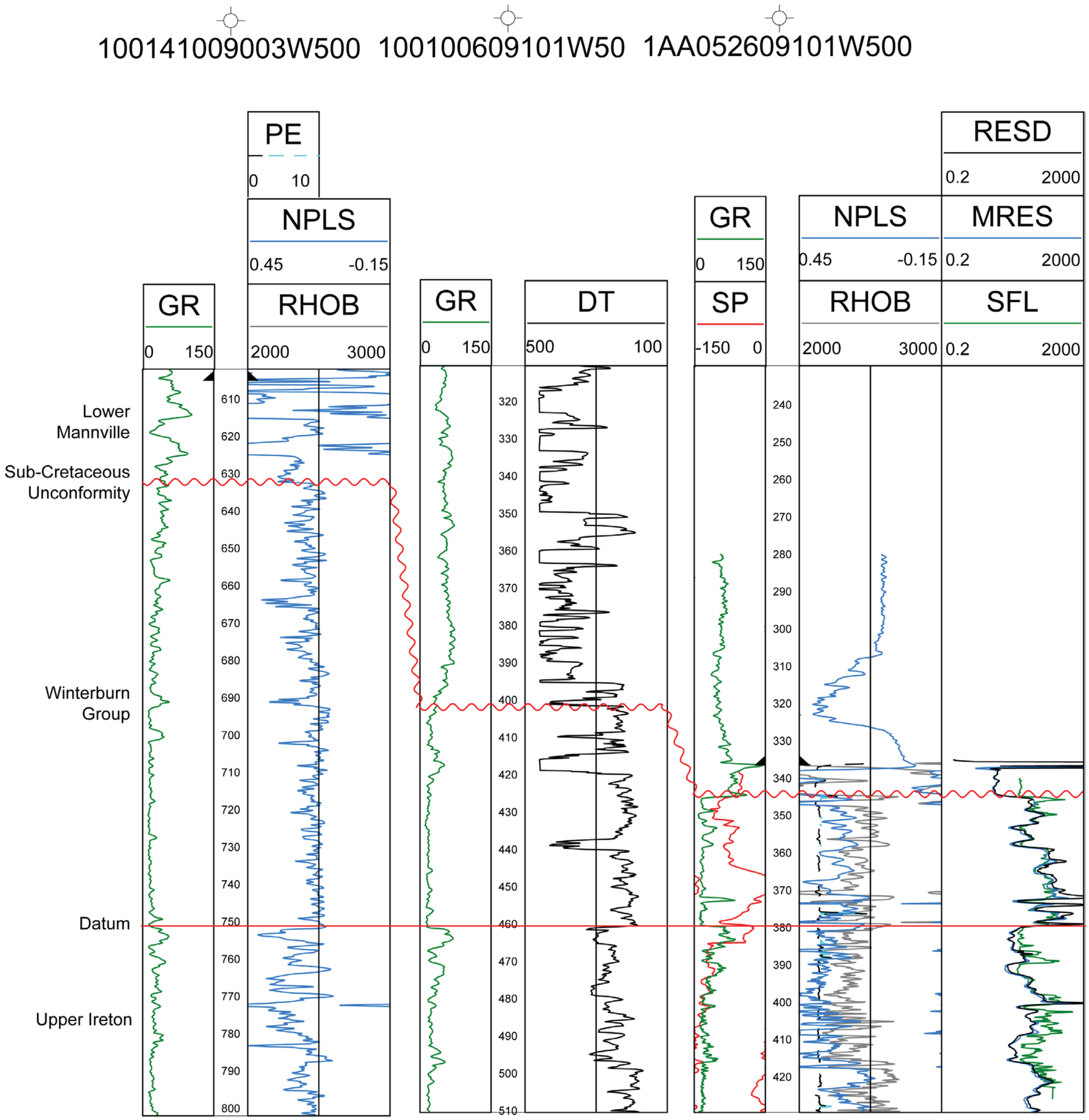


Figure 12. Stratigraphic cross-section (datum=top Ireton Formation) with log examples of the Winterburn Group. Note the location of casing in relation to the unconformity pick in 100111708904W500. Log mnemonics are as follows: GR=gamma ray, SP=spontaneous potential, PE=photoelectric effect, NPLS=neutron porosity limestone, RHOB=bulk density, DT=sonic travel time, RESD=deep resistivity, MRES=medium resistivity, SFL=shallow resistivity.

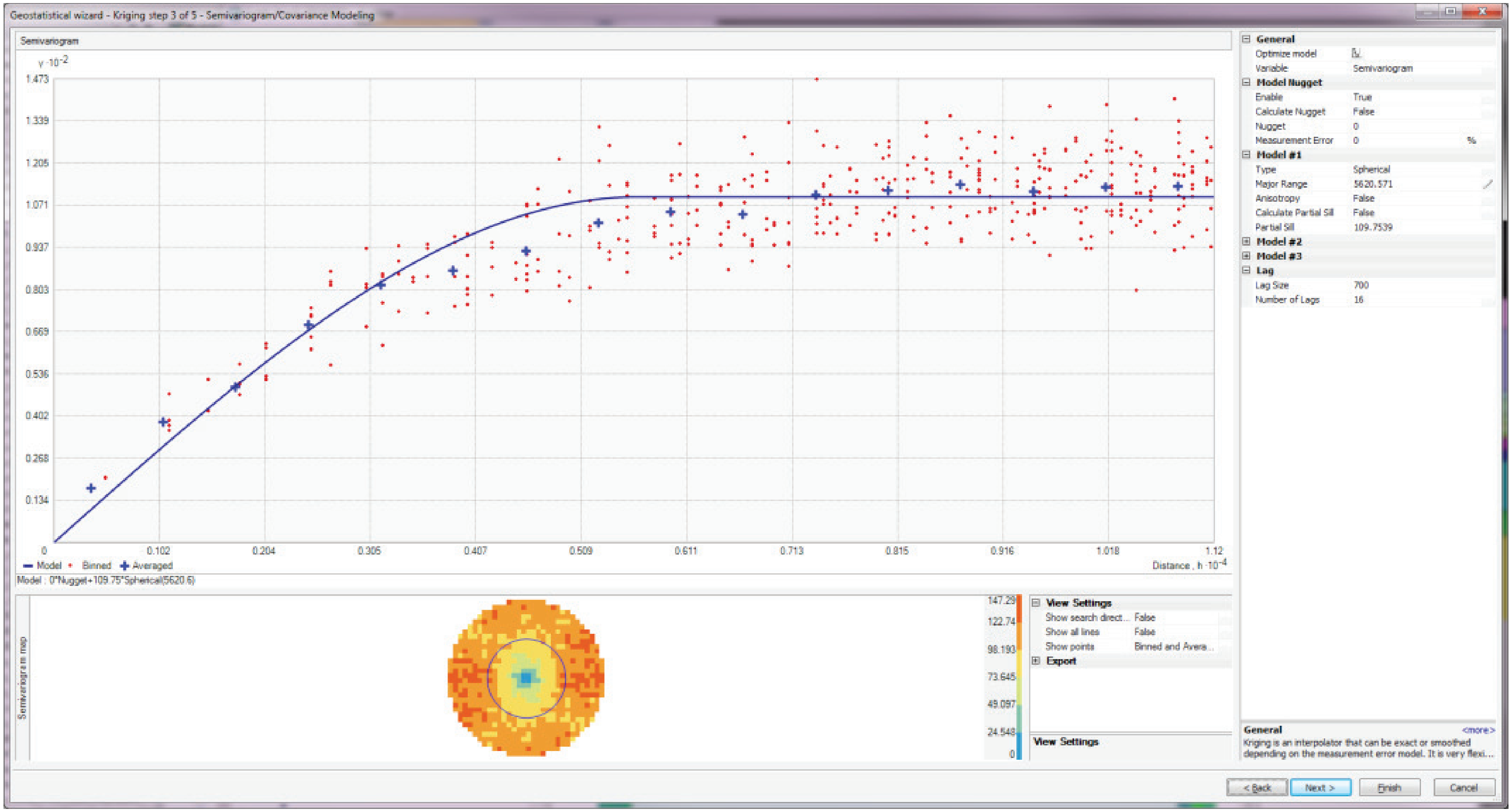


Figure 13. Variogram model showing the spatial correlation of the data. The data was modelled with a spherical variogram using a sill value of 109.8, a range of 5620.6, a nugget value of 0, and a lag size of 700.

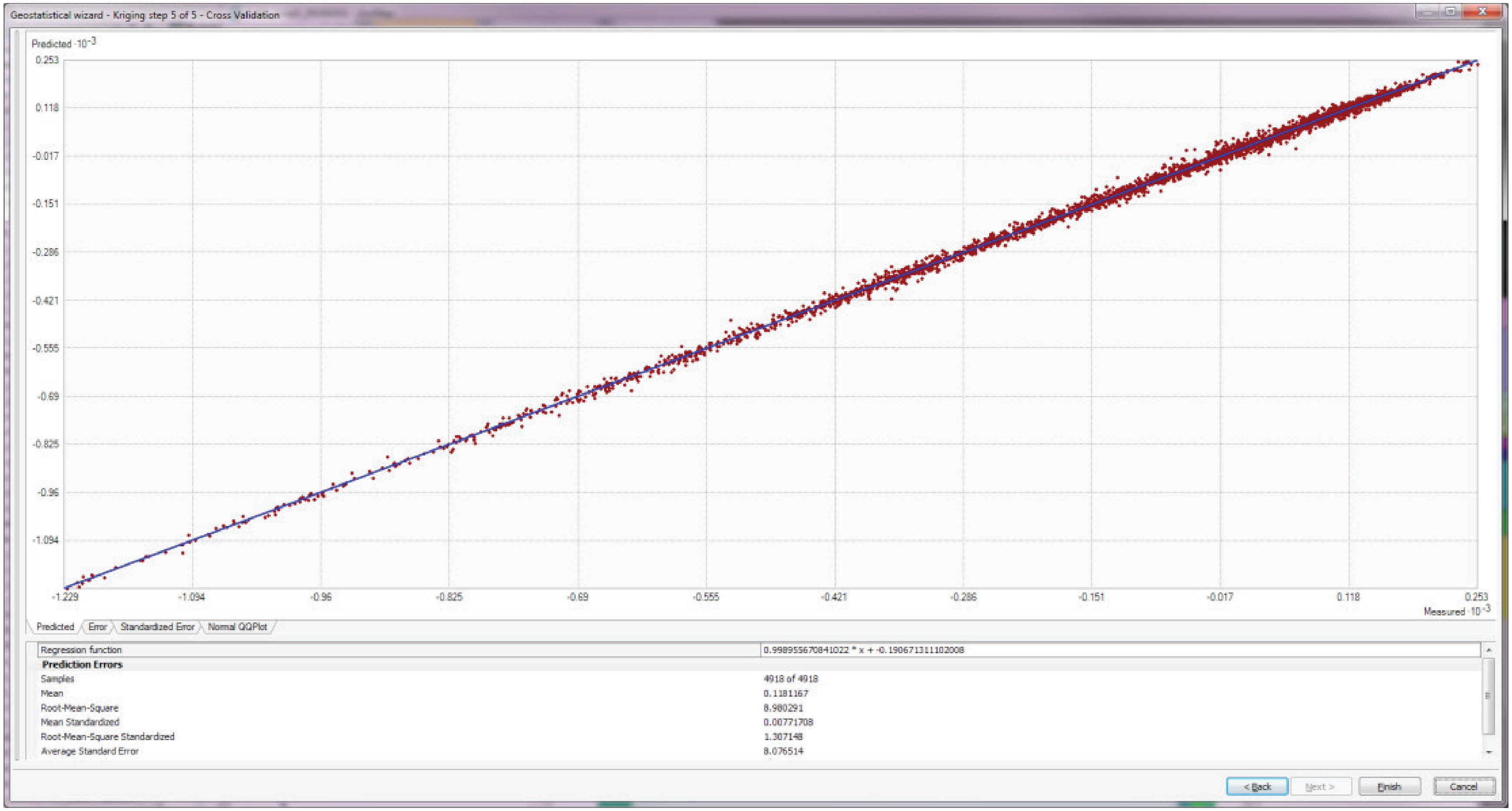


Figure 14. Cross-validation plot showing how well the predicted model values match the observed values.

cross-sections across the study area. The sub-Cretaceous unconformity tops for the 95 data points were then re-evaluated by reviewing logs, and changes were made to the pick values if necessary. Once all of the outliers were checked and corrected, the sub-Cretaceous surface was modelled in ArcGIS using the ordinary kriging algorithm. The first step in modelling the sub-Cretaceous surface was to determine the nature of the regional trend and extract it from the data. Due to the proximity of the study area to the deformation zone of the Canadian Cordillera, a strong southwest-oriented trend was identified and removed from the dataset before geostatistically modelling the surface. The residual values were modelled using the ordinary kriging algorithm on a 500 m grid cell size. The variogram parameters used to model this surface are a partial sill of 109.8, a nugget value of 0, a range value of 5620.6, and a lag size of 700 (Figure 13).

The final model results showed that the model surface was able to conform very well to the data points and produced a root-mean-square error (RMSE) of 8.98, and a standardized RMSE of 1.3 (Figure 14). Ideally the RMSE value should be as close to zero as possible, and the standardized RMSE should be close to 1. Achieving an RMSE of 8.98 for such a large and topographically variable surface is favourable, and the standardized RMSE value of 1.3 indicates that the predicted surface is providing a good representation of the data and may be slightly underestimating the nature variability.

2.3.2 Paleotopography

The paleotopography of the sub-Cretaceous unconformity was derived by subtracting the regional trend model of the study area from the modelled elevation (Figure 15). The residuals from this grid operation provide a representation of what the topography of the sub-Cretaceous unconformity would have looked like before the current structural setting and the onset of Lower Cretaceous Mannville and Bullhead Group sedimentation.

2.3.3 Subcrop Boundaries

The stratigraphic units underlying the sub-Cretaceous unconformity were geostatistically modelled using the available pick data and integrated into a 3D geocellular model using Petrel 2013. This involved geostatistically modelling a2.5D surface (a 2D surface represented in 3D space) for each of the underlying

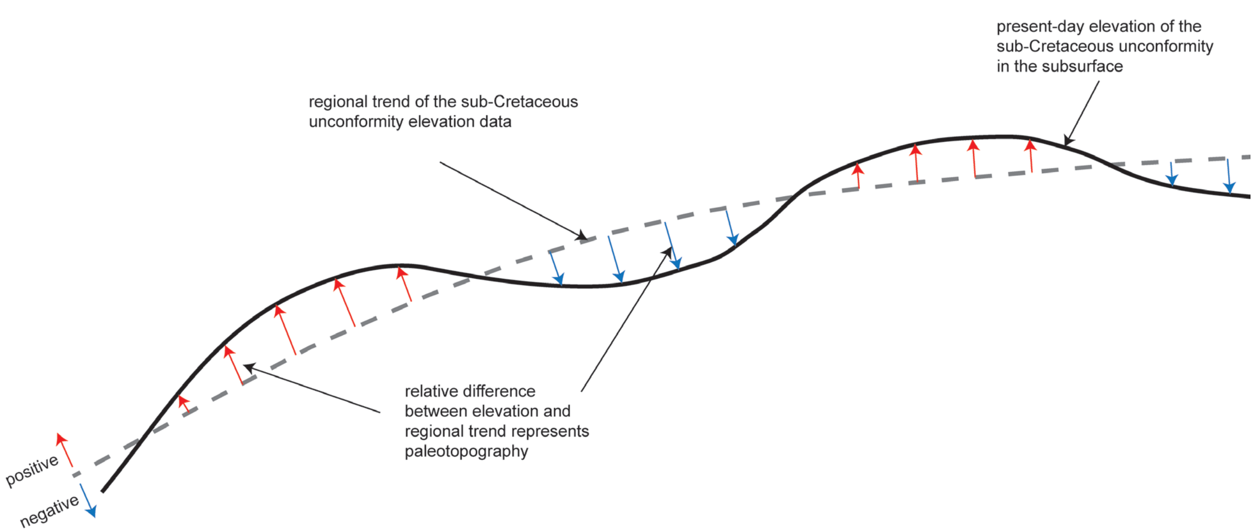


Figure 15. Schematic illustration of paleotopography calculated from current subsurface elevation and regional trend of the sub-Cretaceous unconformity surface.

stratigraphic units, and projecting the surfaces through the modelled surface of the sub-Cretaceous unconformity. This ensured that when the 2.5D surfaces were combined to form the 3D model, there were no gaps along the complex topography of the sub-Cretaceous unconformity where the underlying stratigraphic surfaces were truncated by the unconformity. The 3D model was used to assess the form and geometry of the subcrop boundaries for each stratigraphic unit along the unconformity. To ensure that the modelled subcrop lines were consistent with the eroded formation picks, the model results were cross-validated with well control data, and adjustments were made to the subcrop lines where required.

3 Results

3.1 Elevation

The sub-Cretaceous unconformity surface dips to the southwest, with elevations ranging from 200 metres above sea level (m asl) in the northeast to −1000 m asl in the southwest corner of the study area (Figure 16). The dip of the unconformity surface across the study area is not uniform. In the northeast portion of the study area, the dip is gradual, at a rate of 1 m/km. The dip of the unconformity surface begins to increase roughly at the centre point of the study area and steadily increases to the southwest towards the deformation front, with an average dip rate of 6.4 m/km measured from the centre of the study area to the southwest corner. Localized variations can be seen in the elevation surface identified by colour variations and highlighted by the presence of hill shading. Due to the large contour interval of 100 metres, these small-scale perturbations are not easily seen in the contours.

3.2 Paleotopography

The paleotopography of the sub-Cretaceous unconformity surface is a reconstruction of what the surface looked like before the deposition of the Lower Cretaceous Mannville Group and equivalent Bullhead Group and is represented by the relative distance of the unconformity surface to the regional trend (Figure 15). Within the study area, the paleotopography ranges approximately between 70 metres above and below the regional trend for this area (Figure 17; see Peterson and MacCormack, 2015, for a larger image). Major paleotopographic features identified in the study area, such as the Red Earth Highlands, Fox Creek Escarpment, and Edmonton Valley, spatially coincide with features previously identified by Smith (1994). The overall trend of the paleotopography is a series of northwest-trending ridges and valleys, with tributary valleys oriented roughly perpendicular to the main valleys, which progressively erode the major highlands on their course towards the main valley systems.

Similar to the previously published Map 573 (Peterson and MacCormack, 2014a), which depicts the area directly south of this study area (Figure 1), the paleotopography shows a continuation of the northwest-trending Fox Creek Escarpment, separating the topographic lows of the Spirit River Valley to the southwest and a distinct ridge that appears to follow the same trend as the western edge of the Pembina Highlands to the south. Roughly perpendicular to this high are paleovalleys that would have drained into the broad, northwest-trending Edmonton Valley. East of the Edmonton Valley are the Red Earth Highlands. In the southeast corner of the study area, the highland may be considered to be a continuation of the Wainwright Highlands. Another major valley system is found east of the Red Earth Highlands and is narrower and more consistently eroded than the Edmonton Valley to the west.

3.3 Subcropping Unit Boundaries

The stratigraphic units underlying the sub-Cretaceous unconformity have a westerly dip that is greater than that of the unconformity surface and therefore intersect the unconformity surface at an oblique

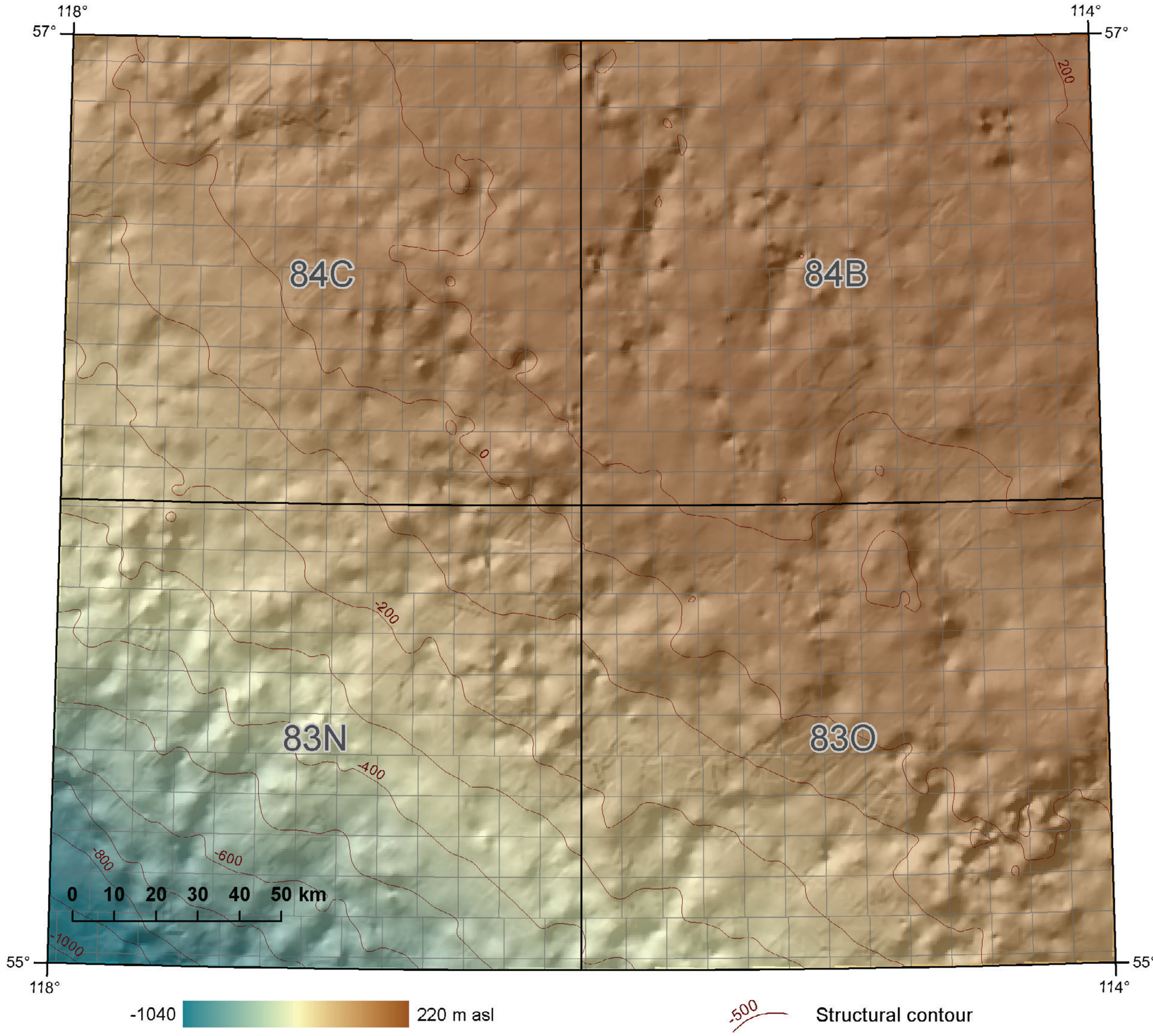
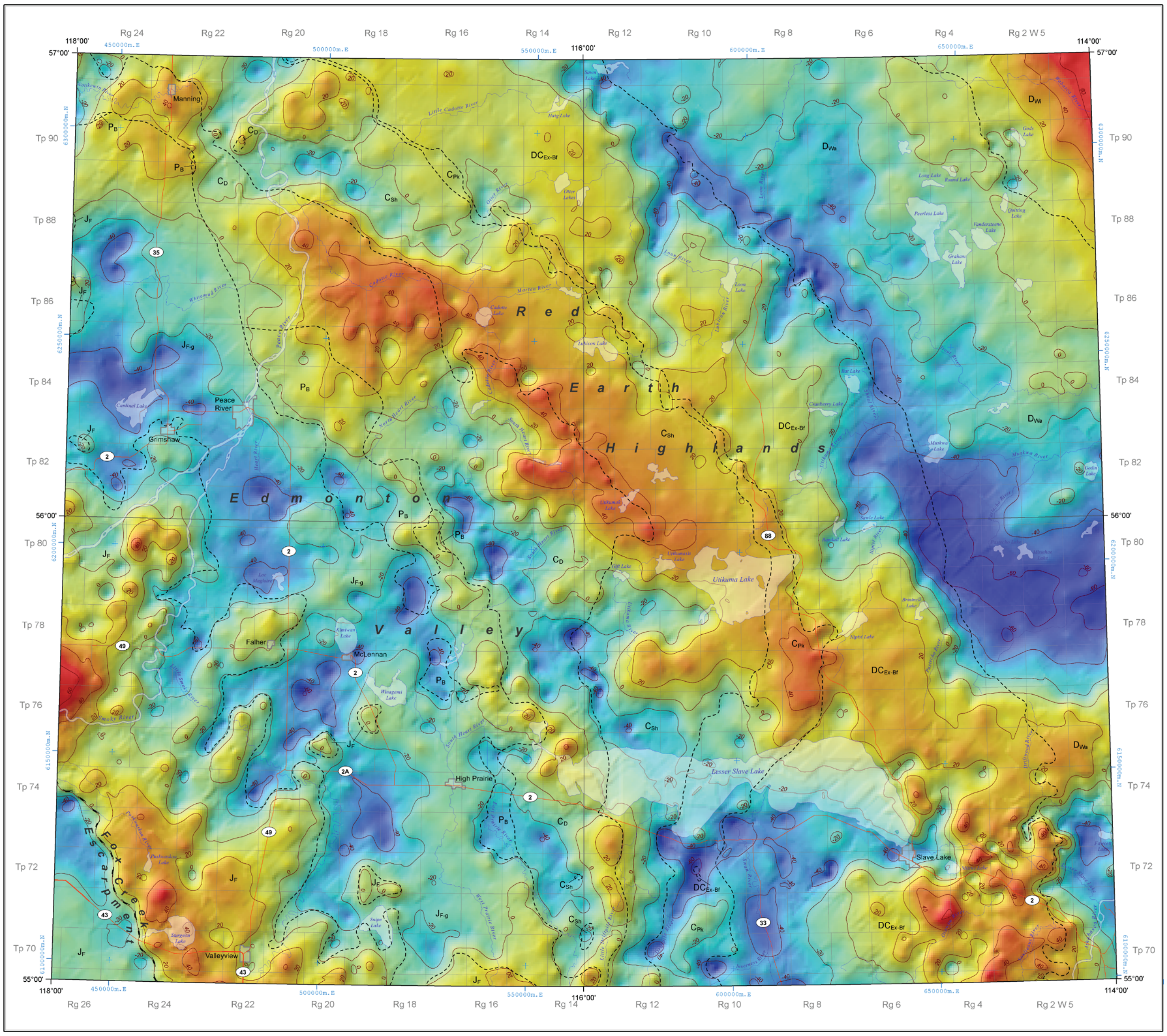


Figure 16. Elevation of the sub-Cretaceous unconformity, displayed with a 100 metre contour interval and shaded relief (azimuth 315°, attitude 45°).



SYMBOL LEGEND

- - - -	Approximate boundary of subcropping stratigraphic unit
J_F	Fernie Formation (undifferentiated)
$J_{F\text{-}g}$	Gordondale Member (Fernie Formation)
P_B	Belloy Formation
C_D	Debolt Formation
C_{Sh}	Shunda Formation
C_{Pk}	Pekisko Formation
$DC_{Ex\text{-}Bf}$	Banff and Exshaw formations
D_{Wa}	Wabamun Group
D_{Wi}	Winterburn Group

Approximate edge of Fox Creek Escarpment

Sub-Cretaceous paleotopography (height in metres relative to regional trend)

-72 72 m

40 Contour line

BASEMAP LEGEND

City or town

Major highway

Primary road

Water body (lake or major river)

River

600000m.E UTM, Zone 11 grid

Figure 17. Paleotopography of the sub-Cretaceous unconformity. Areas of high relative relief are shown in red, while relative lows are shown as blue. Major features include the Fox Creek Escarpment, the Edmonton Valley, and the Red Earth Highlands. See Peterson and MacCormack, 2015, for a larger image.

angle. This creates a subcrop area at the unconformity surface that is defined by the top and base of that stratigraphic unit (Figure 18). Given the westerly dip of the underlying units, the western edge of a given subcropping unit defines where that unit begins to be eroded by the sub-Cretaceous unconformity surface, and the easterly edge defines the zero edge of that unit. This zero edge also represents the stratigraphic top of the next underlying stratigraphic unit.

The stratigraphic units subcropping at the sub-Cretaceous unconformity surface become progressively older to the northeast and form southeast- to northwest-trending subcrop belts (Figure 19 and Figure 20). Within this study area, the undifferentiated Fernie Formation is the youngest stratigraphic unit eroded by the sub-Cretaceous unconformity and subcrops in the southwest corner of the study area. The Fernie Formation zero edge is irregular, with erosional valleys underlain by the Gordondale Member. Three erosional outliers were identified outside the main subcrop line corresponding to paleotopographic highs seen in Figure 19.

The subcrop of the Gordondale Member of the Fernie Formation is bordered on the eastern subcrop margin by the Debolt and Belloy formations (Figure 21). The contact with the Belloy Formation appears to have a consistent western limit, but there are areas where the Gordondale Member overlies the Belloy, creating isolated subcropping areas. The locations where the Belloy Formation subcrops in southern regions of the study area coincide with topographic lows on the unconformity surface within the Gordondale Member subcrop area.

East of the Gordondale Member and Belloy Formation subcrop areas, the remaining subcrop boundaries have a slightly westerly concave appearance (Figure 19). The Debolt Formation subcrop area is widest in the centre of the study area and narrows both the north and to the south. These characteristics are similar in the Shunda Formation subcrop area to the east. The Pekisko subcrop area is a narrow band in the northern part of the study area and widens to the south. There is one area where deep erosion has exposed the underlying Banff Formation. The Banff Formation subcrop area has a consistent width in the northern half of the study area and widens to the south. The Exshaw Formation subcrop area was too thin to model independently for the purpose of this study and was therefore combined with the overlying Banff Formation. Based on the eroded Exshaw Formation picks, it is estimated that, if mapped, the Exshaw subcrop area would consist of narrow, discontinuous belts at the eastern margin of the mapped subcrop area. The contact between the combined Banff and Exshaw subcrop area and the Wabamun subcrop area is relatively smooth in the northern half of the study area and becomes more undulatory to the south, possibly a consequence of increased data density (Figure 19). Except for the area between townships 74 and 76, the subcrop boundary with the Wabamun Group coincides with a major topographic low (Figure 17). The Wabamun subcrop area is a wide belt that is cut by the eastern study area boundary.

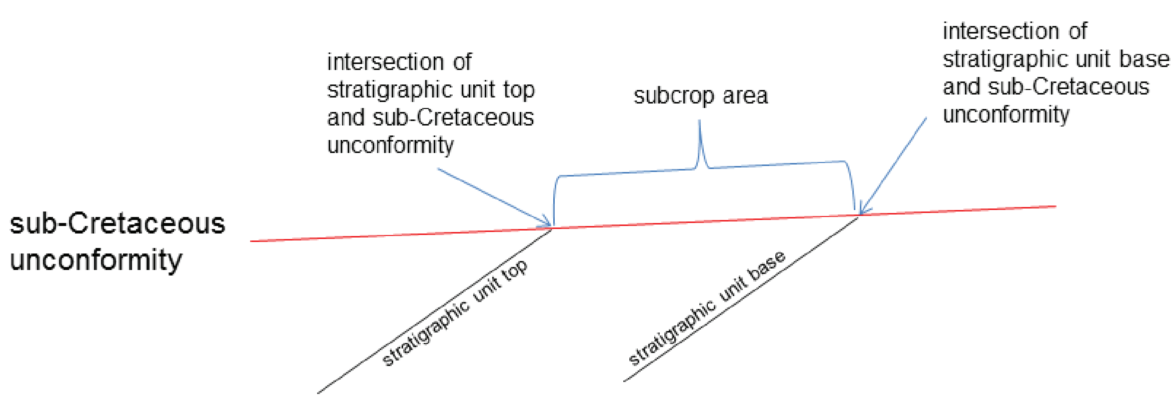


Figure 18. Schematic diagram illustrating subcrop areas on the sub-Cretaceous unconformity surface resulting from the intersection of underlying stratigraphic units.

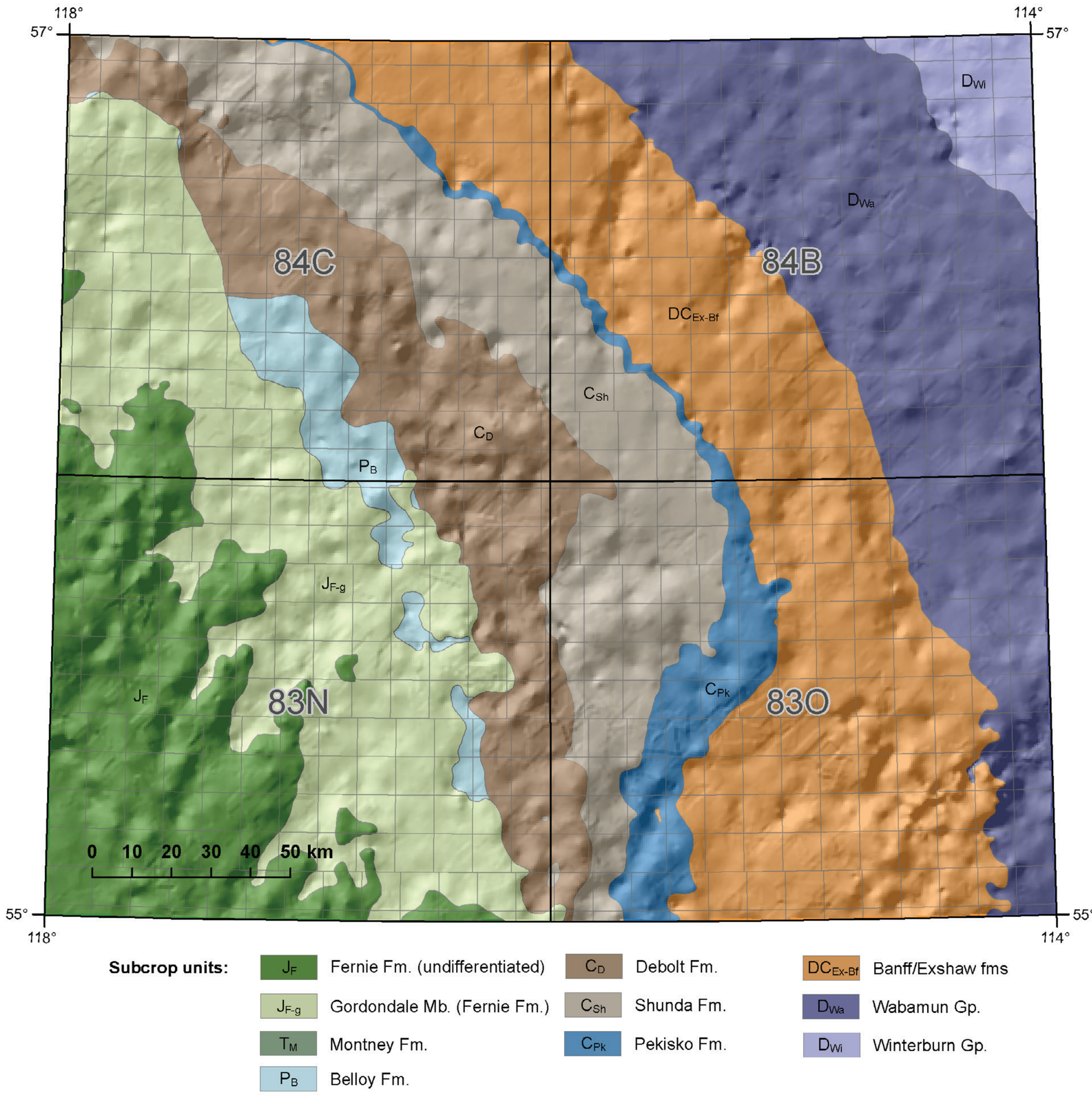


Figure 19. Plan view of study area showing the distribution of stratigraphic units subcropping at the sub-Cretaceous unconformity.

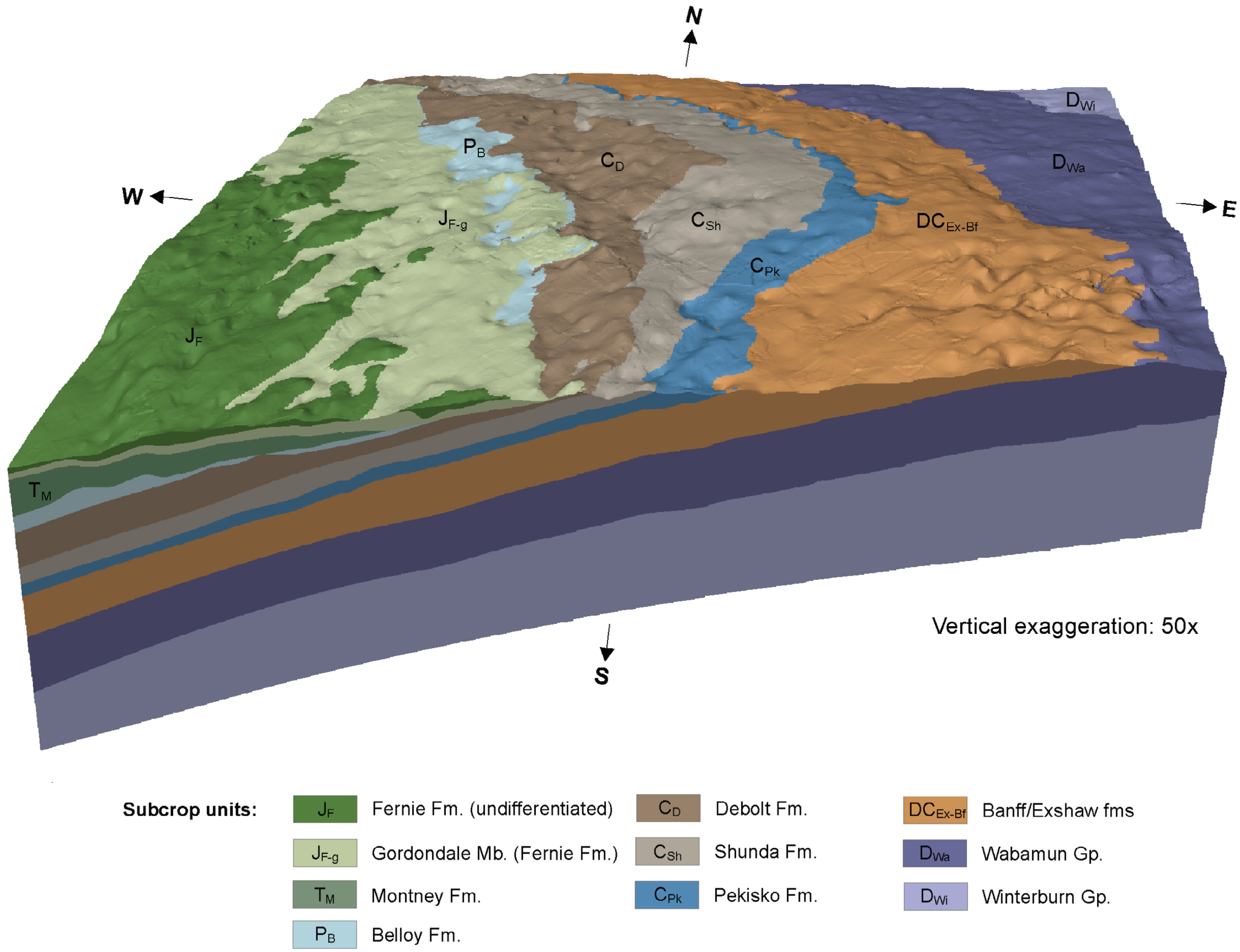


Figure 20. Three-dimensional oblique view of the sub-Cretaceous unconformity model highlighting the intersection of the underlying stratigraphic units and the unconformity surface.

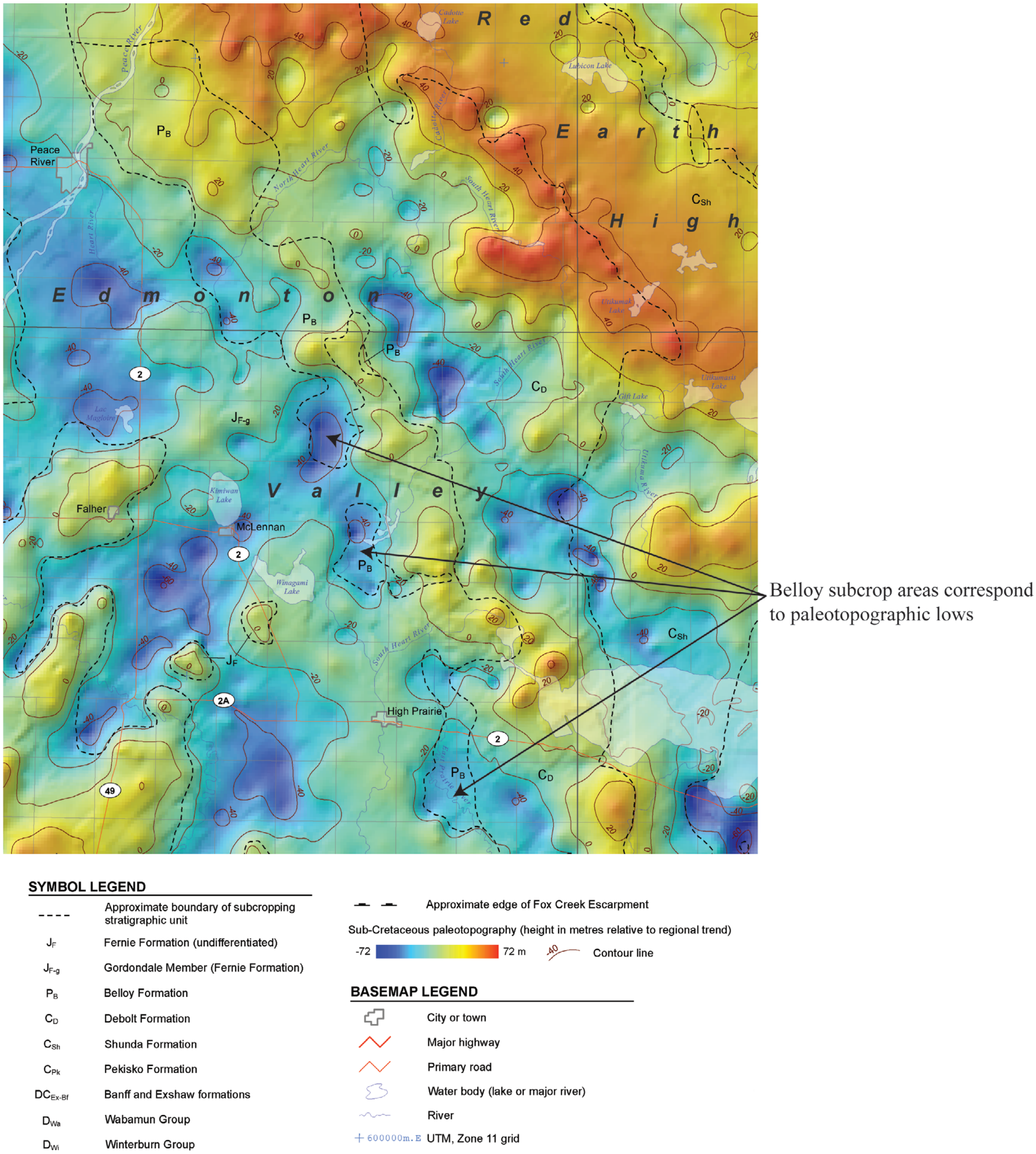


Figure 21. Inset map of the paleotopography of the sub-Cretaceous unconformity showing the link between topographic lows and the Belloy Formation subcrop areas.

A small portion of Winterburn Group subcrops in the northeast corner of the study area and forms a topographic high compared to much of the Wabamun Group subcrop area (Figure 19).

4 Summary

The sub-Cretaceous unconformity was mapped across the study area by reviewing the well logs for 4175 wells to identify the elevation of the unconformity surface. Elevation data for the sub-Cretaceous was modelled, accounting for regional trends, with a 500 metre grid spacing to create an elevation surface. Underlying stratigraphic units were independently modelled and were intersected with the unconformity surface to create subcropping unit boundaries. These boundaries were compared with the well control data and adjusted where necessary. The paleotopography of the study area was predicted by subtracting the regional trend from the modelled sub-Cretaceous elevation surface. The residual values that remained represent the paleotopography of the sub-Cretaceous unconformity surface.

Assessing the sub-Cretaceous unconformity and underlying stratigraphic units provides insight into how these units intersect this important regional surface and form subcropping areas at the unconformity surface. Examining the paleotopography of the sub-Cretaceous unconformity provides insight into the Cretaceous depositional systems, such as remnant highlands and paleovalley systems.

The sub-Cretaceous unconformity will continue to be mapped across the province in regional-scale study areas and eventually incorporated into a provincial-scale composite map. The modelled sub-Cretaceous unconformity surface resulting from this work is a critical surface that will be incorporated into the 3D geological framework model of the Alberta subsurface.

5 References

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