ERCB/AGS Open File Report 2010-10

Top of the Belly River Group in the Alberta Plains: Subsurface Stratigraphic Picks and Modelled Surface

Energy Resources Conservation Board

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Abstract

This report presents subsurface stratigraphic picks for the top of the Belly River Group in the Alberta Plains (Townships 1 to 50, Ranges 1W4 to 2W5) made from wireline geophysical well logs. Representative geophysical logs are used to demonstrate the criteria used to make picks and to highlight regional geological variability. Well data were screened to detect errors resulting from deviated wells, as well as incorrect ground and kelly-bushing elevation data. Statistical methods were used to identify local and regional statistical outliers, which were examined individually and either confirmed or removed. The stratigraphic picks are presented in Digital Dataset DIG 2010-0022.

A structure contour map for the top of the Belly River Group is included to illustrate regional structure. Areas of anomalous local structure were identified in two areas. Deviations from regional strike on the structure map, consistent with transverse faults, are present near Lethbridge, where the Monarch Fault Zone has been mapped. A bowl-shaped structural anomaly with a central uplift was identified southeast of Calgary near Bow City. The Bow City anomaly, which affects bedrock but has little surface expression, is broadly similar in shape and size to the Eagle Butte Impact Structure, which is located on the eastern flank of the Cypress Hills.

1 Introduction

The contact between the Bearpaw Formation and the underlying Belly River Group represents an important lithostratigraphic and hydrological interface within the shallow (<500 m) bedrock of the Alberta Plains. An internally consistent set of stratigraphic picks for the top of the Belly River Group for the entire Alberta Plains is of potential use to stakeholders who require detailed and accurate three-dimensional knowledge of the near-surface bedrock. The stratigraphic picks are presented in Digital Dataset DIG 2010-0022 (Glombick, 2010).

This report briefly discusses the geology of the upper Belly River Group and lower Bearpaw Formation before describing the criteria used to make stratigraphic picks. It is not intended as a comprehensive geological review. Readers interested in the geology of the Bearpaw Formation or the Belly River Group are directed to other publications (Dowling, 1917; Russell and Landes, 1940; Link and Childerhose, 1931; Clark, 1931; Lines, 1963; Given and Wall, 1971; McLean, 1971; Eberth and Hamblin, 1993; Hamblin, 1997, 2004; Eberth, 2005).

2 General Stratigraphy

Late Cretaceous sedimentary rocks of the Belly River Group[1] form an eastward-thinning clastic wedge deposited within the Western Canada Sedimentary Basin during the Claggett and Bearpaw cycles of Kauffman (1977). In central and southern Alberta, the Belly River Group is overlain by the Bearpaw Formation, which records rising relative sea level within the Western Canada Sedimentary Basin during the Late Campanian to Early Maastrichtian (Caldwell et al., 1993; Catuneanu et al., 1997). The Bearpaw Formation forms a northwestward-thinning wedge of dominantly marine shale that overlies the Belly River Group and underlies (and locally interfingers with) rocks of the Horseshoe Canyon Formation (Figure 1).

Northwest of Edmonton, rocks approximately coeval with those of the Belly River Group and the overlying Horseshoe Canyon Formation are not distinguished from one another, as the intervening Bearpaw Formation is absent. This unsubdivided succession of nonmarine rocks is known as the Wapiti Formation (Figure 2; Dawson et al., 1994a; Fanti and Catuneanu, 2009).

Much of the southern Alberta Plains are underlain by Upper Cretaceous rocks of the Belly River Group. In southern Alberta, the Belly River Group has been divided into the Foremost, Oldman and Dinosaur Park formations (Figure 1). The Dinosaur Park Formation is the uppermost formation of the Belly River Group. Over most of south-central Alberta, marginal to nonmarine rocks of the Dinosaur Park Formation are separated from underlying nonmarine rocks of the Oldman Formation by a regional discontinuity (Eberth and Hamblin, 1993). Fining-upward, metre-thick, multistorey channel sandstone bodies (typically showing inclined heterolithic stratification) and associated siltstone, mudstone and minor bentonite and coal of the Dinosaur Park Formation overlie fluvial sandstone and siltstone of the Oldman Formation. Rocks of the Dinosaur Park Formation have been interpreted as being deposited in a coastal to fluvial plain environment and are considered to record rising relative sea level during the Bearpaw transgression (Eberth and Hamblin, 1993; Hamblin, 1997; Eberth, 2005). The discontinuity is recognized in outcrop, core and well logs across much of the southern Alberta Plains, as well as northern Montana (Rogers,

[1] The name 'Judith River Group' is currently used in Montana and Saskatchewan for the correlative of the Belly River Group in Alberta. The Judith River Group has historical precedence and several workers have proposed that it be adopted in Alberta, but its use has generally been abandoned in Alberta in favour of the Belly River Group. See McLean (1971) and Eberth and Hamblin (1993) for a historical review of the nomenclature of the Belly River Group in Alberta.

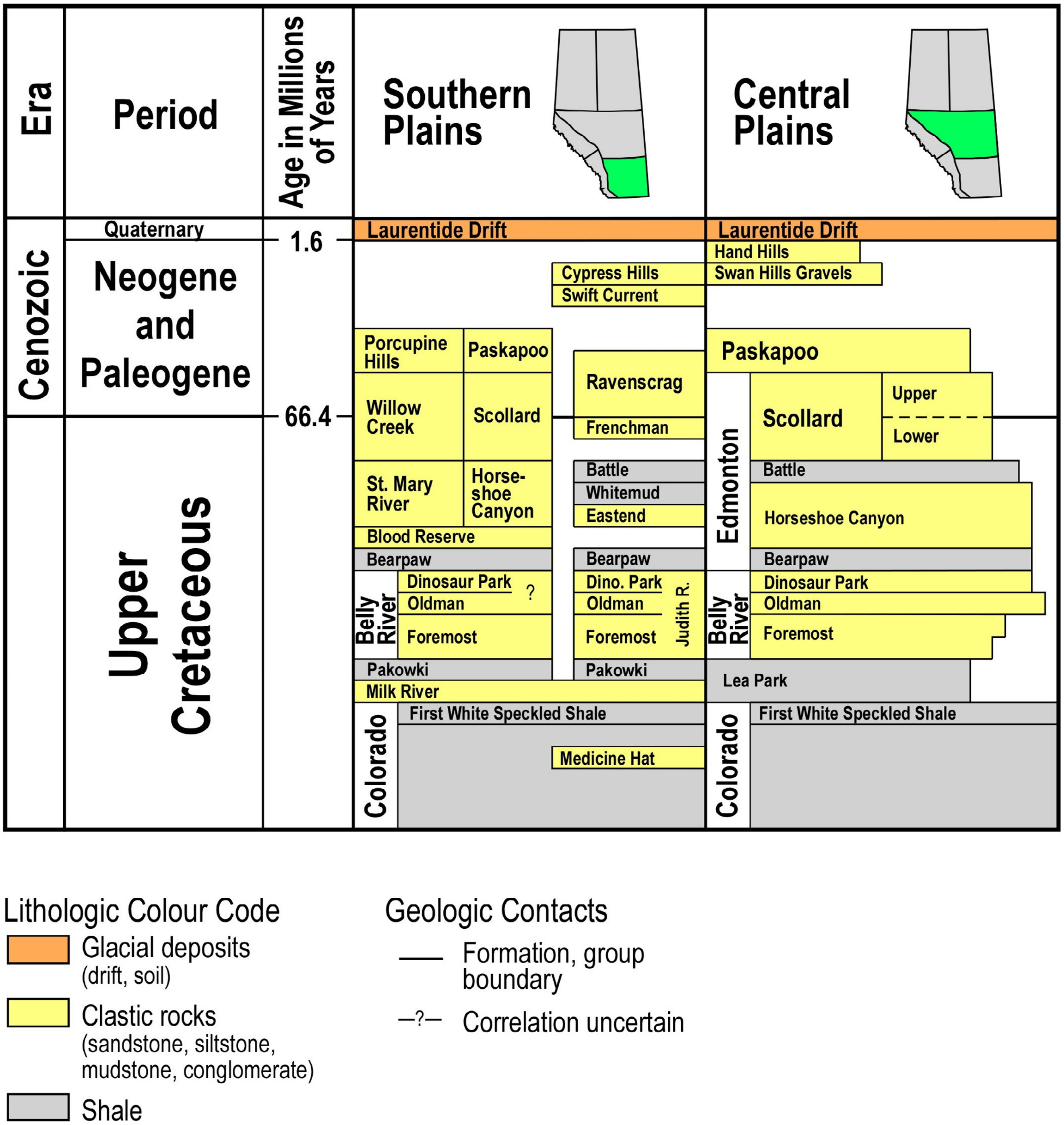


Figure 1. Schematic stratigraphic column showing the distribution of Upper Cretaceous and early Tertiary bedrock in southern and central Alberta (modified from Energy Resources Conservation Board, 2009).

1998) and west-central Saskatchewan (Eberth et al., 1990). In southwestern, southeastern and north-central Alberta, the presence of a discontinuity separating the Oldman and Dinosaur Park formations is uncertain and has yet to be mapped in detail. In these areas, the term 'Oldman unrestricted' is used in this report to refer to the Oldman Formation of Russell and Landes (1940), which includes both the Dinosaur Park and the Oldman (restricted) formations of Hamblin (1997).

The Bearpaw Formation—named by Stanton and Hatcher (1905) after the Bearpaw Mountains of north-central Montana—forms the uppermost bedrock over a large area of east-central Alberta (Figure 2).

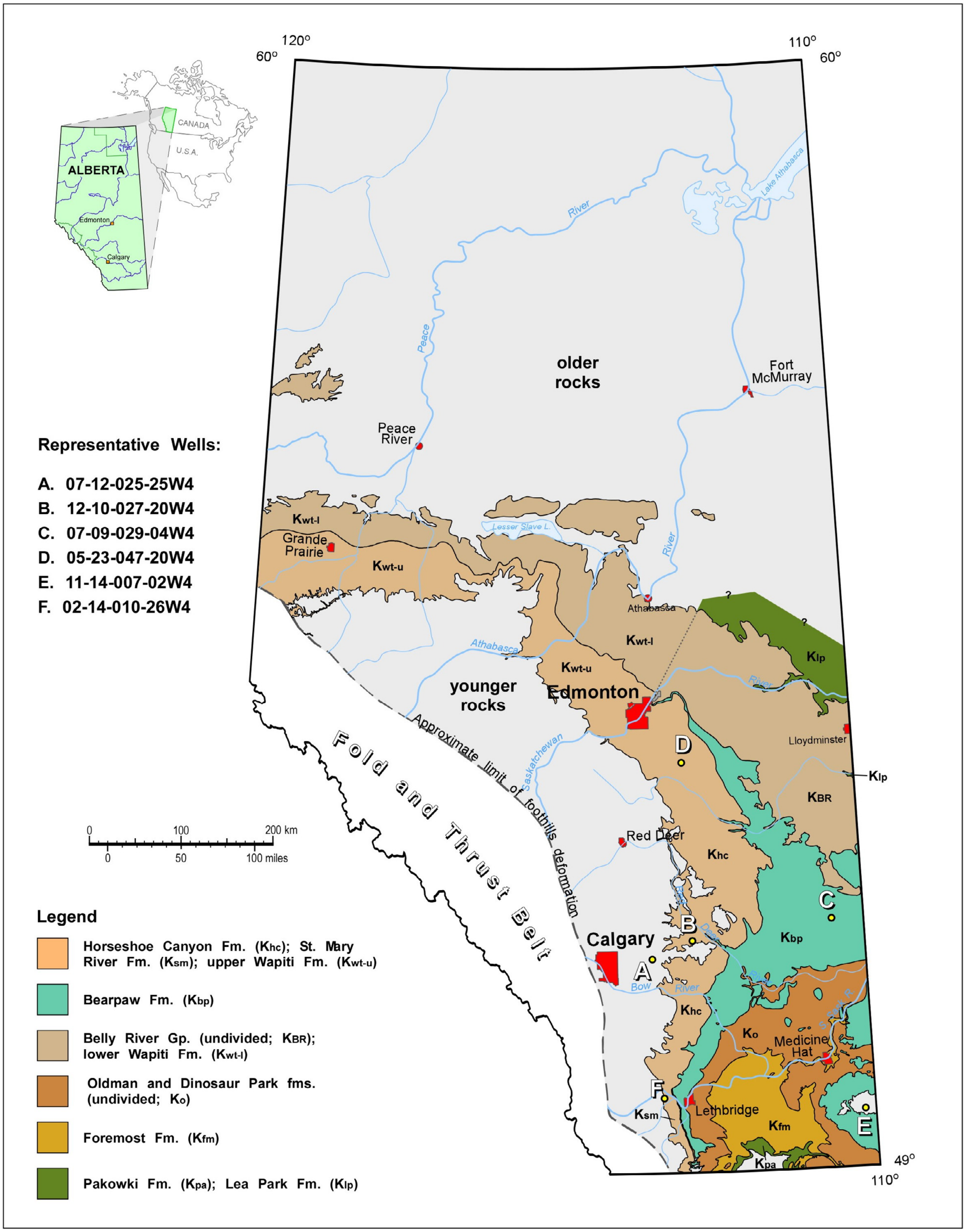


Figure 2. Simplified geological map showing the distribution of Belly River Group rocks in central and southern Alberta and location of representative wells used in this project (geology modified from Hamilton et al., 1999).

Rocks of the Bearpaw Formation are typically recessive, with outcrop restricted to river valleys and areas characterized by badlands topography. The map patterns of Upper Cretaceous rocks in southern Alberta, including those of the Bearpaw Formation, are primarily controlled by the shallowly northeast-plunging Bow Island Arch. In southern Alberta, the Bearpaw Formation has been eroded over the crest of the Bow Island Arch, leaving bedrock exposures on the western flank of the arch, and several outliers along the east flank of the arch, north of the Cypress Hills area (Figure 2).

The Bearpaw Formation is characterized by dark grey to dark brownish grey mudstone, silty mudstone, siltstone or shale. Thin layers of bentonite, typically less than 1 m thick, are common and permit local correlation (Link and Childerhose, 1931; Russell and Landes, 1940; Lines, 1963).

3 Upper Surface of the Belly River Group

The contact between the Belly River Group and the overlying Bearpaw Formation is generally sharp. It is characterized by an abrupt upward change in lithology from a heterogeneous sequence of interbedded siltstone, sandstone, carbonaceous mudstone and coal (forming the uppermost Belly River Group) to a relatively homogeneous sequence of mudstone or shale that form the Bearpaw Formation. It has been suggested that the contact is a ravinement surface (Catuneanu et al., 1997).

Over much of south-central Alberta, a succession of thin coal seams interbedded with mudstone, siltstone and bentonite, generally known as the Lethbridge coal zone, is present within the upper Belly River Group. In southwestern Alberta, the Lethbridge coal zone locally reaches a thickness of more than 25 m (80 feet; e.g., Russell and Landes, 1940, p. 65), but is typically only several metres thick. Where coal is not present, there is commonly a zone of interbedded bentonite and carbonaceous mudstone immediately below the overlying contact with the Bearpaw Formation.

In his pioneering work, Dawson (1883, 1885) included coals of the Lethbridge coal zone within his Pierre Group:

> *The Pierre [Bearpaw Formation] is, however, as a whole, the best marked and most easily recognized formation of the district.* ***The most persistent coal-bearing horizon is included in its base.*** [1883, p. 7B; emphasis added]
>
> *The actual base of the Pierre is best shown in the head waters of a small stream which flows into Middle Coulee Creek. The shales here to some extent lose their characteristic dark tint, become grayish or brownish and earthly looking, and hold several small seams of coal and carbonaceous shales. The most considerable coal seam is not more than eighteen inches thick, and the section here is closely comparable with that previously described in Milk River south of the ridge.* [1885, p. 39C]
>
> *An oyster-bed identical with that observed at the mouth of the St. Mary River at the same horizon, occurs in association with the coals.* [1885, p. 50C]
>
> *The base of the Pierre shales is reached at the mouth of the St. Mary River and the angle between the two rivers to the east, shows, in a scarped bank, the greyish and yellowish-grey shales and sandstones of the next subdivision of the Cretaceous in descending order, with the associated coal, which is considered as forming the base of the Pierre group.* [1885, p. 69C]

From these passages, it appears that Dawson included the Lethbridge coal zone within the Bearpaw Formation, rather than within the underlying Belly River Group. The reason is not clear, but it could have been because the coal seams are typically interbedded with dark, fine-grained clastic rocks resembling those of the Bearpaw Formation.

Dowling (1917), however, placed the base of the Bearpaw Formation above the Lethbridge coal zone, at the change to homogeneous mudstone typical of the Bearpaw Formation and included the Lethbridge coal zone within his 'Pale beds' (Oldman Formation of Russell and Landes, 1940). Dowling's definition was adopted by subsequent workers (Clark, 1931; Hake and Addison, 1931; Link and Childerhose, 1931; Powers, 1931; Russell and Landes, 1940; Crockford, 1949; Lines, 1963; Hamblin, 1997; Catuneanu et al., 1997).

In many areas of southern Alberta, the uppermost coal seam of the Lethbridge coal zone is directly overlain by shale or mudstone of the Bearpaw Formation. In other areas, however, a thin oyster bed, coquina bed, chert-pebble conglomerate or approximately 1–3 m (2–8 feet) of grey-brown, fine-grained sand occur between the underlying Lethbridge coal zone and the overlying mudstone of the Bearpaw Formation (e.g., Dowling, 1917; Link and Childerhose, 1931; Russell and Landes, 1940; Lines, 1963; Catuneanu et al., 1997).

Crockford (1949, p. 505), who mapped the contact in southern Alberta, wrote:

> *The Bearpaw-Oldman contact is ordinarily sharp and easy to identify. Basal Bearpaw beds in the form of dark brown shale, brown shale with sandstone pellets, or sandstone with marine fossils rest on coal seams or dark brown carbonaceous shales of the Lethbridge member. In a few places Bearpaw shales overlie typical Oldman sandstone, the Lethbridge member being absent. This feature, together with sandstone pellets in the basal shale suggest that the contact in places has the nature of an erosional unconformity. In the vicinity of Lethbridge the contact is not easy to place, but is usually drawn so as to include in the Oldman, beds of* Ostrea *shells that occur there.*

The above passage highlights the locally erosional character of the contact, as indicated by the presence of sandstone pellets in the basal Bearpaw shale and, possibly, by the absence of the Lethbridge coal zone. Crockford (1949) also described the arbitrary convention of including the shell bed present at the top of the Belly River Group in the Lethbridge area within the Oldman Formation, rather than within the Bearpaw Formation. Other workers in the Lethbridge area, however, have placed the contact at the base of the oyster coquina (Catuneanu et al., 1997, p. 80, Figure 4).

In the Cypress Hills area, Russell and Landes (1940, p. 80) observed a sandstone bed overlying the Lethbridge coal zone and placed it within the Bearpaw Formation. Others, such as Link and Childerhose (1931, p. 1229), considered the top of a similar sand to mark the top of the coal measures (correlative to the Lethbridge coal zone?) and the base of the Bearpaw Formation:

> *The brown-weathering ferruginous sandstone bed, which is considered the top of the Lethbridge coal measures, was found throughout this area and proved to be an excellent datum bed for structural work. It ranges in thickness from 9 inches to 2 feet and its top is regarded as the base of the overlying Bearpaw shale.*

Brinkman et al. (2005) described the Lethbridge coal zone in the Dinosaur Provincial Park area, where the coal zone is approximately 20 m thick. In this area, the zone is overlain by several metres of laminated nonmarine sandstone and shale, which, in turn, are overlain by 5–6 m of shale that contains fully marine palynomorphs. This marine shale is, in turn, overlain by a 4–5 m thick succession of tan-coloured mudstone, siltstone and coal of nonmarine origin, hereafter referred to as the 'tan silt unit' (Brinkman et al., 2005). Brinkman et al. (2005) placed the contact between the Belly River Group and the overlying Bearpaw Formation at the top of the tan silt unit (*sensu* Eberth and Hamblin, 1993, Figure A3), placing 6 m of underlying marine shale typical of the Bearpaw Formation within the Dinosaur Park Formation. The placement of the contact by Brinkman et al. (2005) contrasts with the original definition of Dowling (1917) and Russell and Landes (1940), who placed it at the base of the first succession of shale characteristic of the Bearpaw Formation directly overlying the Lethbridge coal zone. Placing the contact according to palynomorphs is not practical in a regional subsurface mapping project and the regional extent of the tan silt unit is not known. In this report, we follow the definition of Russell and Landes (1940) for the top of the Belly River Group and place the contact at the base of the first mudstone or shale succession characteristic of the Bearpaw Formation that overlies the Lethbridge coal zone, except where marine sandstone is known to occur within the lower Bearpaw Formation, such as in the Cypress Hills area. In this case, coarsening-upward sandstone situated above the Lethbridge coal zone is included within the Bearpaw Formation rather than the underlying Belly River Group.

The preceding discussion demonstrates the regional variability in the character of the contact between the Belly River Group and the Bearpaw Formation, and in the criteria used to place the contact by different workers. The issue is further complicated by the time-transgressive and locally interfingering nature of the contact (see, for example, Caldwell et al., 1993, Figure 15). In general, there appears to be a consensus to place the contact either directly above the Lethbridge coal zone or at the relatively abrupt change from marginal or nonmarine rocks to homogeneous marine shale or fine-grained marine sandstone (essentially a lithostratigraphic division). In many locations, these two criteria correspond to the same surface. Where the Lethbridge coal zone is not present, the contact is generally placed instead at the first occurrence of homogeneous mudstone, siltstone, sandstone or shale typical of the Bearpaw Formation. In most cases, this contact is clearly visible on geophysical well logs.

4 Picking Criteria

Reference geophysical well logs for Upper Cretaceous rocks in Alberta have been presented by Dawson et al. (1994b, Figure 24.10). In well 00/16-03-023-17W4/0, they placed the contact between the Belly River Group and the Bearpaw Formation at a depth of 145 m (Figure 3). The Lethbridge coal zone is well developed in this well, and increases in gamma-ray and neutron-porosity values are apparent above the contact.

The criteria used to pick the top of the Belly River Group in this study agree with those of Dawson et al. (1994b, Figure 24.10) and follow the lithostratigraphic criteria described by Russell and Landes (1940). Additional examples are in McCabe et al. (1989, equivalent to their ‘A-top,’ Figure 7), Hamblin (1997, Figure 3; 2004, Figures 14 to 16) and Chen et al. (2005, Figures 2 and 3).

A well-studied core through the entire Bearpaw Formation and Belly River Group was obtained from the Canadian Pacific Oil and Gas C.P.O.G. Strathmore well (00/7-12-25-25W4/0; Harvard, 1970, 1971; Given and Wall, 1971; Wall et al., 1971; Hamblin, 1998; Lerbekmo and Braman, 2005), permitting correlation between the gamma-ray and neutron logs and core (Figure 4). The contact between the Belly River Group and the Bearpaw Formation occurs at a depth of 530 m, where there is a transition from fine-grained, light grey sandstone with carbonaceous partings to light grey bentonite and bentonitic mudstone at the base of the Bearpaw Formation (Figure 4). The gamma-ray log shows a sharp, upward to the right deflection across the contact, whereas the neutron log shows an overall average decrease, possibly reflecting an increase in clay content. Both logs show less vertical variability in the Bearpaw Formation due to the relative homogeneity of the lower Bearpaw Formation compared with the heterolithic character of the underlying Dinosaur Park Formation.

Whenever possible, a suite of gamma-ray–density porosity-resistivity log curves should be used to pick the top of the Belly River Group. Newer logs (post-1980) are preferred because of their enhanced vertical resolution and the presence of the gamma-ray log compared with older log suites. In this project, a combination of neutron and density porosity (sandstone calibration) was preferred over other density tools (e.g., sonic, bulk density). A deep resistivity log is useful for identifying overall depositional trends, such as coarsening- or fining-upward sequences, whereas a shallow resistivity log is more sensitive to thin beds, such as coal seams and bentonites less than a metre thick. Older (pre-1970) resistivity and spontaneous-potential (SP) curves are of little use when picking the top of the Belly River Group and

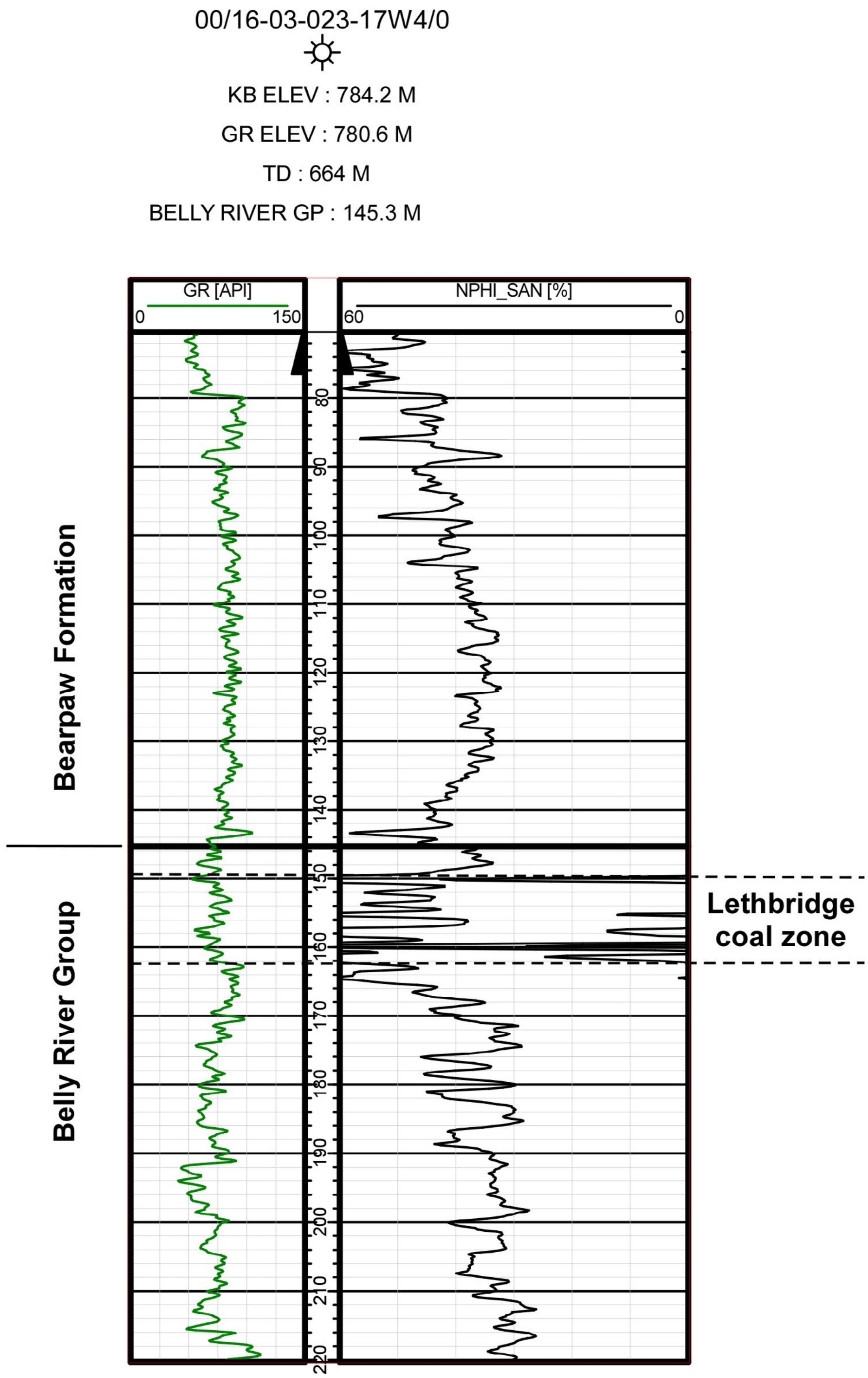
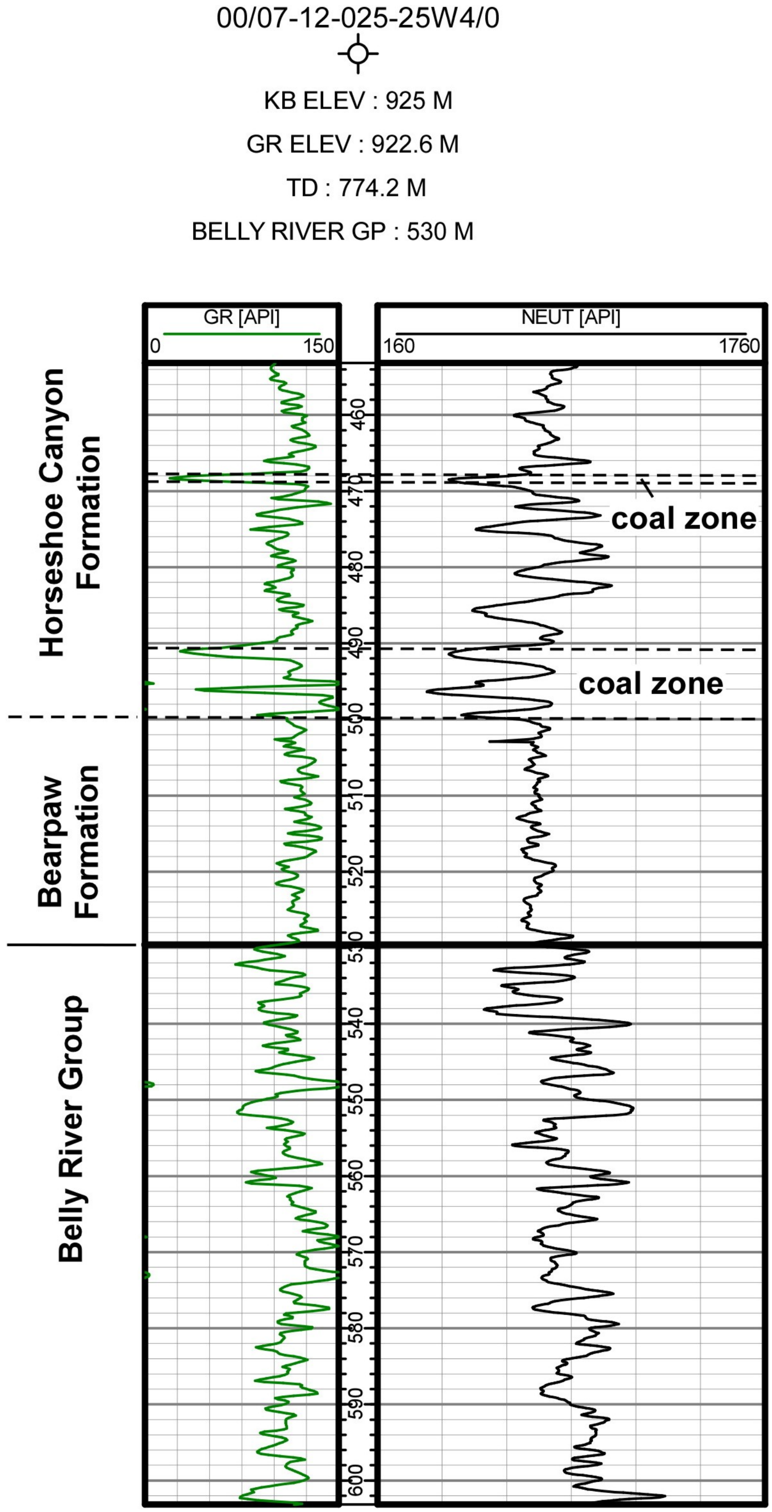


Figure 3. Gamma-ray (GR in API units) and neutron-porosity (sandstone; NPHI_SAN in %) logs for reference well 00/16-03-023-17W4/0 for the Upper Cretaceous section in southern Alberta, showing the Belly River Group–Bearpaw Formation contact (after Dawson et al., 1994b). Vertical scale is measured depth in metres below kelly bushing (KB). Other abbreviations: GP, Group; TD, total depth.



Lithological notes from core (from Havard, 1971)

500 - 527.9 m: Shale; medium grey to grey-brown, very fine to fine-grained, light brown-grey sandstone at 506.3 m, ironstone nodules at 512.4 m, occasional siltstone and mudstone interbeds and lenses, ironstone bands throughout, light grey bentonite at base

527.9 - 530 m: Mudstone; medium to brown-grey, fine lenses of bentonitic siltstone

530 - 532.5 m: Sandstone; light grey, very fine-grained, bedding mostly horizontal but disturbed and burrowed in places, fine carbonaceous partings and resin blebs

532.5 - 533.4 m: Shale; medium green-grey, resin blebs, coal streaks

533.4 - 538.6 m: Mudstone; brown-grey to grey-brown, lenses of siltstone, coaly intervals and resin blebs, occasional ironstone lenses, very carbonaceous dark grey-brown shale near base

Figure 4. Comparison between gamma-ray (GR in API units) and neutron (NEUT in API units) logs, and lithological notes from core for C.P.O.G. Strathmore well 00/07-12-025-25W4/0. Vertical scale is measured depth in metres below kelly bushing (KB). Other abbreviations: GP, Group; TD, total depth.

picks based on these logs are often placed too low. Where the preferred log suites were not available, a minimum of a gamma-ray curve and either a density or a resistivity curve was used to make picks.

Where the Lethbridge coal zone is developed, it is readily identifiable using a combination of gamma-ray, density and resistivity logs. Coal seams and carbonaceous zones are characterized by low gamma-ray, low-density and high-resistivity values. If coal seams are less than approximately 2 m thick, limitations on the resolution of the logging tool may dampen the magnitude of the response. Coal seams are susceptible to wash-out during drilling, indicated by an increase in borehole diameter (visible on the caliper log), particularly in boreholes drilled for Lower Cretaceous or Devonian targets. Borehole wash-outs may cause an apparent increase in porosity and a decrease in resistivity (using freshwater drilling mud) and gamma-ray values. The gamma-ray log is minimally affected by minor borehole irregularities, but will be affected by major wash-out (Rider, 2002).

Where the Lethbridge coal zone is absent, the base of the Bearpaw Formation is marked by a transition from fine-grained sandstone, siltstone, mudstone and coal of the upper Belly River Group to monotonous mudstone interbedded with thin (generally less than 2 m) units of bentonite or bentonitic mudstone. This transition is characterized by an upward overall increase in radioactivity (generally greater than 80 API), an increase in neutron porosity and a sharp decrease in resistivity. The neutron- and density-porosity logs show an increase in separation upward across the contact. Bentonites can be identified by their characteristic high-radioactivity, low-density and low-resistivity log response.

5 Representative Wells

Several representative wells were chosen to illustrate local variations in the log signature of the transition from the Belly River Group to the Bearpaw Formation in the project area and how the pick was made. See ERCB Directive 59 (Energy Resources Conservation Board, 2007, Appendix 2, p. 24) for a guide to unique well identifier (UWI) usage in Alberta.

5.1 South-Central Alberta (UWI 00/12-10-027-020W4/0)

This well displays a well-developed Lethbridge coal zone at the top of the Belly River Group (364–378 m) and an abrupt transition to the overlying mudstone and bentonite of the Bearpaw Formation (Figure 5). The top of the carbonaceous zone—marked by high resistivity, high neutron and density porosity, and low gamma-ray values—occurs at approximately 364 m and is the contact between the Bearpaw Formation and the Belly River Group. Moving upward from below to above the contact, one observes a sharp decrease in resistivity, an overall increase in gamma values and an increase in separation of the density- and neutron-porosity curves, which is believed to result from the increased clay content in the Bearpaw Formation compared with the underlying sediments of the Belly River Group. In general, except for abrupt low-resistivity, high-gamma zones—believed to be caused by bentonite-rich layers—the log curves in the Bearpaw Formation are much less variable than in the underlying Belly River Group, which is marked by extreme vertical (and lateral) lithological heterogeneity.

5.2 Eastern Alberta (UWI 00/07-09-029-04W4/0)

In east-central Alberta, the Lethbridge coal zone is typically poorly developed or absent, and the upper 10–20 m of the Dinosaur Park Formation becomes increasingly fine grained. As a result, placing the contact between the Belly River Group and the Bearpaw Formation becomes problematic, particularly near the Alberta-Saskatchewan border. In addition, the Bearpaw Formation becomes progressively siltier near its northern and western limits. As a result, the lower Bearpaw changes from relatively homogeneous mudstone and shale to a series of stacked, coarsening-upward cycles (Figure 6).

A distinctive, low-resistivity, high-gamma and low-density interval, approximately 2 m thick, occurs at the base of Bearpaw Formation (94–96 m; Figure 6). This interval, which probably represents a bentonite-

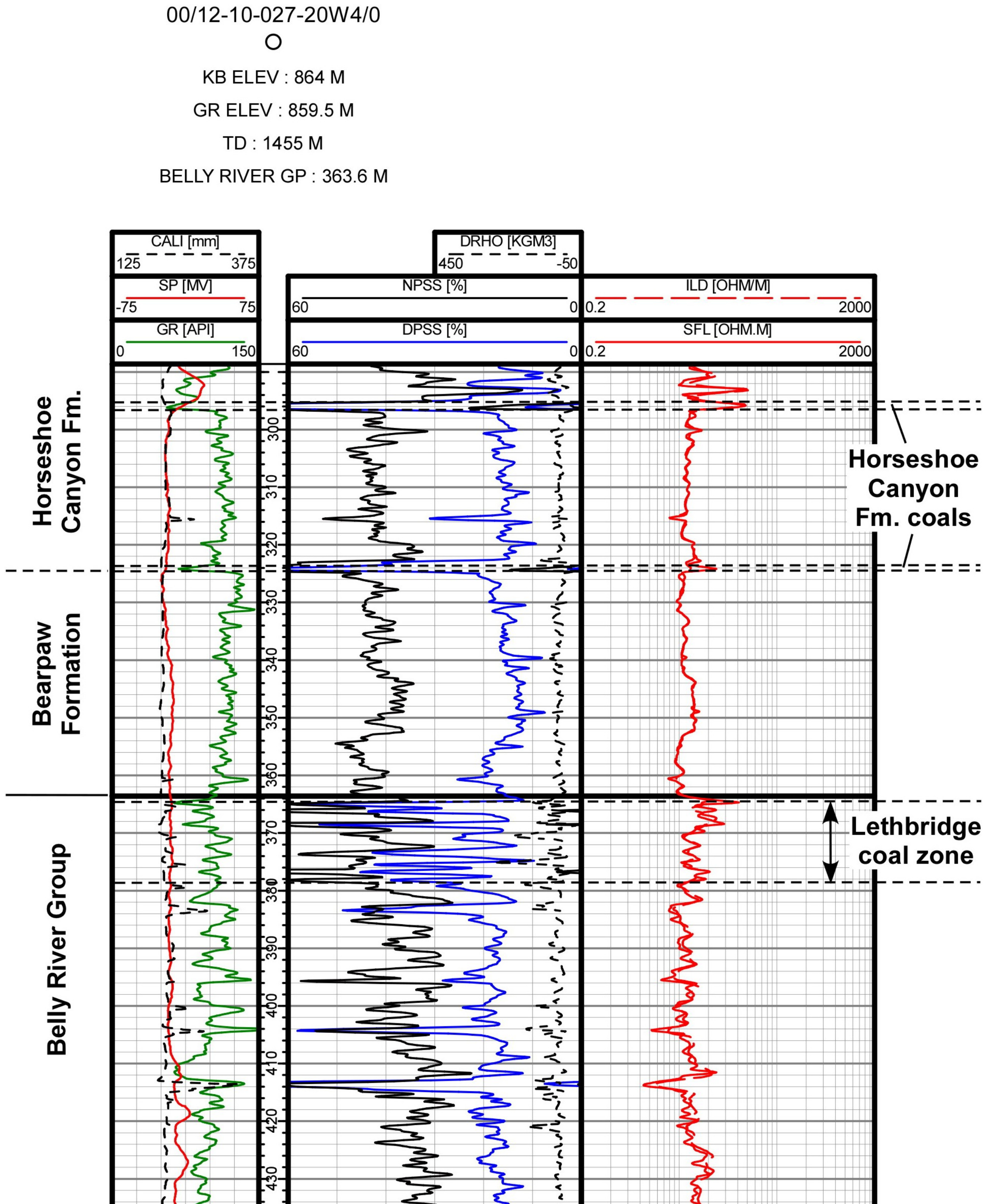


Figure 5. Caliper (CALI in mm), spontaneous-potential (SP in mV), gamma-ray (GR in API units), density correction (DRHO in kg/m^3), neutron-porosity (sandstone; NPSS in %), density-porosity (sandstone; DPSS in %), deep induction (ILD in ohm·m), and spherically focused (SFL in ohm·m) logs for a representative well in south-central Alberta (00/12-10-027-20W4/0). Vertical scale is measured depth in metres below kelly bushing (KB). Other abbreviations: GP, Group; TD, total depth.

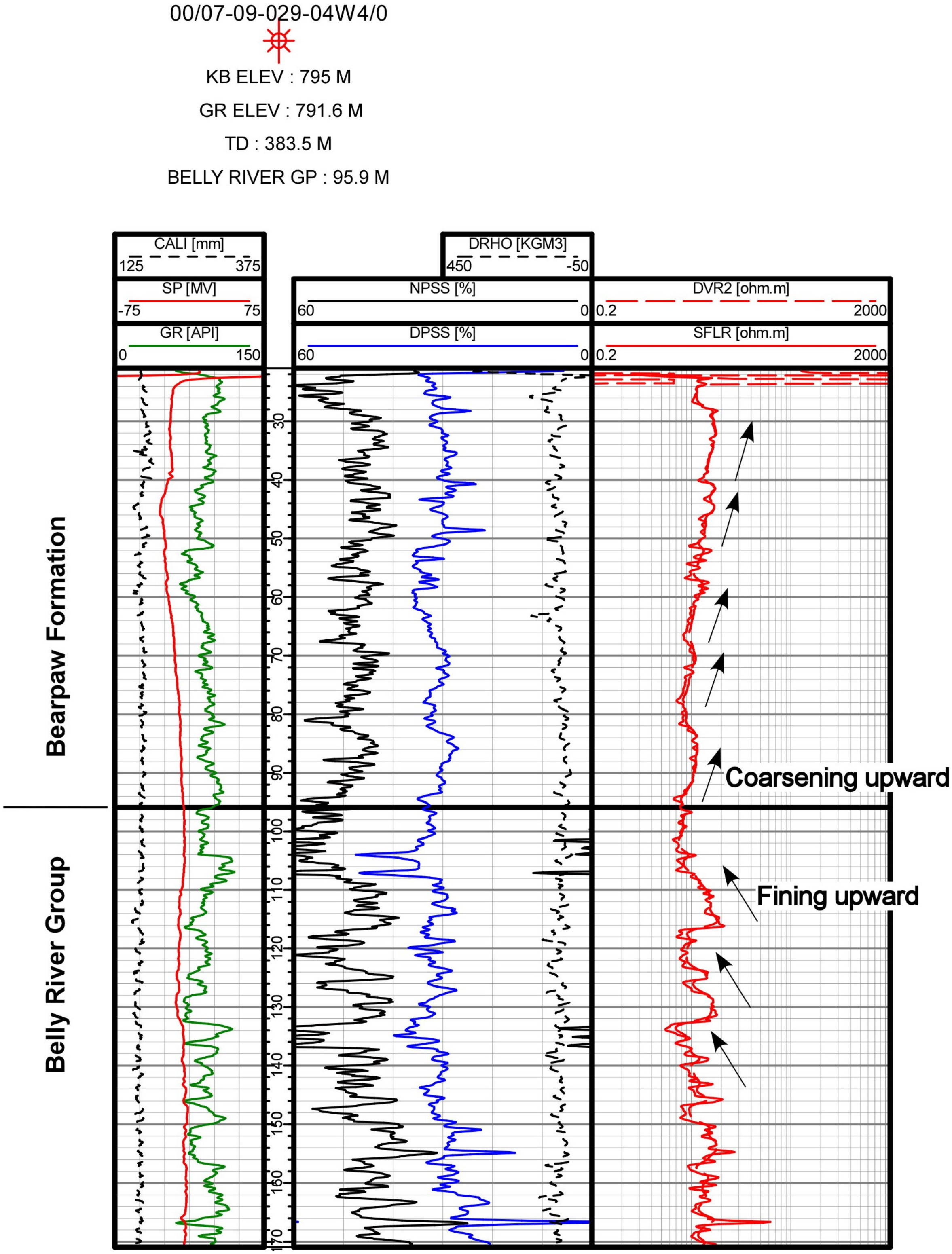


Figure 6. Caliper (CALI in mm), spontaneous-potential (SP in mV), gamma-ray (GR in API units), density correction (DRHO in kg/m^3), neutron-porosity (sandstone; NPSS in %), density-porosity (sandstone; DPSS in %), deep resistivity (DVRS in ohm·m), and spherically focused resistivity (SFLR in ohm·m) logs for a representative well in eastern Alberta (00/07-09-029-04W4/0). Vertical scale is measured depth in metres below kelly bushing (KB). Other abbreviations: GP, Group; TD, total depth. Arrows show interpreted fining- and coarsening-upward trends based on log patterns.

rich layer, is interpreted to represent a nearly isochronous surface. Toward the Alberta-Saskatchewan border, the contact between marine siltstone of the Bearpaw Formation and underlying heterogeneous siltstone and fine-grained sandstone of the Dinosaur Park Formation shifts downward approximately 10 m to a lower stratigraphic level (approximately 107 m in well 00/07-09-029-04W4/0). Close examination of this transition reveals that it reflects the easternmost depositional limit of the upper (younger) nonmarine cycle and that the lithostratigraphic contact 'jumps' down to the top of the underlying (older) nonmarine cycle. The point at which the uppermost cycle pinches out laterally into Bearpaw Formation is gradual and somewhat subjective at the local scale, but consistently mappable at the regional scale. These observations are consistent with the time-transgressive nature of the upper surface of the Belly River Group wedge recorded in southwestern Saskatchewan by Caldwell (1968) using biostratigraphy.

5.3 Central Alberta (UWI 00/05-23-047-20W4/0)

In central Alberta, near the northwestern depositional limit of the Bearpaw Formation, the contact between the Belly River Group and the Bearpaw Formation can be difficult to pick. Moving from southeast to northwest, the Bearpaw Formation thins, becomes richer in silt and sand, and therefore becomes more difficult to distinguish from similar rocks of the underlying Belly River Group, particularly where the Lethbridge coal zone is not present or poorly developed. In addition, where the Bearpaw Formation becomes quite thin, the Lethbridge coal zone, when present, can be easily confused with the lowermost coals in the Horseshoe Canyon Formation. Beyond the western edge of the depositional limit of the Bearpaw Formation in south-central Alberta, these time-transgressive coal zones locally merge into one coal zone (McCabe et al., 1989).

In well 00/05-23-047-20W4/0, for example, the Bearpaw Formation is less than 12 m thick. The contact between the Belly River Group and the Bearpaw Formation occurs at 179 m, and the lowermost coal of the Horseshoe Canyon Formation occurs at 168 m (Figure 7). The transition from the Belly River Group upwards to the Bearpaw Formation is marked by a decrease in resistivity, an increase in neutron porosity and an increase in gamma-ray values. Although the Bearpaw Formation is quite thin in this well, it still shows the characteristic smooth, low-resistivity profile (Figure 7). The gamma-ray values decrease upward, suggesting decreasing clay content and possibly increasing grain size.

5.4 Southeastern Alberta (UWI 00/11-14-007-02W4/0)

In the Cypress Hills region of southeastern Alberta, the base of the Bearpaw Formation is placed above the uppermost occurrence of coal or carbonaceous material, which is included by most workers within the Belly River Group (Russell and Landes, 1940; Furnival, 1946). Although the contact in most areas coincides with the upwards transition from brownish grey siltstone, sandstone and mudstone (along with coal and carbonaceous rocks) of the upper Belly River Group to grey shale and bentonite of the Bearpaw Formation, there is fine-grained marine sandstone present locally within the lower Bearpaw Formation (Russell and Landes, 1940). In general, the contact is placed at the point where there is a transition from a vertically interbedded (on a metre or decimetre scale) succession of sandstone, siltstone and mudstone of the Belly River Group to a consistent, relatively homogeneous overlying succession of mudstone with thin (generally less than 1 m) bentonite beds. The character of this transition on the logs in southeastern Alberta is similar to other regions, with a decrease in overall resistivity and an increase in the separation between the neutron- and density-porosity logs upwards across the contact. In this region, the gamma-ray log may or may not show an increase, likely due to the locally sandy nature of the lowermost Bearpaw Formation. As noted by previous workers, the Bearpaw is marked by greater lateral variability in this region, and mudstone-filled channels are present locally within the Dinosaur Park Formation (Eberth, 1996).

In well 00/11-14-007-02W4/0, the top of the Belly River Group is placed at a depth of 462 m, at the top of the uppermost coal seam (Figure 8). The lowermost 18 m of the Bearpaw Formation show a typical response on the resistivity and density logs, but the gamma-ray values are lower than normal. There are

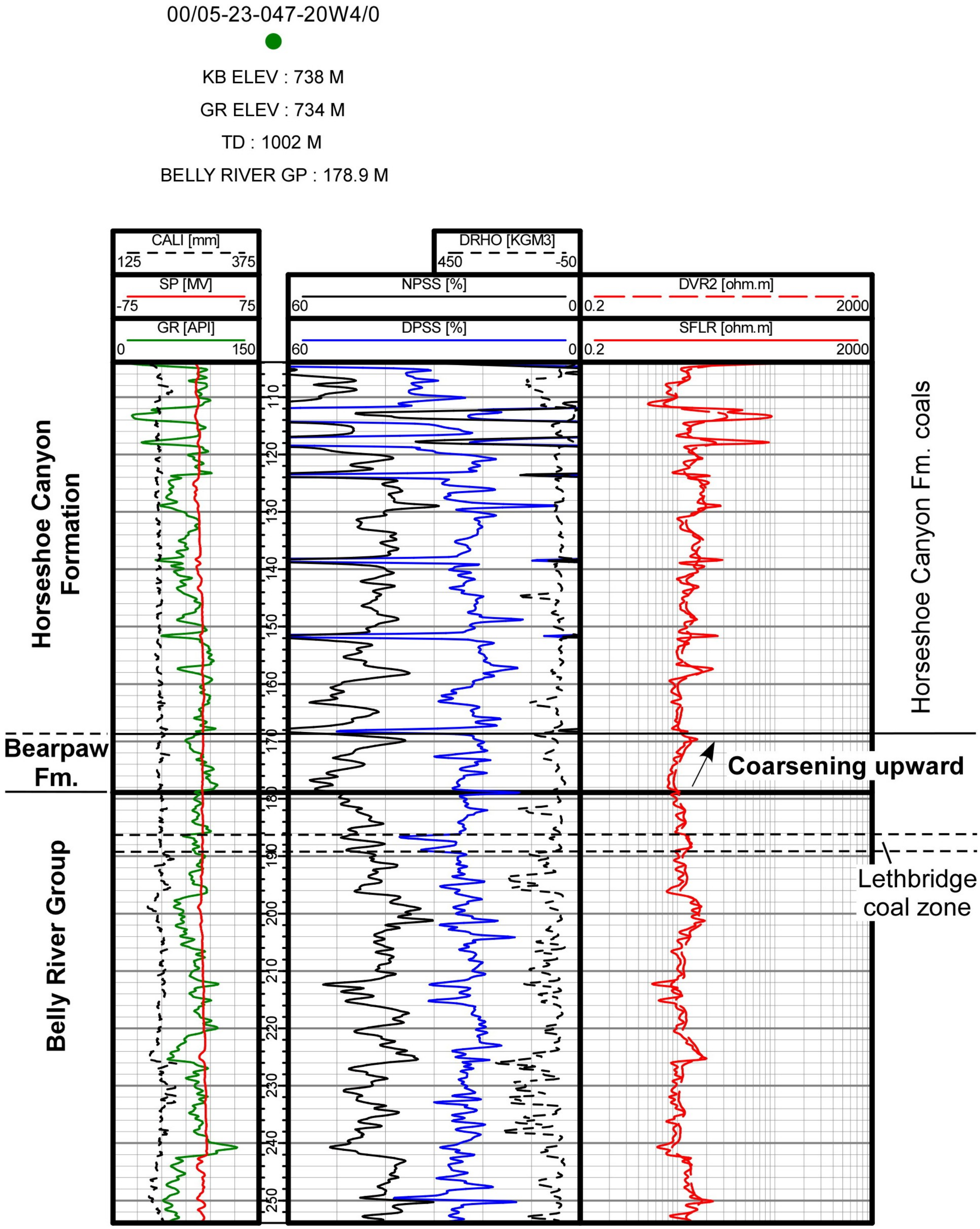


Figure 7. Caliper (CALI in mm), spontaneous-potential (SP in mV), gamma-ray (GR in API units), density correction (DRHO in kg/m^3), neutron-porosity (sandstone; NPSS in %), density-porosity (sandstone; DPSS in %), deep resistivity (DVR2 in ohm·m) and spherically focused resistivity (SFLR in ohm·m) logs for a representative well in central Alberta (00/05-23-047-20W4/0). Vertical scale is measured depth in metres below kelly bushing (KB). Other abbreviations: GP, Group; TD, total depth. Arrows show interpreted fining- and coarsening-upward trends based on log patterns.

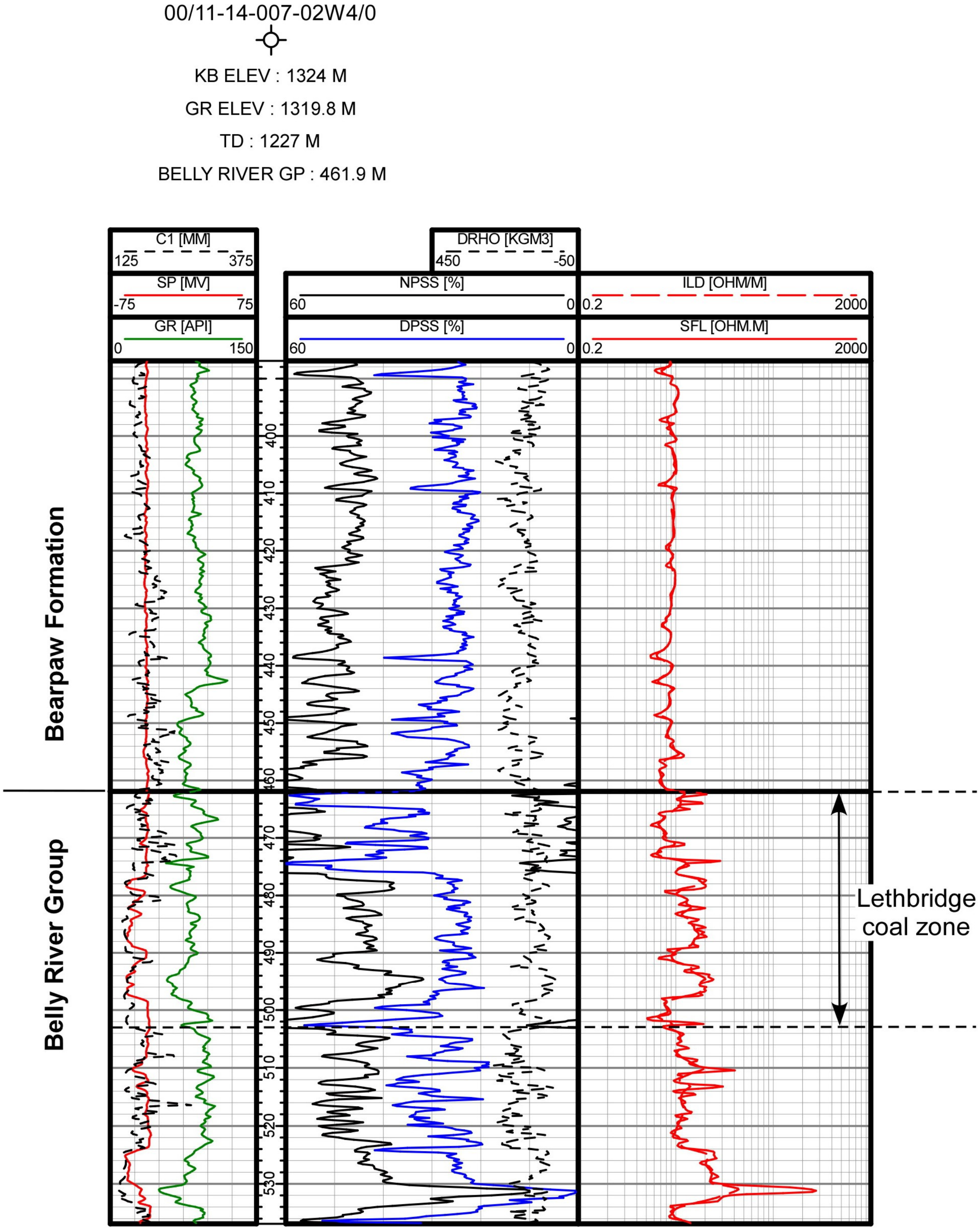


Figure 8. Caliper (C1 in mm), spontaneous-potential (SP in mV), gamma-ray (GR in API units), density correction (DRHO kg/m³), neutron-porosity (sandstone; NPOR in %), density-porosity (sandstone; DPSS in %), deep induction (ILD in ohm·m) and spherically focused (SFL in ohm·m) logs for a representative well in southeastern Alberta (00/11-14-007-02W4/0). Vertical scale is measured depth in metres below kelly bushing (KB). Other abbreviations: GP, Group; TD, total depth.

several low-resistivity, high-neutron and high–density-porosity zones, 1–2 m thick, within the lower 20 m of the Bearpaw Formation that are likely bentonite beds but could be wash-outs.

In areas where the Lethbridge coal zone is poorly developed or absent, the contact between the Belly River Group and the Bearpaw Formation can be difficult to place. In these areas, it is necessary to use a combination of gamma-ray, density (neutron and density porosity) and resistivity (or induction) logs, as well as a comparison between multiple wells, to make reliable and consistent picks.

5.5 Southwestern Alberta (UWI 00/02-14-010-26W4/0)

In well 00/02-14-010-26W4/0, the contact between the Belly River Group and the Bearpaw Formation occurs at a depth of 834 m (Figure 9). This well shows a typical geophysical signature for the contact in southwestern Alberta. The base of the Lethbridge coal zone is situated at a depth of 842 m and the uppermost coal seam occurs at 836 m. There are 3–4 m of moderately resistive rocks situated above the coal zone and below the contact with the overlying Bearpaw Formation, which is marked by an increase in radioactivity and neutron porosity, and a decrease in resistivity. This response is characteristic of the transition from sandstone and siltstone of the upper Belly River Group to mudstone and shale of the Bearpaw Formation. Above the contact, the resistivity shows the characteristic smooth cuspate profile and consistently high gamma-ray values (>95 API) typical of the lower Bearpaw Formation in this area (Figure 9).

6 Dataset and Methods

The data from this study are presented in Digital Dataset 2010-0022, which includes new stratigraphic picks for the top of the Belly River Group from 6966 wells. The dataset is in the zip file that accompanies the PDF of this report at http://www.ags.gov.ab.ca/publications/abstracts/OFR_2010_10.html.

Prior to making picks, the published geological literature was studied with emphasis on type and representative sections. Studies that include both core and geophysical logs are particularly valuable, as they provide a link between the rock and geophysical signatures.

Geophysical well logs (both digital and raster format) were examined using Petra® and Accumap® software and picks were recorded in a database. Where well density and log availability were sufficient, wells were selected according to the following criteria:

1) vertical wells only
2) wells with a spud date between 1975 and the present
3) wells with downhole geophysical well-log suites that include gamma-ray, density or sonic, and resistivity logs

Preference was given to wells where the bottom of the surface casing shoe is less than 50 m deep. If sufficient well density was not available using this criterion, it was relaxed to include wells with the bottom of surface casing in the 50–150 m range. A minimum well density of one well per township was used, although well density greatly exceeds that number in most areas, especially where anomalous structure was detected. Picks were made in wells from approximately 550 townships, resulting in an average density of approximately 13 wells per township.

To facilitate correlation and to check internal consistency, picks were made along a series of intersecting cross-sections, spaced a maximum of 10 km (one township) apart. In this way, a pick in a well was typically compared with several picks in nearby wells to ensure consistency. Picks were gridded using the triangulation method to identify and check outliers, which appear as 'bull's eyes' on a structure contour map.

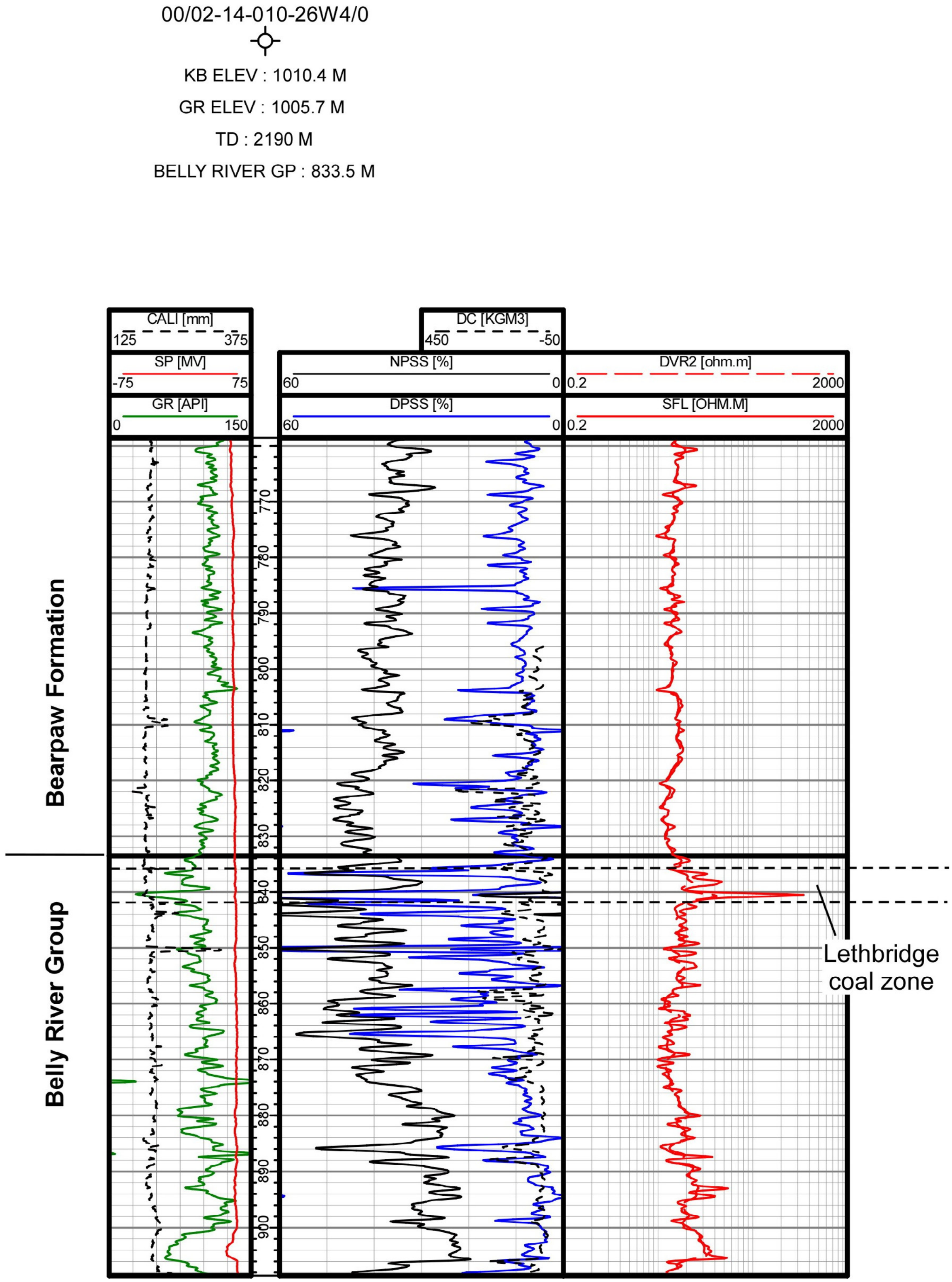


Figure 9. Caliper (CALI in mm), spontaneous-potential (SP in mV), gamma-ray (GR in API units), density correction (DC in kg/m³), neutron-porosity (sandstone; NPSS in %), density-porosity (sandstone; DPSS in %), deep resistivity (DVR2 in ohm·m) and spherically focused (SFL in ohm·m) logs for a representative well in southwestern Alberta (00/02-14-010-26W4/0). Vertical scale is measured depth in metres below kelly bushing (KB). Other abbreviations: GP, Group; TD, total depth.

7 Quality Control Procedures

After making picks and prior to modelling the surface, steps were taken to eliminate error resulting from

- deviated wells,
- incorrect KB elevation data,
- incorrect ground elevation data, and
- incorrect pick depth (due to human error).

Picks and well-header information, including KB elevation, ground elevation, surface location (longitude and latitude in decimal format) and bottom-hole location (longitude and latitude in decimal format), were exported from Petra® (IHS) software. The datum for the well location is NAD83 and the picks are in metres, given as measured depth relative to KB elevation. Subsea pick depths were calculated by subtracting vertical depth from the KB elevation.

A query of the well surface location compared with the bottom-hole location was run to check for deviated wells. If a well is deviated (not vertical), its surface and bottom-hole co-ordinates should be different, and these wells were removed from the dataset. As all remaining wells should be vertical if the surface and bottom-hole co-ordinates are correct, measured depth and true vertical depth should be equal.

Although incorrect KB elevation data can be difficult to detect, the data were screened by comparing the ground elevation and the KB elevation (equal to the derrick-floor height) for each well. An acceptable range of derrick-floor height—calculated by subtracting ground elevation from KB elevation—of 2–6 m was used. Wells with calculated derrick-floor heights outside this range were excluded.

To check for potential gross errors in the ground elevation of wells, ground elevations were compared with shuttle-radar digital elevation model (SRTM; United States Geological Survey, 2004) elevation data extracted for well surface locations. If the difference between the ground elevation and the elevation derived from the DEM data was more than 2 ±6 m (i.e., –4 to 8 m; approximately the mean of this difference plus or minus two standard deviations for all wells in the Alberta Plains), that well was excluded. This method potentially excluded wells for which well ground elevation values are correct, but for which the DEM data for that well location are incorrect. It also may not have detected relatively small errors in either ground or KB elevation data for a well, as long as those values met the screening criteria. It did, however, detect large errors in well KB or ground elevation data.

Data were then screened for both global and local outliers. Outliers are those values that are outside a specified normal range compared with the entire dataset (global outliers) or within a local area (local outliers). If outliers are caused by error, outliers can have a detrimental effect on the accuracy of the interpolated surface. They should be either corrected or removed before modelling a surface.

Outliers may result from one or more of the following factors:

- incorrect ground elevation and/or KB elevation data not detected during the initial screening
- incorrect location data for a well
- deviated wells that are not marked as such and have either incorrect surface or bottom-hole location data
- incorrect pick data due to picking (human) error
- geological structure

A variety of geostatistical methods was used to identify outliers, including examination of neighbourhood statistics, inverse distance weighting interpolation and Voronoi maps. Outliers were flagged and the well data and geophysical logs were examined to determine whether the outliers were due to geological structure or incorrect well data. In cases where a pick was verified and no source of error could be identified, additional picks were made to increase data density in that area. If no geological explanation for the anomaly could be identified after increasing the data density and the magnitude of the anomaly was greater than the expected geological variation for that area, then the data point was removed from the data set. Once initial outliers were either removed or confirmed, the outlier screening process was repeated three times. This iterative process was able to identify increasingly subtle outliers.

8 Modelling Methodology and Results

A modelled structure surface based on the stratigraphic picks made during this study is included to illustrate regional structure on the top of the Belly River Group in the Alberta Plains (Figures 10 and 11). For the regional structure surface, the picks were modelled with Petra® software using the highly connected features (least-squares) method.

The shaded structure map for the top of the Belly River Group illustrates major structural elements in the Alberta Basin. The Belly River Group and overlying strata have been eroded throughout most of southeastern Alberta, where uplift along the Bow Island Arch has occurred (Dawson et al., 1994b, Figure 24.2). Along the east limb of the Alberta Syncline (Figure 11), the dip of the Belly River Group top increases westward towards the foredeep to a regional maximum of approximately 1.7° (100 m per 3.5 km) within the modelled area. It is clear from Figure 11 that the dip of the Belly River Group structure surface is steeper along the southern segment of the Alberta Syncline in the region south of Calgary and extending to the Canada–United States border. Previously published Belly River Group and Bearpaw Formation isopach maps show significant thickening in this region compared to the north (Dawson et al., 1994b, Figures 24.16 and 24.17). The dip of the surface along the east limb of the Alberta Syncline becomes shallower north of Calgary. In east-central Alberta, the dip becomes very gentle (~1º) and, near the Saskatchewan border, the contact between the Belly River Group and the Bearpaw Formation locally dips gently to the east.

Northwest of Lethbridge (Twp. 9–14, Rge. 21–23), structure contour lines show a distinct 'sawtooth' pattern along the eastern limb of the Alberta Syncline (Figure 11, lower left). Geological mapping in this area has revealed evidence of faulting (the Monarch Fault Zone; Figure 11) and offset of geological contacts perpendicular to the regional structural trend of the fold-and-thrust belt (Irish, 1967a, b). Further work is

required on additional surfaces to accurately delineate the subsurface structure of this area and to map the three-dimensional geometry of faults.

A previously unreported, bowl-shaped structural anomaly with an uplifted centre occurs several kilometres west of Bow City (Twp. 17–18, Rge. 17–18; Figure 12). To generate a surface that exactly follows data points, the triangulation method was used to create a structure map. The diameter of the anomaly is approximately 8 km. Low-angle reverse faults, located approximately 100 km to the east of the fold-and-thrust belt, have been mapped at surface along the Bow River north of the anomaly (Irish, 1967a). The central uplift area shown in Figure 12 coincides with a mapped outlier of Belly River Group rocks (Oldman Formation, unsubdivided) that are surrounded by overlying rocks of the Bearpaw Formation. In his report accompanying his geological map of the area (Stewart, 1943), Stewart (1942, p. 3) wrote:

> *One group of faults is mapped on Bow River near Eyremore [Bow City]. There a downfaulted block of the Edmonton [Group] has a vertical stratigraphic displacement of about 300 feet. The strike of the individual faults could only be determined approximately.*

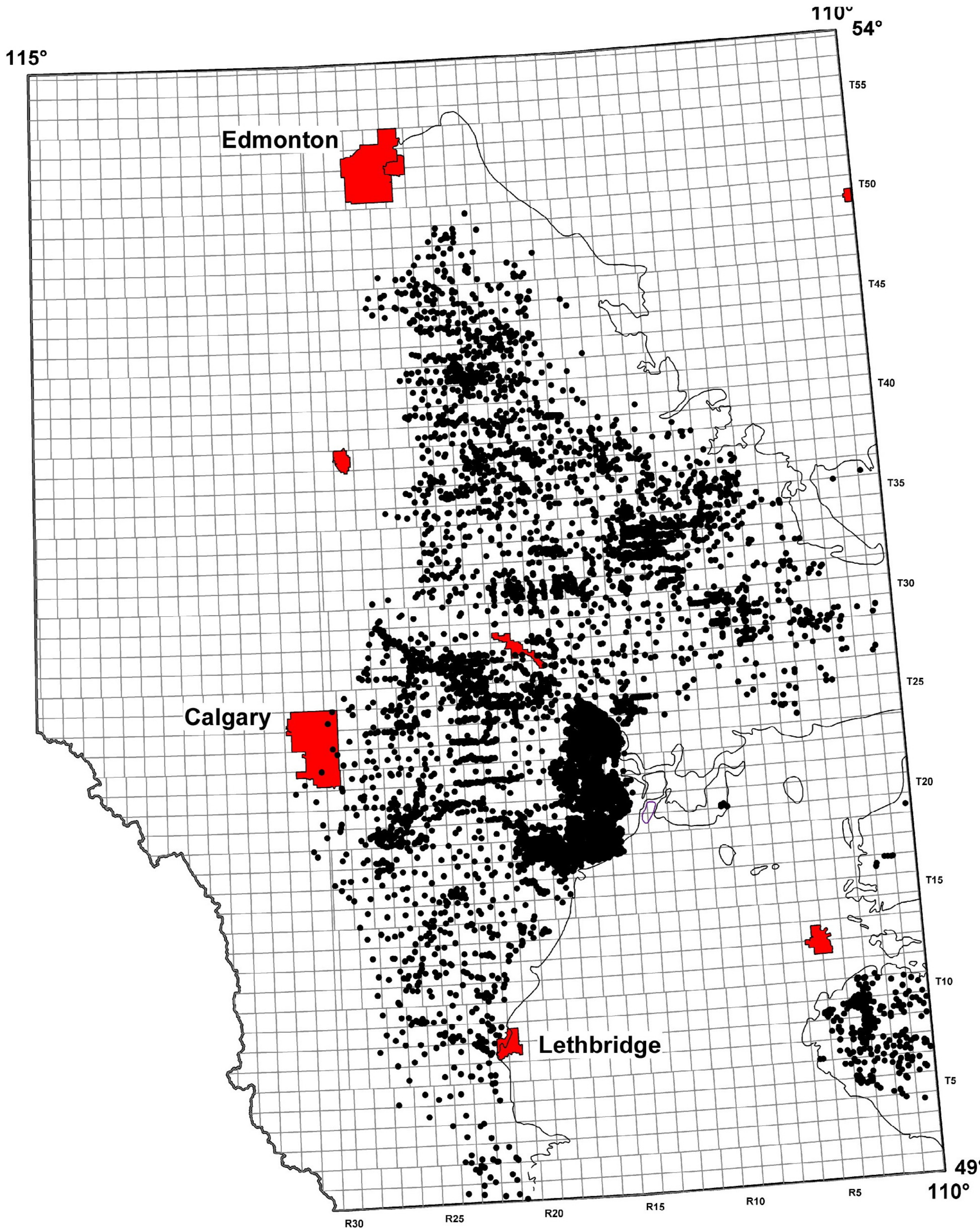


Figure 10. Distribution of the wells used in this project (solid black circles). The map trace for the top of the Belly River Group (modified from Hamilton et al., 1999) is shown as a thin black line. Cities are shown in red.

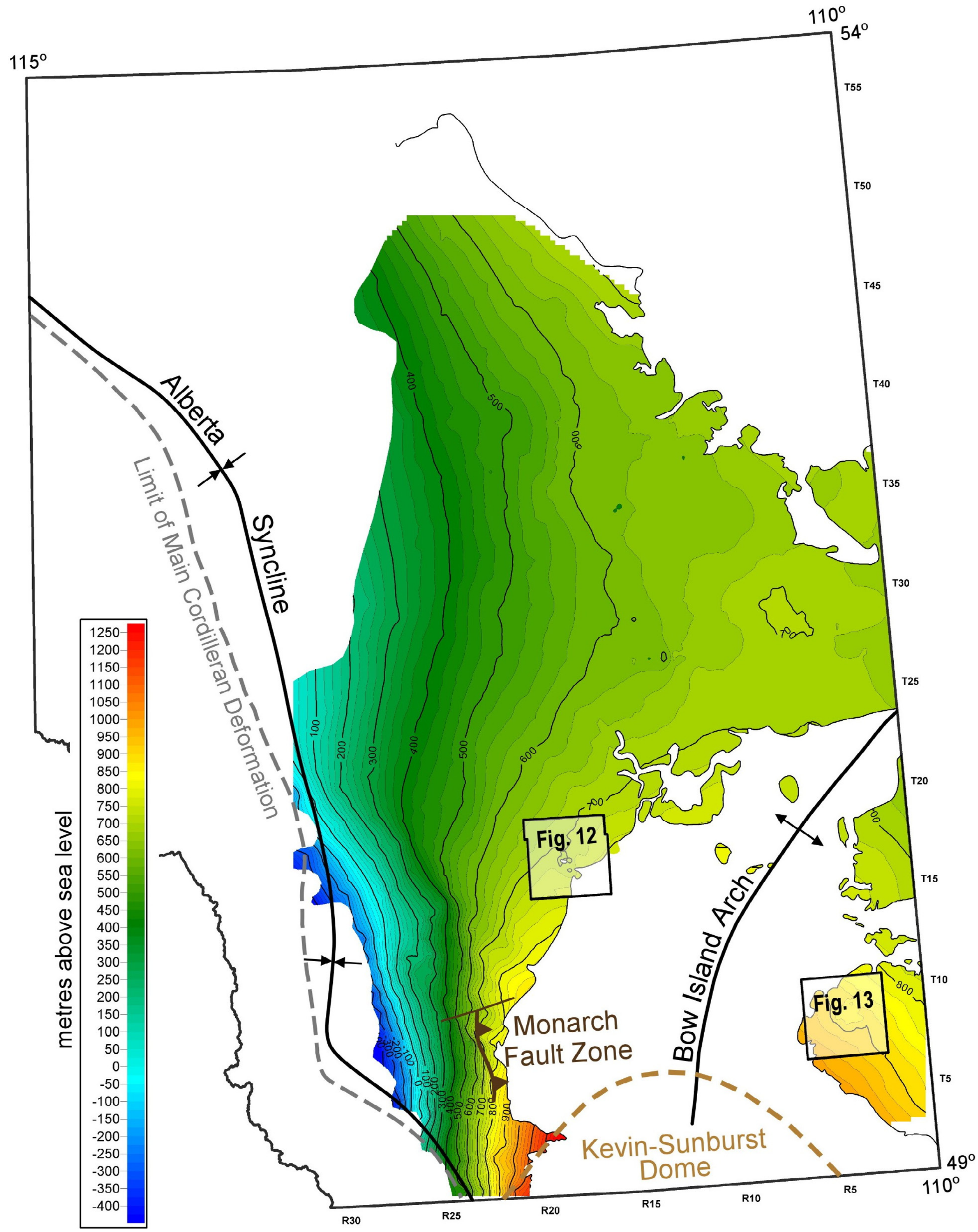


Figure 11. Shaded structure map of the top of the Belly River Group in Alberta. Contour interval is 25 m; contour values are elevation in metres above sea level. The surface is cropped to the surface map trace for the top of the Belly River Group (modified from Hamilton et al., 1999). The locations of Figures 12 (Bow City anomaly) and 13 (Eagle Butte structure) are shown. Structural elements from Wright et al. (1994) and Hamilton et al. (1999).

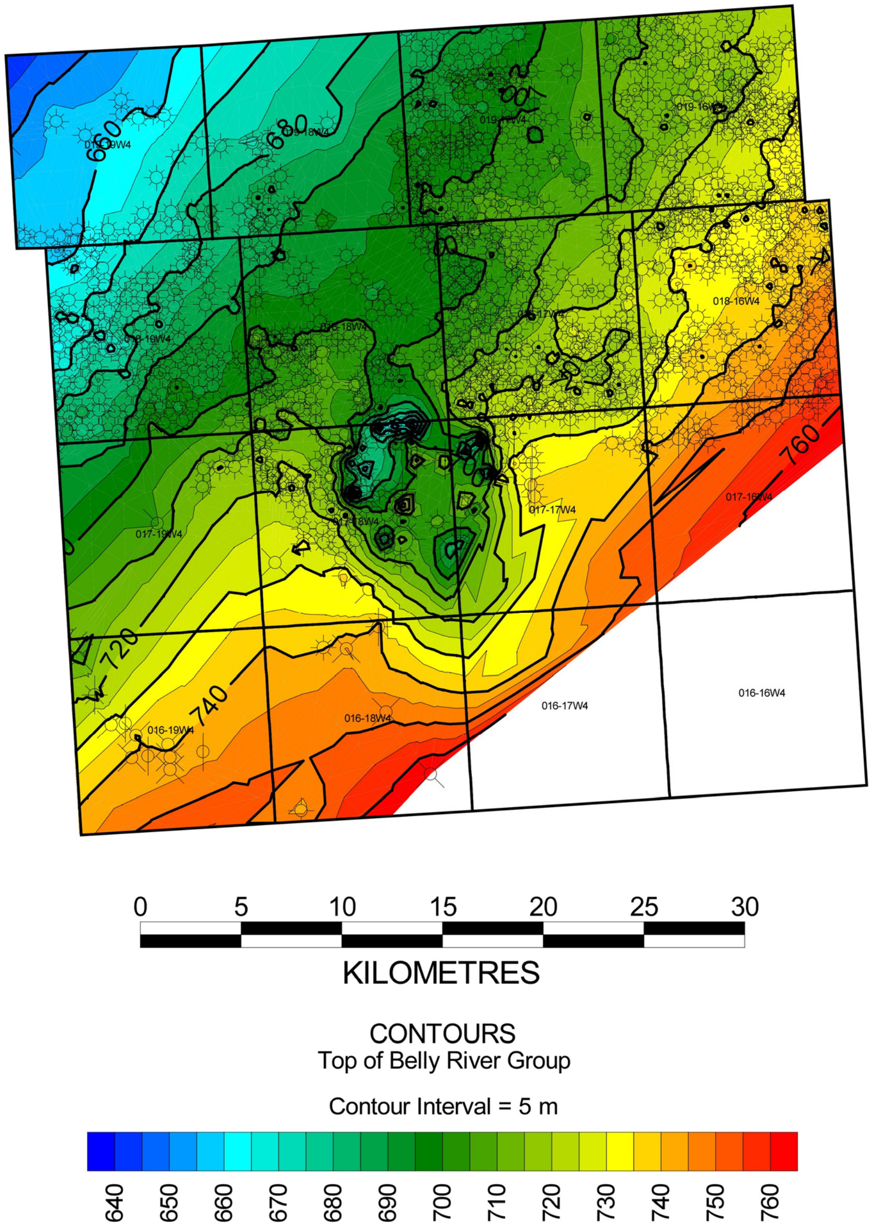


Figure 12. Structure map for the top of the Belly River Group west of Bow City, showing a semicircular anomaly with a central uplift. Contour interval is 5 m. Data were contoured using the triangulated irregular network (TIN), and the modelled surface reflects all data points.

> *A deep well was drilled near Eyremore (SE¼ sec. 26, tp. 17, rge. 18) at a surface elevation of 2,700 feet. It entered Paleozoic limestone at 4,020 feet and reached a total depth of 5,590 feet. Nothing of value was encountered. The well is located on a faulted inlier of the Oldman formation and on beds that, where exposed about a mile to the east of the well, show some steep dips.*

On the map of Irish (1967b), the Edmonton Group beds are not shown and only the inlier of the Oldman Formation is indicated. It is unclear whether Irish rejected Stewart's identification of the Edmonton beds, including them instead within the Oldman Formation, or had some other reason for leaving them out.

Based on the available data, there appears to be evidence of local deformation, including faulting and anomalously steep dips, and uplift of Oldman Formation rocks near the centre of the anomaly.

The size and general shape (including the central uplift) of the Bow City anomaly are similar to those of the Eagle Butte structure, a confirmed impact structure of early Tertiary age (Figure 13; Sawatzky, 1976; Grieve, 2006). The Eagle Butte structure is a complex impact structure, having a central uplift, an annular trough and a structural rim. It is approximately 16 km in diameter; estimates of the magnitude of uplift in the centre range from 575 to 1000 m (Grieve, 2006).

Based on the shape of the structure, which appears to be a circular bowl with an uplifted centre surrounded by a semicircular trough, the documented evidence for faulting and uplift at the surface, and the lack of any known volcanism or salt tectonism in the area, an impact origin for the Bow City anomaly is presently considered the most likely scenario. Additional data are required to confirm or reject this hypothesis.

9 Summary

A new, internally consistent set of 6966 stratigraphic subsurface picks for the top of the Belly River Group was made using geophysical well logs. Well data were screened for potential errors in KB and ground elevation data, as well as for errors in true vertical depth resulting from deviated wells. Local and global outliers were identified using statistical methods and either rejected or confirmed. Additional picks were made to delineate local structure where necessary. A modelled surface shows regional structure on the top of the Belly River Group in Alberta. The data-density and subsurface-mapping techniques employed in this project are sensitive enough to identify local structure, as illustrated by structural anomalies identified northwest of Lethbridge (in the area of the Monarch Fault Zone), and by the identification near Bow City of a previously unreported, bowl-shaped anomaly with a central uplift, possibly a subsurface impact structure.

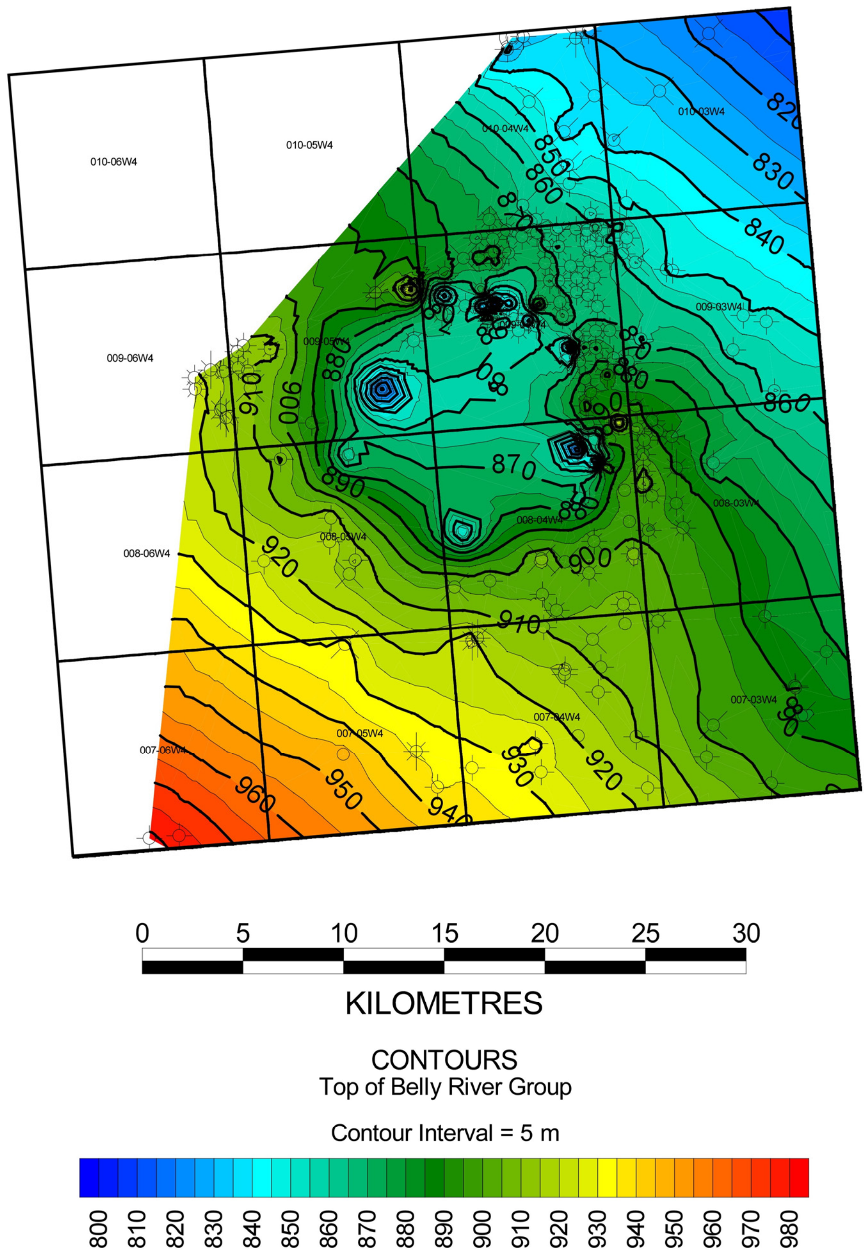


Figure 13. Structure map for the top of the Belly River Group in the region of the Eagle Butte Impact Structure, southwestern Alberta. Contour interval is 5 m. Data were contoured using the triangulated irregular network (TIN), and the modelled surface reflects all data points.

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