ERCB/AGS Open File Report 2011-13

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Energy Resources Conservation Board

Alberta Geological Survey

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P. Glombick

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Alberta Geological Survey
4th Floor, Twin Atria Building
4999 – 98th Avenue
Edmonton, AB  T6B 2X3
Canada

Tel: 780.422.1927
Fax: 780.422.1918
E-mail: AGS-Info@ercb.ca
Website: www.ags.gov.ab.ca

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## Abstract

This report presents documentation to accompany 8799 new subsurface stratigraphic picks released for the top of the Oldman Formation (base of Dinosaur Park Formation) in the Alberta Plains (Townships 1 to 47, Range 1, West 4th Mer. to Range 5, West 5th Mer.) made using wireline geophysical well logs. The stratigraphic picks are published separately (Digital Dataset 2011-0006). Geophysical logs from representative wells are used to illustrate the criteria used to make stratigraphic picks and to highlight regional geological variability. Well data were screened to detect errors resulting from deviated wells or incorrect ground and kelly-bushing elevation data. Statistical methods were used to identify local and regional outliers, which were examined individually and either confirmed or removed from the dataset. A structure contour map for the top of the Oldman Formation is included to illustrate regional structure in the southern Alberta Plains.

# 1 Introduction

Clastic marginal to nonmarine sedimentary rocks of the Upper Cretaceous (Campanian) Belly River Group underlie large areas of central and southern Alberta. Whereas the regional stratigraphic framework of the Belly River Group has been studied during the last two decades (e.g., Eberth and Hamblin, 1993; Hamblin, 1997a, b; Eberth, 2005), the detailed stratigraphy remains poorly defined in many areas, particularly within 200 to 300 m of the surface, as surface casing from oil and gas wells often obscures this shallow interval. Over the past 20 years, however, a dramatic increase in the number of shallow gas and coalbed methane (CBM) wells drilled in the province provides an opportunity to improve the resolution of the stratigraphic framework of the Belly River Group, particularly within the shallow subsurface (0–300 m).

This report, one of several released by the Alberta Geological Survey on the stratigraphy of the Belly River Group (e.g., Glombick, 2010a, b), documents the criteria used to generate a new set of internally consistent subsurface stratigraphic picks and a structure contour map for the top of the Oldman Formation in the Alberta Plains, east of the Cordilleran deformation front. The geology and published literature of the upper Belly River Group is reviewed briefly before describing and illustrating the criteria used to pick the top of the Oldman Formation in this study. Representative downhole geophysical well logs are included for different areas to highlight regional geological variability and the resulting log response across the contact between the Oldman and Dinosaur Park formations. Quality control procedures used in this study—to detect errors in kelly-bushing (KB) and ground elevation data as well as errors in pick elevation (subsea)—are summarized briefly before describing the methods used to model the data.

Readers interested in additional information on the geology of the Belly River Group, specifically the Dinosaur Park and Oldman formations, are directed to the following publications: Dowling (1917), Powers (1931), Russell and Landes (1940), Crockford (1949), Shaw and Harding (1949), Dodson (1971), Given and Wall (1971), McLean (1971), Wall et al. (1971), Speelman and Hills (1980), Wasser (1988), Wood (1989), Eberth and Hamblin (1993), Hamblin and Abrahamson (1996), Hamblin (1997a, b) and Eberth (2005).

# 2 General Stratigraphy

The Belly River Group[1] comprises a westward-thickening clastic sedimentary wedge of paralic to nonmarine rocks deposited within the Western Canada Sedimentary Basin during the Middle to Late Campanian (Figure 1). In southern Alberta, marine mudstone of the Pakowki Formation underlies the Belly River Group (Figures 1 and 2). In central Alberta, the Belly River Group is underlain by marine siltstone and shale of the Lea Park Formation, which are, in part, correlative with the Pakowki Formation in southern Alberta (Figure 1). In east-central Alberta, there exists a complex interfingering between marine mudstone and siltstone of the Lea Park Formation and shallow to marginal marine rocks of the Belly Giver Group resulting from relative base-level fluctuations at the shoreline during deposition of the Belly River Group clastic wedge (Hume and Hage, 1941; Nauss, 1945; Shaw and Harding, 1949; McLean, 1971). Regionally extensive, shallow to marginal marine sandstone members (e.g., Ribstone, Victoria, Brosseau) interfinger with marine tongues of the Lea Park Formation (Grizzly, Vanesti, Mulga).

[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. The term 'Belly River Group' is used in this report. See McLean (1971) and Eberth and Hamblin (1993) for a historical review of the nomenclature of the Belly River Group in Alberta.

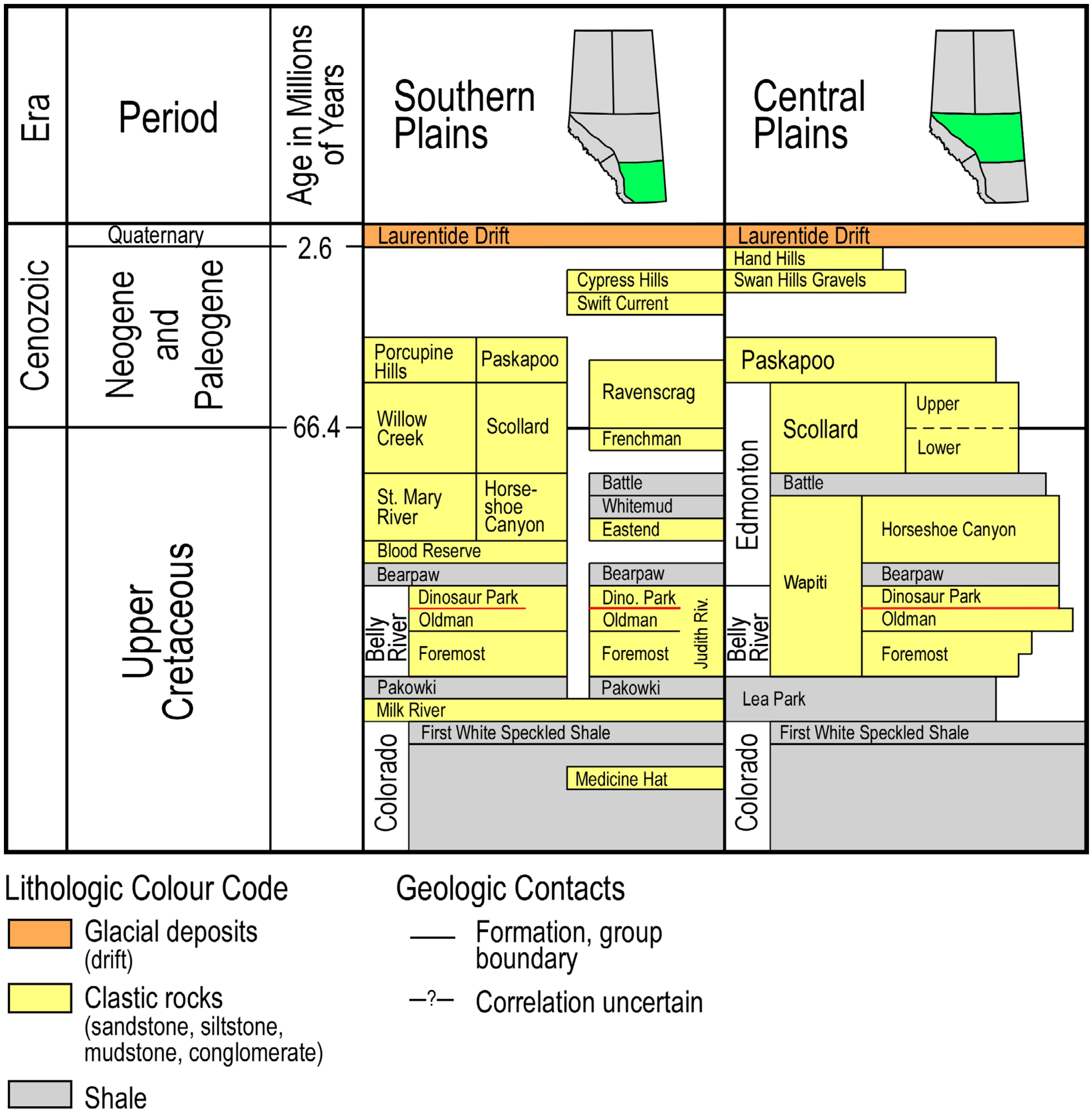


Figure 1. Schematic stratigraphic column showing the distribution of Upper Cretaceous bedrock in southern and central Alberta (modified from Energy Resources Conservation Board, 2009; modifications include the addition of the Dinosaur Park Formation). The red line indicates the stratigraphic contact picked in this report.

The Belly River Group is overlain by marine shale of the Bearpaw Formation, which records rising relative sea level within the Western Canada Sedimentary Basin during the Late Campanian (Caldwell et al., 1993). The northern depositional limit of the Bearpaw Formation coincides with the approximate latitude of the city of Edmonton. North and west of Edmonton, nonmarine clastic rocks, approximately coeval with those of the Belly River Group, the Bearpaw Formation and the Horseshoe Canyon Formation, collectively comprise the Wapiti Formation (Figure 2; Dawson et al., 1994b; Fanti and Catuneanu, 2009).

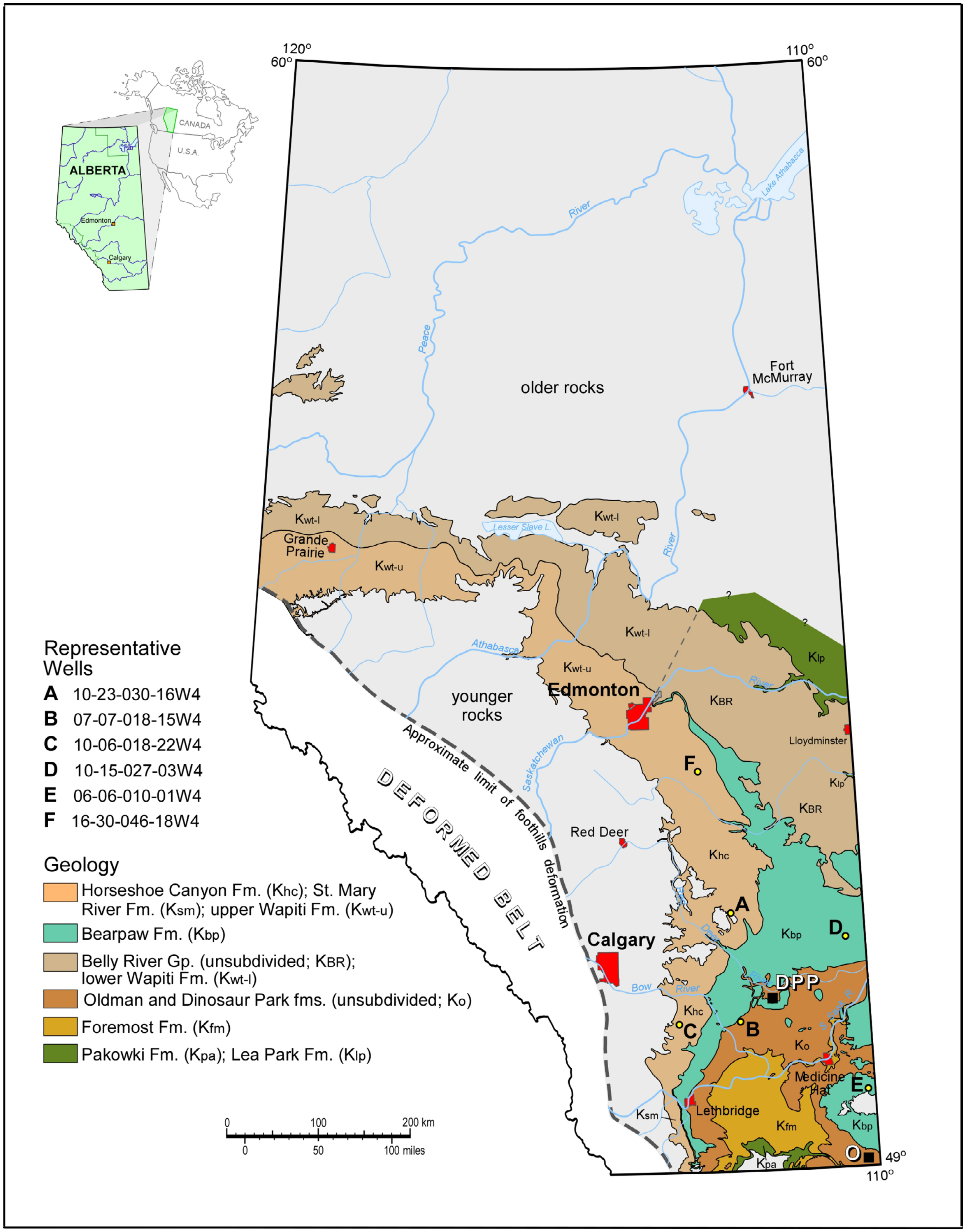


Figure 2. Simplified geological map showing the distribution of Belly River Group and surrounding rocks in central and southern Alberta and location of representative wells (A–F) used in this project (geology modified from Hamilton et al., 1999). Locations of reference sections in Dinosaur Provincial Park (DPP) and village of Onefour (O) also indicated.

Dawson (1883, 1885) first mapped rocks of the Belly River Group in southern Alberta. His ‘Belly River series’ included the presently defined Belly River Group, as well as the underlying Pakowki and Milk River formations (see McLean, 1971, for a detailed review of the so-called ‘Belly River problem’). Dawson subdivided his upper Belly River series into a lower, yellow and sombre-coloured unit, and an upper pale-coloured unit, which he named the ‘Yellowish’ and ‘Pale’ beds, respectively. Dowling (1917) followed Dawson (1885) in recognizing the Yellowish and Pale beds in southern Alberta, but changed the name of the Yellowish beds to the ‘Foremost beds.’ Despite the locally arbitrary and gradational nature of the contact between the Foremost beds and the overlying Pale beds in outcrop (see, for example, Dawson, 1885; Williams and Dyer, 1930; Powers, 1931; Slipper and Hunter, 1931; McLean, 1971), Dowling (1917) was able to differentiate the Foremost and Pale beds in southern Alberta.

Williams and Dyer (1930) suggested that Dawson had intended to include only the marginal-marine to nonmarine rocks situated between the underlying Pakowki Formation and the overlying Bearpaw Formation in his Belly River series. As a result, he proposed that Dawson’s Belly River series be modified from the original definition to include only the Yellowish beds (Foremost) and Pale beds of Dawson (1885). Other workers (e.g., Slipper and Hunter, 1931), however, favoured retaining the original definition of Dawson (1885), despite the nomenclatural problems associated with it.

In their definitive report on the geology of southern Alberta, Russell and Landes (1940) proposed replacing the problematic Belly River series of Dawson (1885) with the Milk River, Pakowki, Foremost and Oldman formations. They followed Dawson (1885) and Dowling (1917) in recognizing the Foremost and Oldman formations, but suggested that the term Pale beds be replaced with the ‘Oldman Formation.’ This usage eventually came to be accepted by most workers.

McLean (1971) reviewed the geology of the Belly River Group and argued that the divisions of Dowling did not constitute mappable units and proposed, therefore, that all rocks situated above the Pakowki (Claggett) Formation and below the Bearpaw Formation should be included within the Judith River Formation.

More recently, based on detailed examination of outcrop, core and well logs in southwestern Alberta, western Saskatchewan and northwestern Montana, Eberth and Hamblin (1993) recognized a regional discontinuity within the Oldman Formation of Dowling (1917). They proposed separating the Oldman Formation into two distinct lithostratigraphic units: the Oldman Formation (restricted) and the overlying Dinosaur Park Formation, named after Dinosaur Provincial Park where the formation is well exposed. In addition, they suggested that the Judith (Belly) River Formation of McLean (1971) be raised to group status, composed of the Foremost, Oldman (restricted) and the Dinosaur Park formations. Eberth and Hamblin (1993) designated the type section of the Dinosaur Park Formation, which is located along the Red Deer River several kilometres downstream of the eastern park boundary (L.S. 9, Sec. 33, Twp. 21, Rge. 10, W 4$^{th}$ Mer. [abbreviated 9-33-21-10W4]). Two reference sections were also designated, an outcrop section occurring near the village of Onefour, Alberta (9-25-2-4W4; Figure 2), and a length of core extending from 24.5 to 52.0 m in Alberta Research Council (ARC) corehole 1-83 (Eberth and Hamblin, 1993) drilled in Dinosaur Provincial Park (1-2-20-12W4; Figure 2).

Hamblin (1997a, b) extended the results of Eberth and Hamblin (1993) into the subsurface of south-central Alberta, but instead adopted ‘Belly River Group’—following the traditional usage of the hydrocarbon industry in Alberta—over the ‘Judith River’ Group, which is used in Montana and Saskatchewan (e.g., Rodgers, 1998) and has historical precedence.

## 3 The Contact Between the Dinosaur Park and Oldman Formations

In outcrop, the primary criteria used to distinguish the Dinosaur Park and Oldman (restricted) formations of Eberth and Hamblin (1993) are sedimentological. The Oldman Formation (restricted) is dominated by fine- to very fine grained sandstone and siltstone, with lesser mudstone. Sandstone bodies are commonly lenticular and fine upwards, with complex internal geometry and limited lateral extent (several to tens of metres; Eberth and Hamblin, 1993). Low-angle and horizontal stratification, trough cross-bedding and ripple laminations are common. Gradational transitions between coarse and fine members (often of limited lateral extent) make delineation of discrete, mappable units difficult. In outcrop, sandstone beds are commonly resistant and weather brownish yellow. Siltstone and mudstone are light grey, greenish grey or yellowish grey. Coal is rare to absent. Evidence of subaerial exposure includes rootlets, burrows, carbonaceous woody material and ganisters (siliceous paleosols).

Based on outcrop and subsurface data in the form of geophysical logs and core, Hamblin (1997b, p. 160) proposed a two-fold division of the Oldman Formation (restricted) into a lower, sandstone-dominated unit, characterized by low gamma-ray values, and an upper siltstone-dominated unit, which he informally named the 'upper siltstone member.' He proposed a correlation between the lower sandstone-dominated unit—mappable on geophysical well logs in the subsurface over much of southern and south-central Alberta (Twp. 5 to 45, Rge. 1, W 4$^{th}$ Mer. to Rge. 2, W 5$^{th}$ Mer.)—with a resistant sandstone unit that crops out near the former town site of Comrey, Alberta (Twp. 1 to 2, Rge. 5 to 7, W 4$^{th}$ Mer.). This sandstone unit, first described and named by Russell and Landes (1940) as the Comrey sandstone, is generally between 2 and 30 m thick (Hamblin, 1997b, p. 160).

The upper siltstone member of Hamblin's (1997b) Oldman Formation (restricted) is characterized by greenish-grey, thinly bedded, noncalcareous bentonitic siltstone, with lesser amounts of light grey, fine- to very fine grained sandstone and minor carbonaceous mudstone. Rootlets, carbonaceous fragments, burrowing traces and shells are present within the fine-grained beds. Individual sandstone beds are typically 1 to 20 cm thick and may exhibit sharp erosional bases, rip-up clasts, trough cross-bedding and ripple laminations (Hamblin, 1997b). Sandstone beds commonly coarsen upwards. Characteristic exposures of the upper siltstone member occur along the Oldman River between Rge. 13 and 19, W 4$^{th}$ Mer. (Hamblin, 1997b, p. 158). The contact between the upper siltstone member and the overlying Dinosaur Park Formation is erosive in nature, with several metres of relief visible in outcrop.

The lower Dinosaur Park Formation is dominated by fine- to medium-grained lithic arenite, commonly organized into multi-storied sheets. Trough cross-bedding, inclined stratification and inclined heterolithic stratification are common within the coarse-grained members, which are generally both fining and thinning upwards in nature. Carbonaceous drapes and ironstone are common. Extraformational pebbles and cobbles, composed of grey to black chert, quartzite and rare metamorphic rock fragments, are often present within the lower 20 m of the Dinosaur Park Formation. Laterally extensive siltstone and mudstone enclose multi-storied sandstone sheets. Siltstone increases in abundance upwards, becoming dominant within the upper half. Sandstone beds commonly weather a pale grey to brownish grey, whereas mudstone and siltstone weather greenish grey, brownish grey or brown.

Coal is commonly present within the upper half of the Dinosaur Park Formation, particularly near the upper contact. In the Lethbridge area, where this coal occurs in a zone up to 25 m thick and has been mined commercially, this zone is informally known as the Lethbridge coal zone. Over much of southern and central Alberta, the Lethbridge coal zone is typically thinner (a few metres thick) or even absent, although some carbonaceous material is usually present in the upper 10 m of the Dinosaur Park Formation. Coal seams within the Lethbridge coal zone are typically thin, tens of centimetres to several metres thick, and are interbedded with very fine grained sandstone, siltstone, bentonite and carbonaceous mudstone. Locally, shell hash, coquina or chert pebbles are present at the contact between the Dinosaur Park Formation and overlying Bearpaw Formation.

Eberth and Hamblin (1993) investigated the compositional differences between sandstones of the Oldman (restricted) and Dinosaur Park formations using 19 sandstone samples taken from ARC corehole 1-83 over a length of 120 m. In the Oldman Formation (restricted), sandstone is dominated by quartz grains

(20–60%), with abundant reworked calcite grains (up to 15%), less than 2% volcanic rock fragments and plagioclase feldspar/potassium feldspar ratios of 1.0 to 2.5 (Eberth and Hamblin, 1993, Figure 6). The Dinosaur Park Formation is comparatively richer in volcanic rock fragments (~7%), contains less quartz (~26%) and calcite grains (~1%), with a plagioclase feldspar/potassium feldspar ratio of about 2.0. Abundant smectite is present in the matrix of sandstones above the discontinuity, but it is rare below (Eberth and Hamblin, 1993, p. 179).

Eberth and Hamblin (1993) and Hamblin (1997a, b) mapped the discontinuity between the Oldman and Dinosaur Park formations along the Red Deer, Oldman, Bow and South Saskatchewan rivers in southern Alberta. Where there was some uncertainty in outcrop sections with respect to the exact stratigraphic position of the contact, Eberth and Hamblin (1993, p. 177) placed the contact at the base of the lowermost sandstone that exhibited the typical characteristics of the Dinosaur Park Formation.

In the subsurface, Hamblin (1997b) mapped the contact between the upper siltstone member of the Oldman Formation and the Dinosaur Park Formation over much of south-central Alberta (Twp. 5 to 45, Rge. 1, W $4^{th}$ Mer. to Rge. 7, W $5^{th}$ Mer.) using downhole geophysical well logs from oil and gas wells. In large areas of south-central and east-central Alberta, the contact is often situated within 200 m of the surface, an interval that is commonly cased in oil and gas wells and is therefore not logged. Near the northern limit of the area mapped by Hamblin (1997b), near Twp. 45, a facies change within the upper Oldman Formation or the overlying Dinosaur Park Formation makes recognition of the contact between the upper siltstone member and the overlying Dinosaur Park Formation difficult or impossible, as the upper siltstone member and/or the basal Dinosaur Park Formation sandstone are missing or difficult to recognize.

In southwestern Alberta and northern Montana, near the type locality of the Judith River Group, Eberth and Hamblin (1993, p. 183) described the difficulty in identifying the contact between the Oldman and Dinosaur Park formations, as the upper Belly River Group sediments (possibly correlative to the Dinosaur Park Formation) are similar in nature to those of the Oldman Formation:

> *The discontinuity and overlying Dinosaur Park Formation are not present in exposed sections of the Judith River Group near Lethbridge, along the flanks of the Milk River Ridge, or in the exposures of the Two Medicine Formation in northwestern Montana. In these areas the entire interval between the Taber and Lethbridge coal zones comprises Oldman Formation facies. At present, our data are equivocal regarding the presence of absence of the Dinosaur Park Formation in the type area of the Judith River Group along the Missouri River east of Judith Landing, Montana. If present, the unit is restricted to the uppermost 10-20 m of the formation in that area.*

Although the observations of Eberth and Hamblin (1993) in southwestern Alberta and northern Montana call into question the possibility of subdividing the Oldman Formation (*sensu* Russell and Landes, 1940) into the Oldman and Dinosaur Park formations, Jerzykiewicz (1997) correlated the Drywood Creek Formation—occurring within the foothills of southwestern Alberta near the town of Lundbreck—with the Dinosaur Park Formation based on the occurrence of a coal zone near the contact with the overlying Bearpaw Formation and the occurrence of freshwater to brackish fauna within the Drywood Creek Formation. The brackish conditions recorded in the Drywood Creek Formation are similar to those recorded within the rocks of the Dinosaur Park Formation, as opposed to the Oldman Formation, which is fully nonmarine. The Drywood Creek Formation is composed of dark grey to black, organic-rich mudrock, bentonite, coaly shale and coal (Jerzykiewicz and Norris, 1994). The difficulty of recognizing the contact between the Dinosaur Park and the Oldman (restricted) formations along the Oldman River north of Lethbridge and near the Milk River ridge, despite the presence of the Lethbridge coal zone in that area, suggests that further work is required to test the validity of the correlation between the Drywood Creek and Dinosaur Park formations in southwestern Alberta.

In areas where the Oldman (restricted) and Dinosaur Park formations are lithologically similar or where the upper siltstone member of the Oldman Formation (restricted) cannot be identified—either in the subsurface or at the surface—rocks of the upper Belly River Group cannot be subdivided according to the criteria defined by Eberth and Hamblin (1993). Where this is the case, in this report, these rocks are referred to as upper Belly River Group (undivided) and are equivalent to the Oldman Formation as defined by Russell and Landes (1940). In the remainder of this report, the Oldman Formation refers to the Oldman Formation, in the restricted sense, of Eberth and Hamblin (1993).

Isopach maps and paleocurrent indicator data suggest that the Oldman Formation was probably sourced from the south or southwest, whereas the overlying Dinosaur Park Formation was probably sourced from the northwest (Eberth and Hamblin, 1993; Hamblin, 1997a, b). The temporal and spatial relationship between these distinct clastic wedges at the basin scale has yet to be determined. One interpretation is that the discontinuity between the Oldman and Dinosaur Park formations is time-transgressive from north to south, and there is a relatively little time gap across the discontinuity (Eberth and Hamblin, 1993, Figure 19b). In this scenario, the deposition of the lower Dinosaur Park Formation beds in the north was coeval with the deposition of the upper Oldman Formation beds (the upper siltstone member) in the south. An alternate explanation is that the discontinuity results from a regionally significant base-level fall and that the Dinosaur Park Formation is, in entirety, younger than the Oldman Formation (Eberth and Hamblin, 1993, Figure 19a). The second scenario requires a greater time gap across the discontinuity than the first. The resolution of existing geochronological, stratigraphic and paleontological data is insufficient to distinguish between these alternatives, but in any case, the contact between the Oldman and Dinosaur Park formations in south-central Alberta may be erosional, or it may reflect the partial overlap of two distinct clastic wedges shed from the fold-and-thrust belt.

# 4 Picking Criteria

Based on the study of three cored intervals (Eberth and Hamblin, 1993) spanning the discontinuity (ARC corehole 1-83; Canadian Pacific Oil and Gas [CPOG] Strathmore, 7-12-25-25W4; Fina Dome Farrow, 6-36-20-25W4), Eberth and Hamblin (1993, p. 182–183) defined the criteria used to identify the contact between the Oldman Formation and the overlying Dinosaur Park Formation using geophysical logs (Figures 3 and 4):

> *Examination of geophysical-log data across the discontinuity, including spontaneous potential, resistivity, density, neutron, and gamma ray, has shown that the gamma ray best discriminates the contact between the Oldman and Dinosaur Park formations in the subsurface... In each case, gamma ray shows an interval of strong peaks at the top of the Oldman Formation followed by an abrupt leftward deflection [decrease in gamma ray units] across the discontinuity. Because gamma-ray peaks in the Dinosaur Park Formation rarely match or exceed those marking the top of the Oldman Formation, we place the discontinuity on geophysical logs at the first major leftward gamma-ray deflection following a maximum gamma-ray peak or a series of peaks between the Taber and Lethbridge coal zones. In accordance with our procedure of recognizing the discontinuity in outcrop, this places the discontinuity at the base of the first sandstone member in the uppermost sequence with low gamma-ray peaks.*

The above passage highlights two important points: 1) the best log in which to consistently recognize the internal stratigraphic subdivision of the upper Belly River Group is the gamma-ray log; and 2) the radioactive spikes in the upper siltstone member are the most recognizable feature on logs. The siltstone and sandstone beds within the siltstone unit of the Oldman Formation are relatively radioactive compared with the overlying basal sandstone beds of the Dinosaur Park Formation. Indeed, the top of the siltstone unit is best picked using the gamma-ray log exclusively, and other logs, such as density and neutron porosity and resistivity, are unreliable in locating the position of the contact.

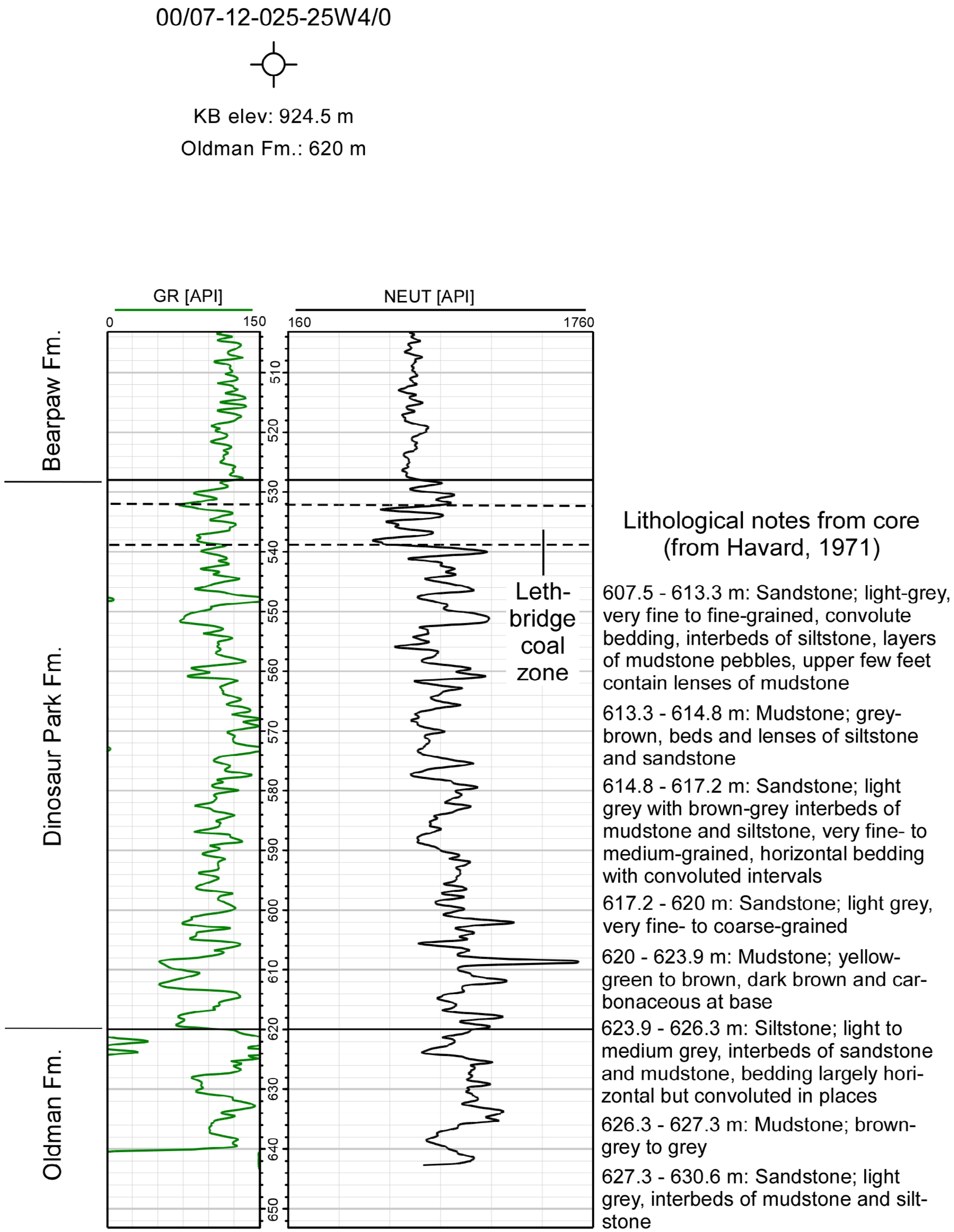


Figure 3. Comparison between gamma-ray (GR in API units) and neutron (NEUT in API units) logs for Canadian Pacific Oil and Gas (CPOG) Strathmore well 00/07-12-025-25W4/0, south-central Alberta. Location of contact between the Oldman and Dinosaur Park formations (from Eberth and Hamblin, 1993) based on core (descriptions from Havard, 1971). Kelly-bushing (KB) elevation given is in metres above sea level. Vertical log scale is measured depth (in metres) below KB. Other abbreviations: elev, elevation; Fm, Formation.

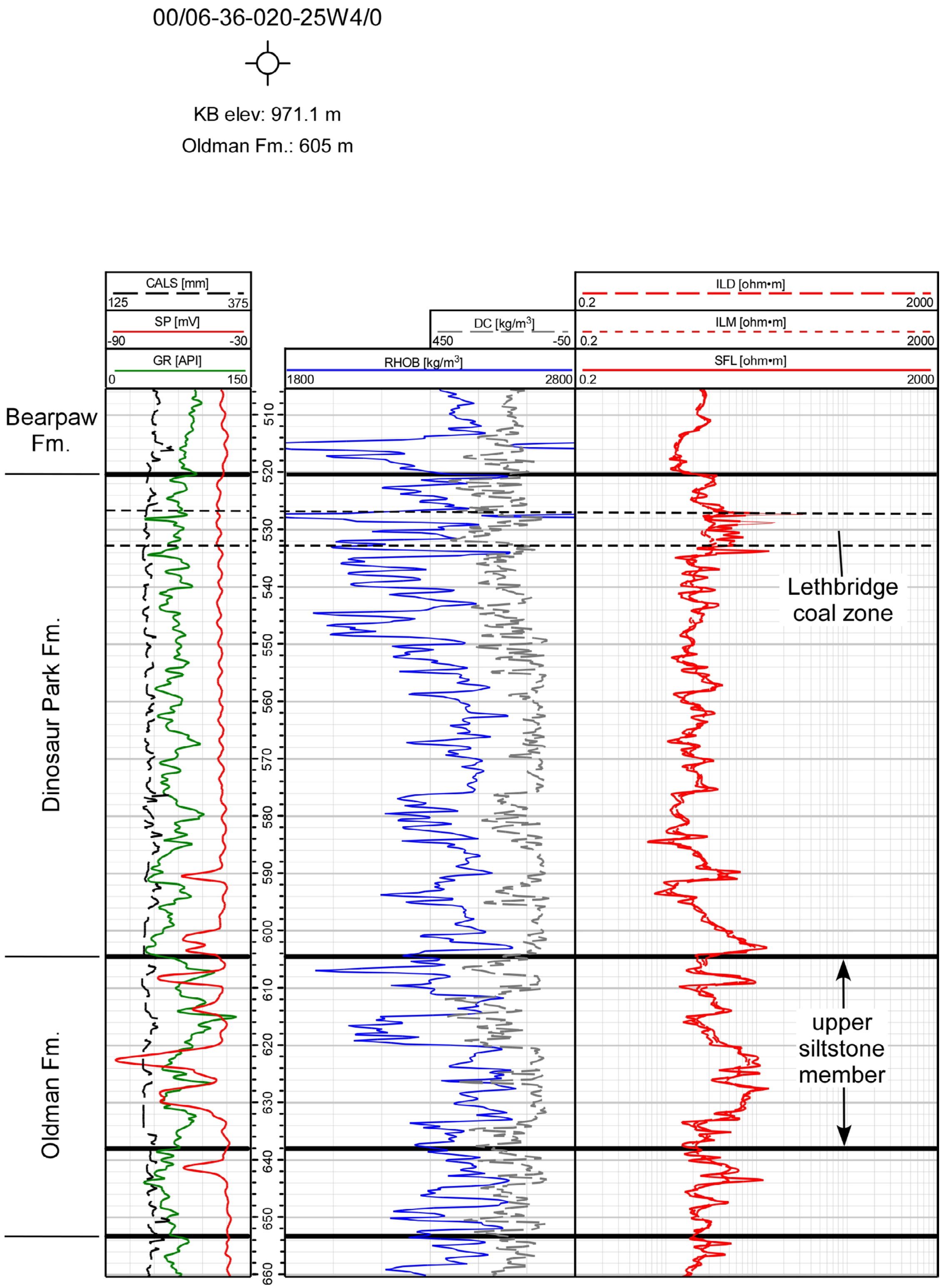


Figure 4. Caliper (CALS in mm), spontaneous-potential (SP in mV), gamma-ray (GR in API units), density correction (DC in kg/m³), bulk density (RHOB in kg/m³), deep induction (ILD in ohm•m), medium induction (ILM in ohm•m) and spherically focused (SFL in ohm•m) logs for Fina Dome Farrow well (00/06-36-020-25W4/0), south-central Alberta. Picks from Eberth and Hamblin (1993) based on core. Kelly-bushing (KB) elevation given is in metres above sea level. Vertical log scale is measured depth (in metres) below KB. Other abbreviations: elev, elevation; Fm, Formation.

Recognition of the upper siltstone member of Hamblin (1997b) is critical in picking the base of the Dinosaur Park Formation and the top of the Oldman Formation. Indeed, if the spiky radioactive peaks of the siltstone unit cannot be recognized on logs, then the Dinosaur Park and Oldman formations cannot be reliably differentiated in the subsurface using well logs. Where the lower Dinosaur Park Formation is radioactive on the gamma-ray log, such as in mudstone or bentonite-rich intervals, using the criteria defined by Eberth and Hamblin (1993) to define the top of the Oldman Formation may erroneously lead to the inclusion of lower Dinosaur Park Formation beds within the siltstone unit of the upper Oldman Formation. This may yield an anomalous thickness of the Oldman Formation within that well. The potential for this problem increases in central Alberta (approximately north of Twp. 45), where the upper siltstone member of the Oldman Formation thins and becomes less radioactive on the gamma-ray log compared with basal beds of the overlying Dinosaur Park Formation, making the discontinuity between the two formations difficult to identify. In addition, the basal beds of the Dinosaur Park Formation in central Alberta become increasingly radioactive on the gamma-ray log, possibly from increasing amounts of bentonite and mudstone, making the contact difficult to place with certainty.

# 5 Representative Wells

Representative wells illustrate the characteristic log response across the contact between the Oldman and Dinosaur Park formations in six different areas of Alberta and provide examples of the criteria used to make the picks during this study. See Figure 2 for the location of representative wells. For a guide to the use of unique well identifiers (UWI) in Alberta, see Energy Resources Conservation Board Directive 59 (Energy Resources Conservation Board, 2007, Appendix 2, p. 24).

Although representative logs are a useful tool to illustrate the generalized log response of a unit contact, like any nonmarine to marginal marine succession of clastic sedimentary rocks, the Belly River Group is characterized by significant lateral and vertical heterogeneity from the bed to the regional scale. The representative logs, therefore, are examples where the upper siltstone member is generally well developed for that area and the contact with the overlying Dinosaur Park Formation is clearly recognizable. In any given area, there exists significant lithological heterogeneity, and, in certain wells, the contact may be difficult or impossible to identify (see Section 6).

## 5.1 Representative Well for South-Central Alberta (UWI 02/10-23-030-16W4/0)

A typical geophysical log response for the upper Oldman Formation and the lower Dinosaur Park Formation in south-central Alberta is shown in Figure 5. Variable, but overall high, gamma-ray values are typical of the upper siltstone member, which shows a ‘spiky’ response on the gamma-ray log (400–373 m). Three particularly radioactive (90–150 API) intervals, each 5 to 12 m thick, are present (at 400–395 m, 392–386 m, 382–373 m), separated by two 4 to 6 m thick intervals with gamma-ray values between 75 and 105 API. This ‘splitting’ of the upper siltstone member of the Oldman Formation into two or three particularly radioactive zones separated by one or more less radioactive intervals is common in south-central Alberta. The radioactive zones within the upper siltstone member are generally characterized by higher gamma-ray values than mudstone and bentonite-rich radioactive units present within the lower Dinosaur Park Formation.

The upper limit of the Oldman Formation is placed, according to the criteria of Eberth and Hamblin (1993, p. 182–183), at a depth of 373 m, where the gamma-ray log shows a sharp leftward deflection upwards, from values characteristic of the siltstone unit in this area (105–150 API) to values more typical of the lower Dinosaur Park Formation (60–105 API). Whereas the density porosity log shows a sharp deflection to the left moving upwards across the contact in this particular well, this response is not typical, and other logs are typically of little or no use in picking the top of the Oldman Formation.

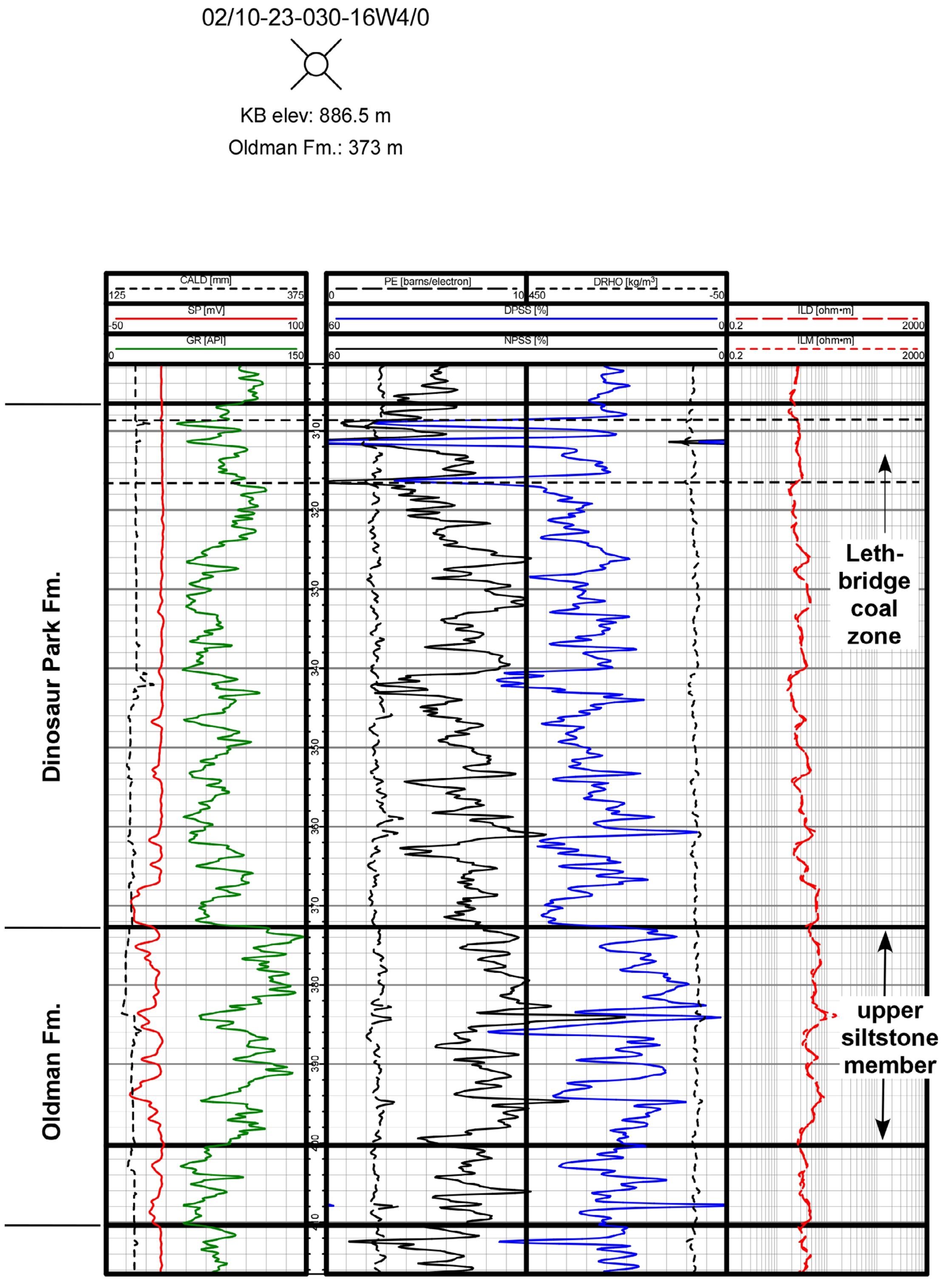


Figure 5. Representative well for south-central Alberta (02/10-23-030-16W4/0). Logs shown are caliper (CALD in mm), spontaneous-potential (SP in mV), gamma ray (GR in API units), photoelectric factor (PE in barns/electron), density correction (DRHO in kg/m$^3$), density-porosity (sandstone; DPSS in %), neutron-porosity (sandstone; NPSS in %), deep induction (ILD in ohm•m) and medium induction (ILM in ohm•m). Kelly-bushing (KB) elevation given is in metres above sea level. Vertical log scale is measured depth (in metres) below KB. Other abbreviations: elev, elevation; Fm, Formation.

## 5.2 Representative Well for Southern Alberta (UWI 02/07-07-018-15W4/0)

In southern Alberta, the contact between the Dinosaur Park and Oldman formations is relatively easy to pick, as the upper siltstone member is recognizable in most wells. In well 02/07-07-018-15W4/0, for instance, the upper siltstone member is present between 149 and 121 m depth. The upper siltstone member comprises three different distinctly radioactive intervals (gamma-ray values ranging from 90–150 API), each interval between 5 and 9 m thick, interbedded with less radioactive units (gamma-ray values ranging from 75–90 API), with thicknesses between 4 and 6 m (Figure 6). The variability in gamma-ray values within the upper siltstone member in well 02/07-07-018-15W4/0, the representative well for southern Alberta, can also be observed in the upper siltstone member present within the representative well shown for south-central Alberta (Figure 5), where three radioactive intervals are separated by two less radioactive intervals. The less radioactive intervals within the upper siltstone member are typically 15 to 30 API units more radioactive than the underlying sandy beds present within the lower Oldman Formation (Comrey sandstone of Hamblin, 1997a, b), as well as the basal sandstones within the overlying Dinosaur Park Formation, which commonly yield minimum values in the 45 to 60 API range.

Just below the contact between the Oldman and Dinosaur Park formations in this well, there is a particularly radioactive layer with API values of up to 150 API. At the contact, the gamma-ray log shows the characteristic sharp leftward deflection upwards across the contact to values more typical of the lower Dinosaur Park Formation (60–75 API). Although the resistivity log shows an increase in resistivity upwards across the contact, this response is by no means universal, and instances of the reverse trend or no change at all can be observed in other wells. The same can be said for the spontaneous-potential (SP) log, which also shows a slight change upwards across the contact in this particular well, but is not generally useful for picking the location of the contact.

## 5.3 Representative Well for Southwestern Alberta (UWI 00/10-06-018-22W4/0)

In well 00/10-06-018-22W4/0, the siltstone unit of Hamblin (1997b) is well developed, showing consistent highly radioactive values (90–150 API) between 508 and 474 m (Figure 7). Low-radioactivity zones within the upper siltstone member are confined to thin (1–2 m) intervals. This gives a spiky appearance to the gamma-ray log in the upper siltstone member, showing what is likely vertical metre-scale (and possibly less) geological variability within the upper siltstone member (cf. Hamblin, 1997b, Figures 10 and 11). The contact between the Oldman and Dinosaur Park formations is easily recognized at 474 m, where a sharp leftward deflection is observed upwards across the contact. This response is characteristic of the contact in this area—interpreted as a discontinuity (Eberth and Hamblin, 1993; Hamblin, 1997b)—which is sharp in both core and outcrop.

## 5.4 Representative Well for East-Central Alberta (UWI 00/10-15-027-03W4/0)

Figure 8 shows a representative well for east-central Alberta. The upper siltstone member is still recognizable, but is less radioactive and therefore less distinct compared with south-central Alberta. The top of the upper siltstone member occurs at a depth of 198 m and the contact is abrupt on the gamma-ray log (Figure 8). The base of the upper siltstone member, however, is less distinct and somewhat gradational in nature, occurring at an approximate depth of 224 m, depending on the gamma-ray cut-off that is used. There are three radioactive zones within the upper siltstone member, becoming less radioactive with increasing depth. The uppermost radioactive zone, occurring at a depth of 203 m, has peak values of approximately 150 API. Between 202 and 198 m, gamma-ray values fall from 150 API to between 105 and 120 API, before dropping at the contact (198 m) to values typical of the Dinosaur Park Formation (60–75 API) in this area.

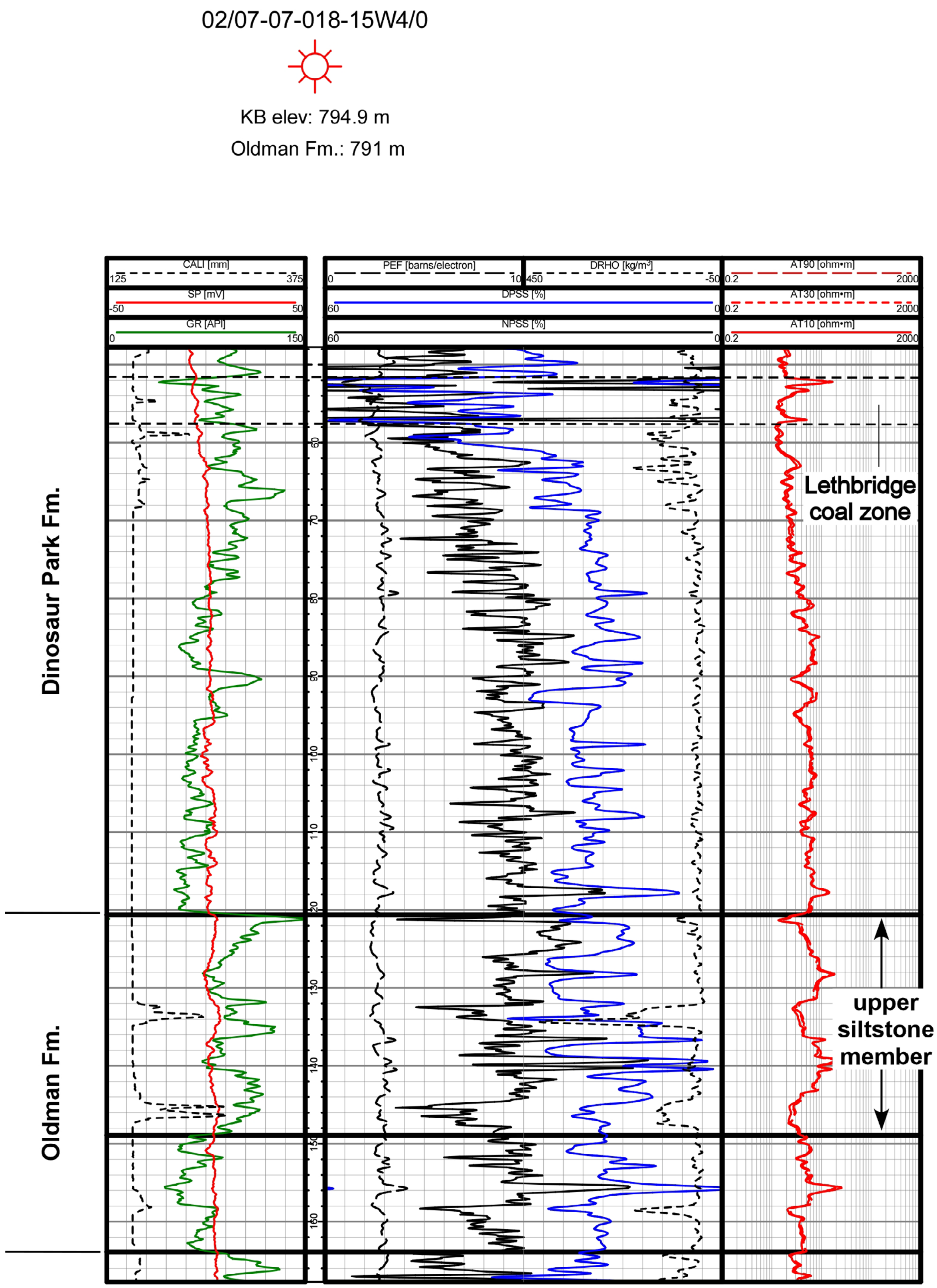


Figure 6. Representative well for southern Alberta (02/07-07-018-15W4/0). Logs shown are caliper (CALI in mm), spontaneous-potential (SP in mV), gamma ray (GR in API units), photoelectric factor (PEF in barns/electron), density correction (DRHO in kg/m$^3$), density-porosity (sandstone; DPSS in %), neutron-porosity (sandstone; NPSS in %), deep resistivity (AT90 in ohm•m), medium resistivity (AT30 in ohm•m) and shallow resistivity (AT10 in ohm•m). Kelly-bushing (KB) elevation given is in metres above sea level. Vertical log scale is measured depth (in metres) below KB. Other abbreviations: elev, elevation; Fm, Formation.

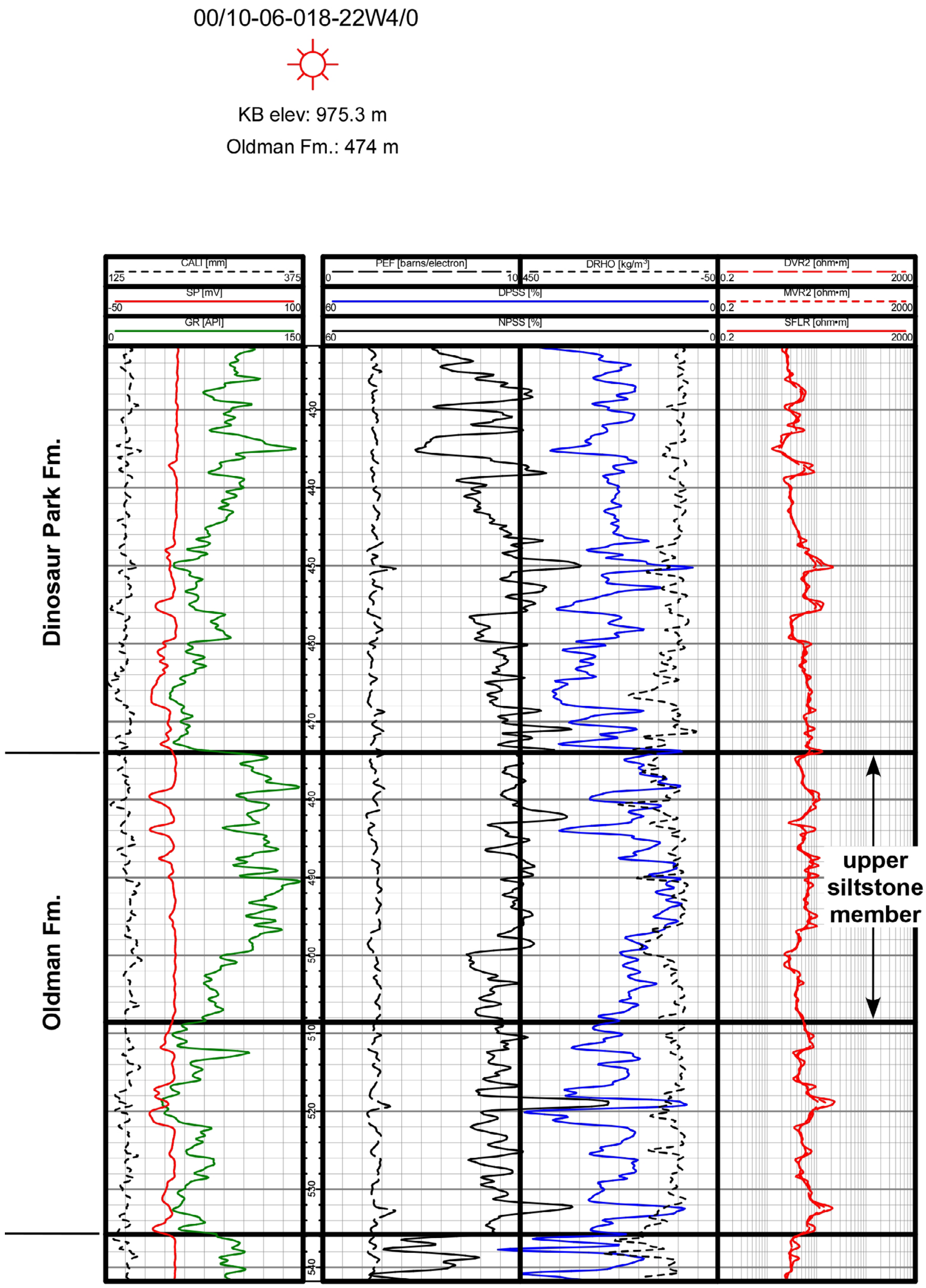


Figure 7. Representative well for southwestern Alberta (UWI 00/10-06-018-22W4/0). Logs shown are caliper (CALI in mm), spontaneous-potential (SP in mV), gamma ray (GR in API units), photoelectric factor (PEF in barns/electron), density correction (DRHO in kg/m³), density-porosity (sandstone; DPSS in %), neutron-porosity (sandstone; NPSS in %), deep resistivity (DVR2 in ohm•m), medium resistivity (MVR2 in ohm•m) and spherically focussed (SFLR in ohm•m). Kelly-bushing (KB) elevation given is in metres above sea level. Vertical log scale is measured depth (in metres) below KB. Other abbreviations: elev, elevation; Fm, Formation.

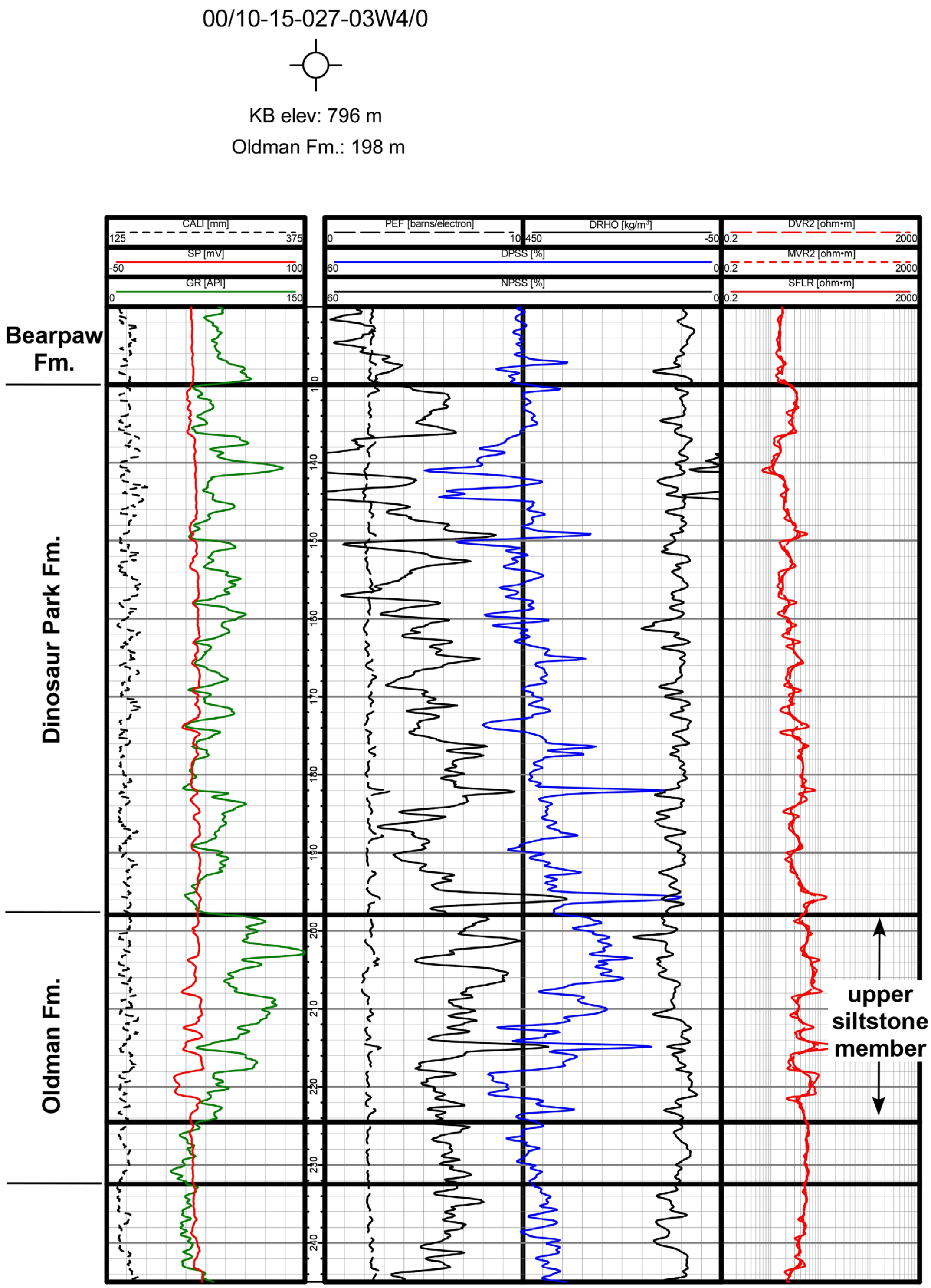


Figure 8. Representative well for east-central Alberta (UWI 00/10-15-027-03W4/0). Logs shown are caliper (CALI in mm), spontaneous-potential (SP in mV), gamma ray (GR in API units), photoelectric factor (PEF in barns/electron), density correction (DRHO in kg/m³), density-porosity (sandstone; DPSS in %), neutron-porosity (sandstone; NPSS in %), deep resistivity (DVR2 in ohm•m), medium resistivity (MVR2 in ohm•m) and spherically focussed (SFLR in ohm•m). Kelly-bushing (KB) elevation given is in metres above sea level. Vertical log scale is measured depth (in metres) below KB. Other abbreviations: elev, elevation; Fm, Formation.

Although three radioactive zones are present within the upper siltstone member in well 00/10-15-027-03W4/0, the member in east-central Alberta shows significant variability with respect to the thickness and number of radioactive zones. In general, at least one ‘spiky’ radioactive interval with peak values of between 120 and 150 API can be identified. The base of the Dinosaur Park Formation is picked, according to the criteria established by Eberth and Hamblin (1993), at the base of the first interval characterized by a sharp drop in radioactivity to values more typical of the Dinosaur Park Formation.

### 5.5 Representative Well for Southeastern Alberta (UWI 00/06-06-010-01W4/0)

In the representative well for southeastern Alberta, the contact between the upper siltstone member of the Oldman Formation and the overlying Dinosaur Park Formation is placed at a depth of 307 m. At this point, there is a sharp leftward deflection on the gamma-ray log to lower values of 30 to 60 API, moving upwards from approximately 307 to 297 m (Figure 9). This 10 m thick interval, interpreted as a sandstone-rich interval present within the lower Dinosaur Park Formation, is overlain by more radioactive rocks with gamma-ray values similar to those of the upper siltstone member of the Oldman Formation in this area. Where the lower sandstone-rich interval is not present or poorly developed in this area, recognition of the contact between the Oldman and Dinosaur Park formations becomes problematic.

### 5.6 Representative Well for Central Alberta (UWI 00/16-30-046-18W4/0)

In well 00/16-30-046-18W4/0, located within central Alberta, the upper siltstone member is well developed, with two distinct, highly radioactive intervals (150–180 API) situated between 227 and 207 m (Figure 10). The contact with the overlying Dinosaur Park Formation occurs at 207 m, where there is a sharp, leftward deflection on the gamma-ray log to values characteristic of the lower Dinosaur Park Formation in this area (75–90 API).

## 6 Mappable Limits of the Dinosaur Park Formation

Although Eberth and Hamblin (1993) and Hamblin (1997a, b) were able to map the discontinuity between the Oldman and Dinosaur Park formations using outcrop and well logs over much of south-central Alberta, the discontinuity becomes increasingly difficult to map in several areas of the province. The well distribution shown in Figure 11 reflects the mappable limits of the Dinosaur Park Formation.

West of approximately Rge. 21, W 4$^{th}$ Mer. and north of Twp. 34, there is a gradual change in the character of the siltstone unit of the Oldman Formation and placing the contact between the Oldman and Dinosaur Park formations becomes increasingly difficult, even using closely spaced cross-sections. Some of this difficulty may reflect the inherently heterogeneous character of nonmarine fluvial sedimentary rocks. Nevertheless, the upper siltstone member appears to thin westwards and northwards and loses its characteristic highly radioactive signature on the gamma-ray log. As a result, the Oldman and Dinosaur Park formations are difficult to differentiate using geophysical well logs in this area. Locally, the upper siltstone member appears to be absent whereas in other places the upper siltstone member appears to split into an upper and lower member separated by a less radioactive interval, 4 to 10 m thick. In addition, the Belly River Group becomes increasingly coarse grained to the west, as the distance to the sediment source decreases. This may account, at least in part, for the gradual loss of the fine-grained, radioactive, upper siltstone member facies that is easily recognizable using the gamma-ray log.

Approximately north of Twp. 45 (and east of Rge. 21, W 4$^{th}$ Mer.), the upper siltstone member thins and becomes less radioactive compared with areas to the southeast. Maximum gamma-ray values within the upper siltstone member are comparable with radioactive intervals in the overlying Dinosaur Park Formation. As a result, the Oldman and Dinosaur Park formations appear increasingly similar on the gamma-ray log and cannot be distinguished with certainty.

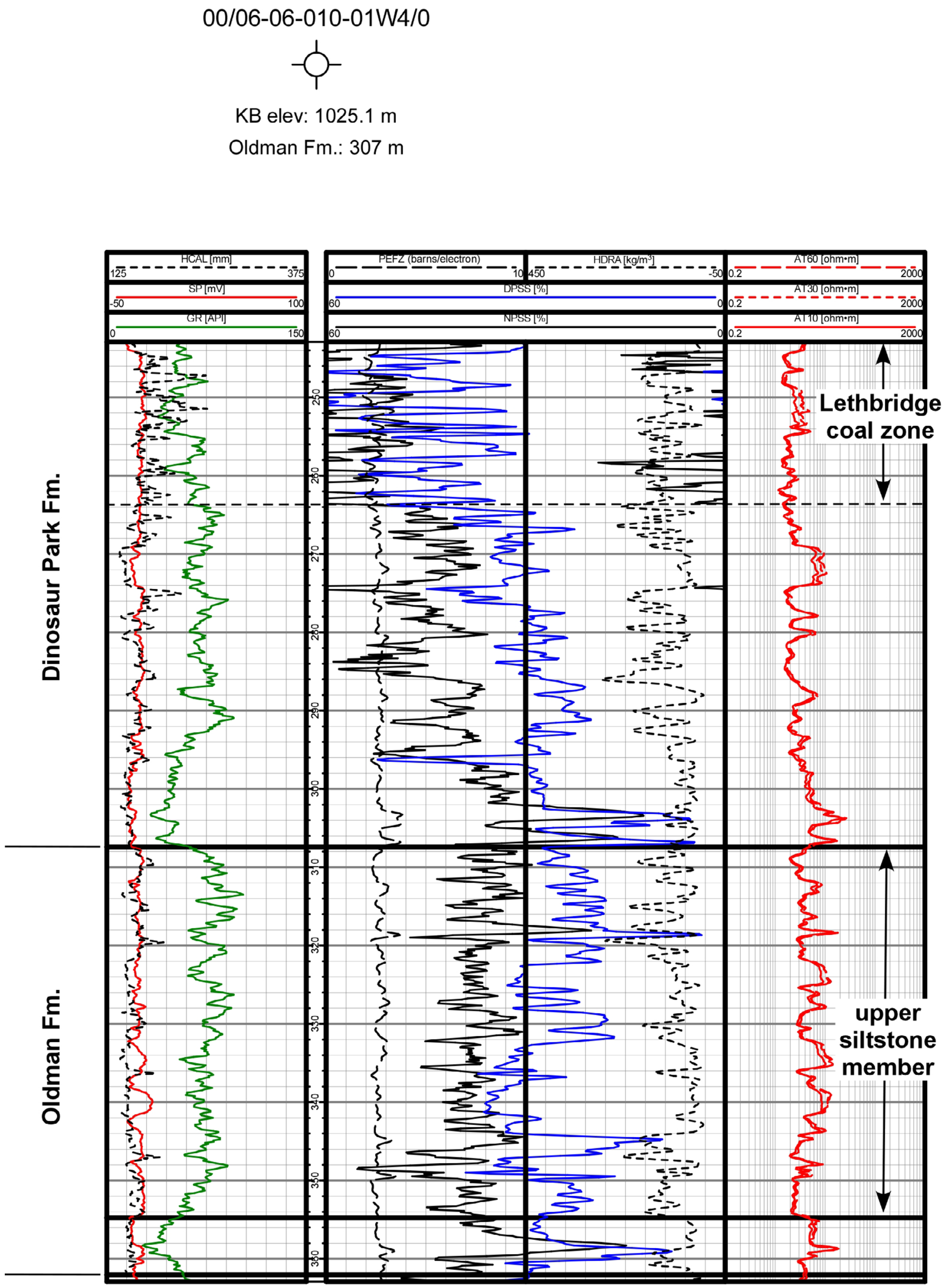


Figure 9. Representative well for southeastern Alberta (UWI 00/06-06-010-01W4/0). Logs shown are caliper (HCAL in mm), spontaneous-potential (SP in mV), gamma ray (GR in API units), photoelectric factor (PEFZ in barns/electron), density correction (HDRA in kg/m$^3$), density-porosity (sandstone; DPSS in %), neutron-porosity (sandstone; NPSS in %), deep resistivity (AT60 in ohm•m), medium resistivity (AT30 in ohm•m) and shallow resistivity (AT10 in ohm•m). Kelly-bushing (KB) elevation given is in metres above sea level. Vertical log scale is measured depth (in metres) below KB. Other abbreviations: elev, elevation; Fm, Formation.

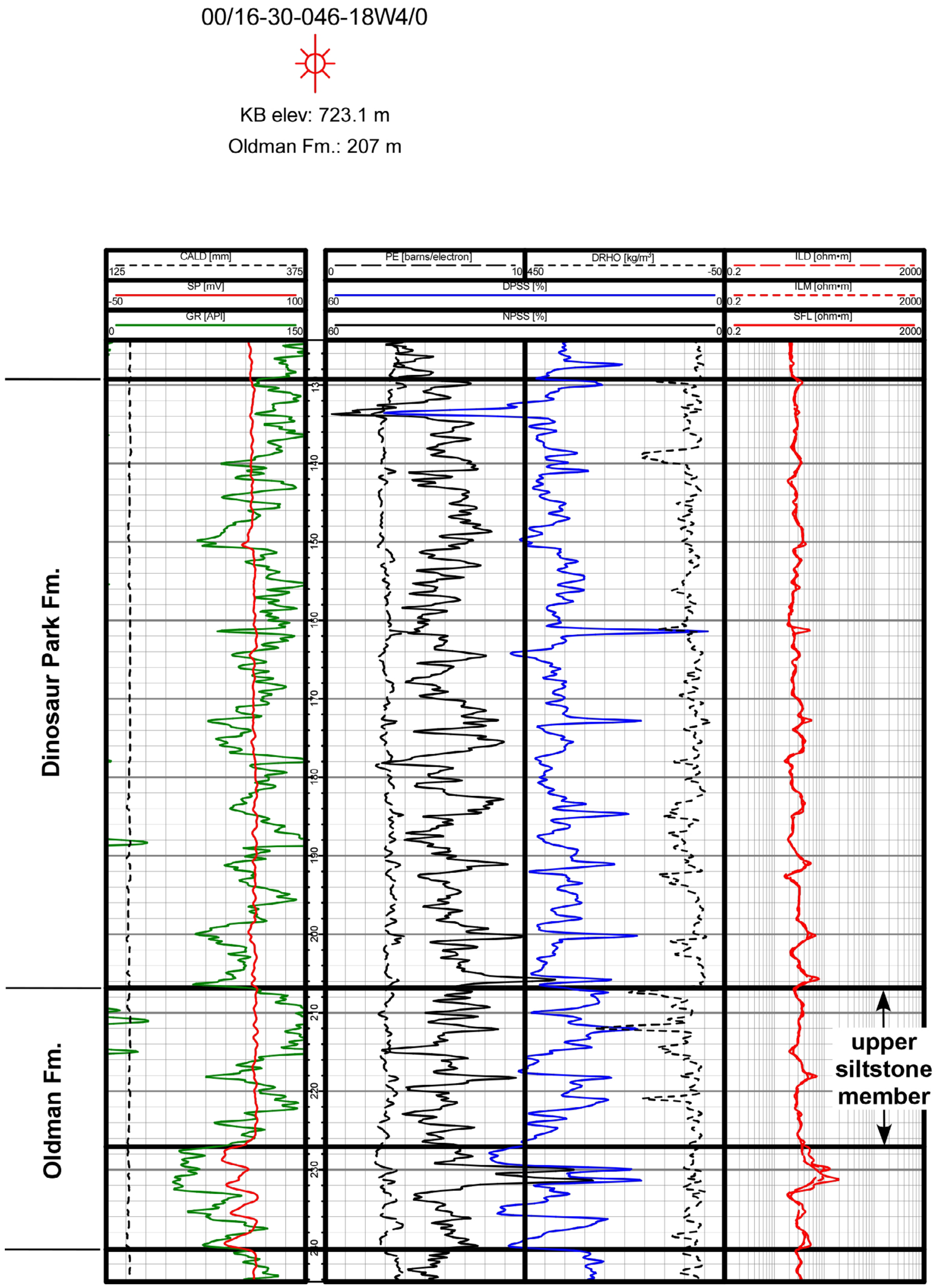


Figure 10. Representative well for central Alberta (UWI 00/16-30-046-18W4/0). Logs shown are caliper (CALD in mm), spontaneous-potential (SP in mV), gamma ray (GR in API units), photoelectric factor (PE in barns/electron), density correction (DRHO in kg/m³), density-porosity (sandstone; DPSS in %), neutron-porosity (sandstone; NPSS in %), deep induction (ILD in ohm•m), medium induction (ILM in ohm•m) and spherically focussed (SFL in ohm•m). Kelly-bushing (KB) elevation given is in metres above sea level. Vertical log scale is measured depth (in metres) below KB. Other abbreviations: elev, elevation; Fm, Formation.

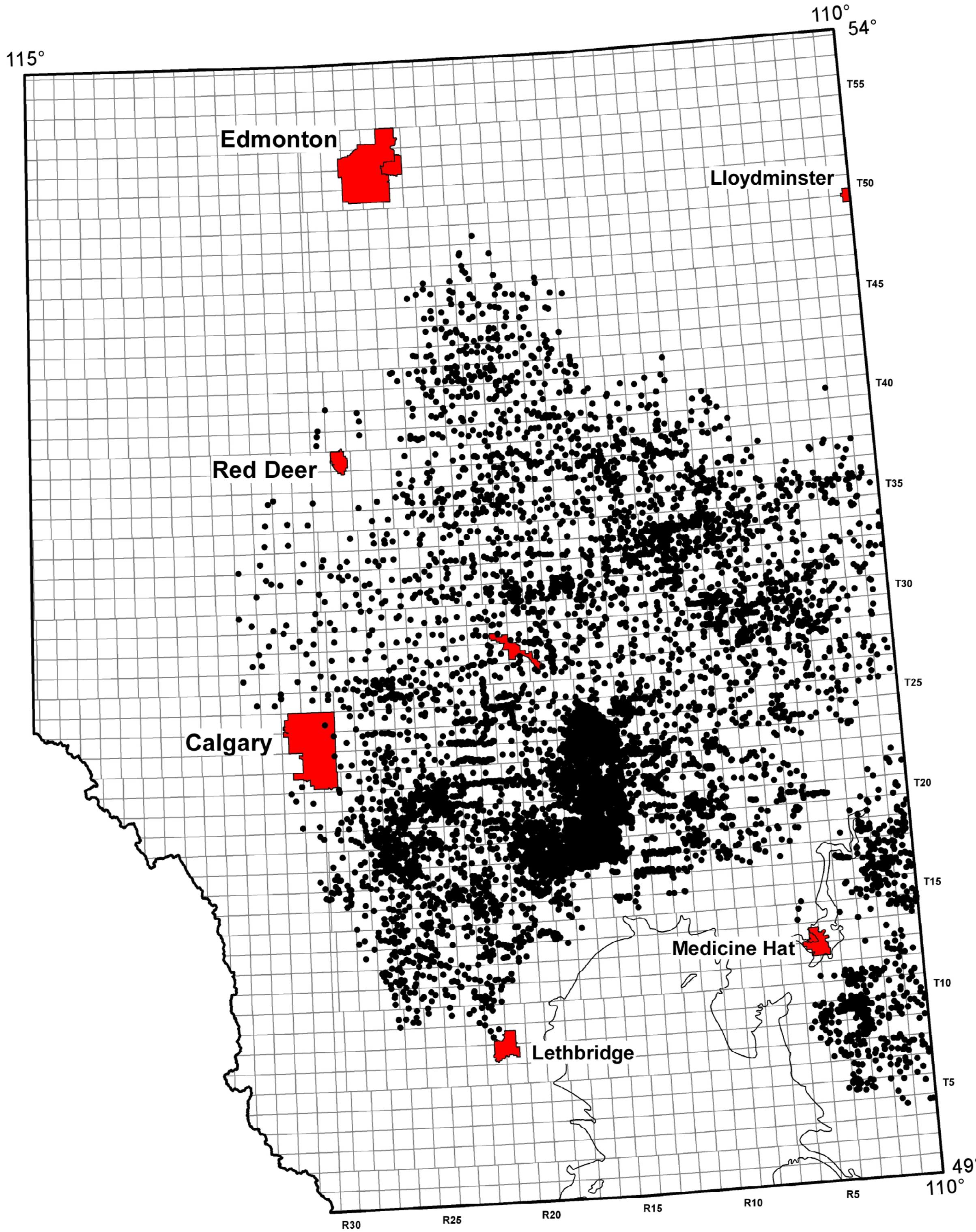


Figure 11. Distribution of the wells (solid black circles) used in this project, southern Alberta. The surface trace for the top of the Foremost Formation (base of Oldman Formation; from Hamilton et al., 1999) is shown as a thin black line. Cities are shown in red.

The recognition of the disconformity between the Dinosaur Park and Oldman formations is also problematic in southeastern Alberta, where rocks of the Belly River Group are preserved in the Cypress Hills region (Figure 2). Near the village of Onefour, Alberta, Eberth and Hamblin (1993) examined a stratigraphic section of upper Belly River Group rocks and placed the base of the Dinosaur Park Formation at the base of a cross-bedded sandstone, located approximately 27 m below the base of the Lethbridge coal zone (the upper contact of the Dinosaur Park Formation is not exposed at this location). They determined an approximate thickness of 30 m for the Dinosaur Park Formation in this area. Based on subsurface correlation, Hamblin (1997a) determined a thickness of approximately 50 m for the Dinosaur Park Formation in the Cypress Hills area, located approximately 30 to 40 km to the north of the measured outcrop section at Onefour. The difference in the thickness of the Dinosaur Park Formation between the two areas indicates either rapid lateral thickness changes within the formation or difficulty in consistently picking the top of the Oldman Formation in southeastern Alberta.

In this study, the Oldman Formation was found to be both thicker and less radioactive (60–90 API) in the Cypress Hills area of southeastern Alberta, compared to other areas of south-central Alberta. As a result, the contact between the Dinosaur Park and Oldman formations becomes increasingly difficult to pick south of Twp. 5 in southeastern Alberta. In addition, one or more low radioactivity intervals—with gamma-ray values similar to those of the overlying Dinosaur Park Formation—may be present within the upper siltstone member and have little lateral continuity at the regional scale. This is opposed to the basal sandstone unit within the lower Oldman Formation (equivalent to the Comrey sandstone of Hamblin, 1997b), which typically shows considerable lateral continuity at the regional scale in the subsurface over much of southern Alberta.

In southwestern Alberta, south of approximately Twp. 9 and east of the deformed belt, near the city of Lethbridge and southwards to the international border, facies typical of the Dinosaur Park Formation cannot be recognized in outcrop (Eberth and Hamblin, 1993; Hamblin, 1997b). In this area, rocks of the upper Belly River Group resemble those of the Oldman Formation exposed elsewhere within southern Alberta. In the subsurface, a similar transition is observed at the approximate latitude of the city of Lethbridge (Twp. 10), south of which neither a consistent upper siltstone member, nor a consistent set of basal Dinosaur Park Formation sandstones can be mapped. The upper Belly River Group in this area—equivalent to the Oldman and Dinosaur Park formations in other parts of south-central Alberta—is marked by significant lateral and vertical heterogeneity and a lack of mappable markers making subdivision difficult.

# 7 Dataset and Methods

Digital Dataset 2011-0006 (Glombick, 2011) includes new stratigraphic pick data for the top of the Oldman Formation (base of the Dinosaur Park Formation) from 8799 wells. The data are included in the zip file that accompanies the PDF of this report at
http://www.ags.gov.ab.ca/publications/abstracts/OFR_2011_13.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 to 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 8799 wells from approximately 800 townships, resulting in an average density of approximately 11 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.

# 8 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 NAD 83 and the picks are in metres, given as measured depth relative to KB elevation. Pick elevations (subsea) 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; 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 (approximately equal to the drilling derrick-floor height) for each well. An acceptable range of derrick-floor height—calculated by subtracting ground elevation from KB elevation—of 2 to 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 obtained by subtracting the ground elevation derived from the DEM from the ground elevation provided in the well 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 removed from the dataset. 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 dataset. 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.

# 9 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 Oldman Formation in the Alberta Plains (Figures 11 and 12). The data was modelled with Petra software using the highly connected features (least-squares) method.

The broad structural elements of the southern Alberta Basin are visible on Figure 12. The Kevin-Sunburst Dome extends northwards from northern Montana into southern Alberta and controls the gross regional structure and the trend of structure contours, which wrap around the northern margin of the dome. Numerous undulations, or warps, are visible on the northwest margin of the dome (Figure 12, lower left). The extension of the Bow Island Arch (Figure 12) northeastward from the northern margin of the Kevin-Sunburst Dome separates the Alberta Basin to the west from the Williston Basin to the east (Tovell, 1958; Lorenz, 1982; Wright et al., 1994).

The regional structure within the western half of the study area is dominated by the Alberta Basin, with dips varying from west to southwest, dipping towards the fold-and-thrust belt (Figure 12). In southwestern Alberta, a west-plunging positive structural feature, known as the Calgary Arch (Dawson et al., 1994a, Figure 24.2; Figure 12), divides the Alberta Basin into arcuate southern and northern sub-basins. The smaller southern region, bounded in the north by the Calgary Arch and in the west by the deformation front, exhibits relatively steep dips to the southwest. Previous studies have shown that the thickness of the Belly River Group increases south of the Calgary Arch (Dawson et al., 1994a, Figure 24.16). A similar trend occurs within the overlying Bearpaw Formation (Dawson et al., 1994a, Figure 24.17). Although subtle thinning over the Calgary Arch is apparent on the Belly River Group isopach map, it is more pronounced on the isopach map of the Bearpaw Formation. South of the Calgary Arch, northwest of the city of Lethbridge, local deviations from the regional structural trend occur (Figure 12).

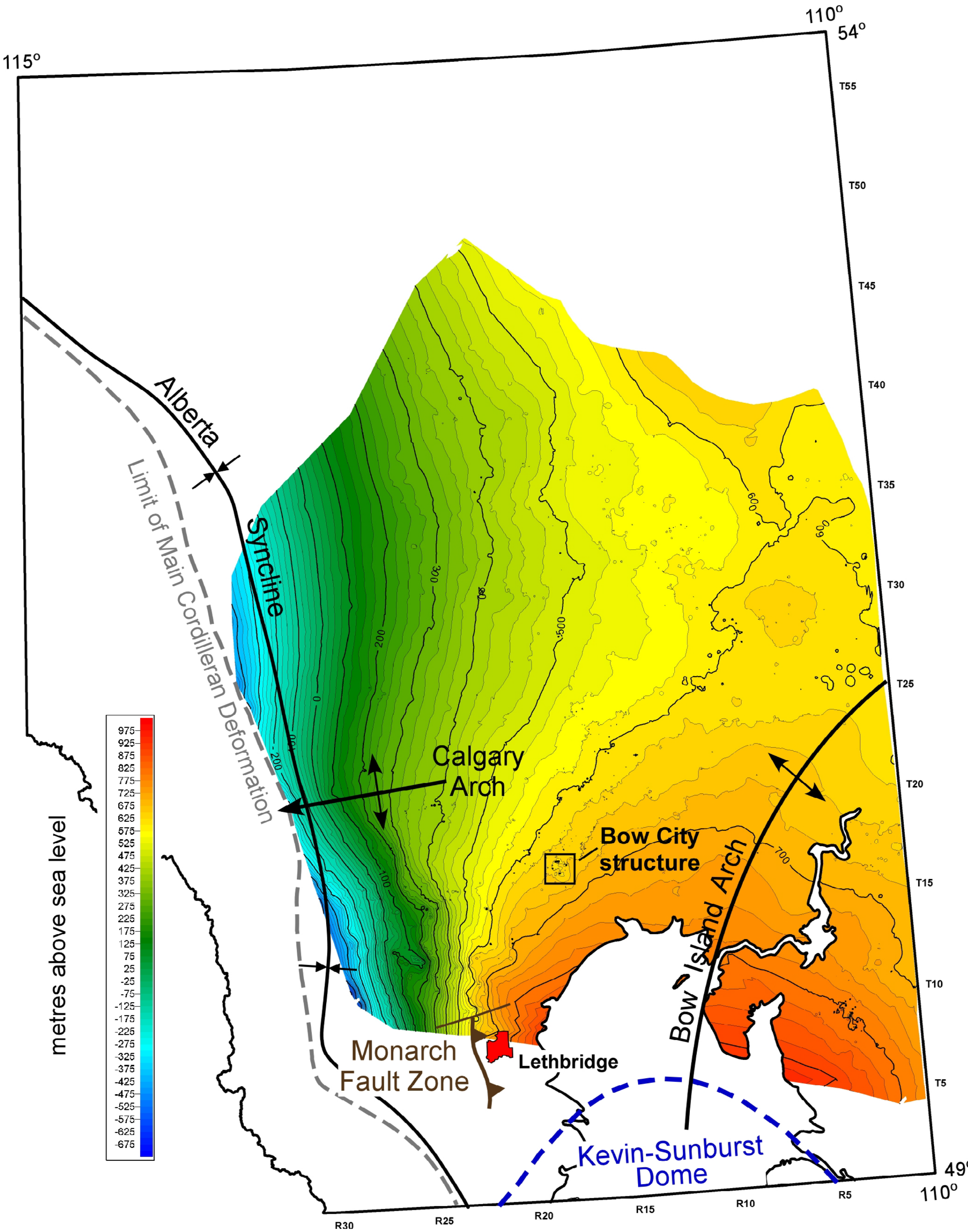


Figure 12. Shaded structure map for the top of the Oldman Formation in southern Alberta. Contour interval is 25 m; contour values are elevation in metres above sea level. Surface trace for the top of the Foremost Formation (base of Oldman Formation) is shown as a thick black line (modified from Hamilton et al., 1999).

The deviations generally take the form of alternating northwest- and northeast-trending segments, resulting in a saw-tooth pattern on the map. As summarized by Glombick (2010a), the surface trace of the Monarch Fault Zone crops out in this area. Both normal and reverse faults are visible in seismic reflection data of Upper Cretaceous and older strata in the area (e.g., Wright et al., 1994; Lemieux, 1999).

A local structural feature, visible on Figure 12, occurs near Bow City, where a round, bowl-shaped anomaly approximately 9 km in diameter with a central uplift has been mapped in the subsurface (Twp. 17 and 18, Rge. 17 and 18, W 4th Mer.). Thrust faults have been mapped in outcrop and anomalously steep dips occur locally. Detailed structural cross-sections through the area show localized uplift and thinning or thickening of strata locally within strata of the Belly River Group, but little effect is present within the underlying Milk River Formation. This structure, named by Glombick (2010a) as the Bow City anomaly, is possibly a partially eroded impact structure. Additional work is required to test this hypothesis.

# 10 Summary

A new, internally consistent set of 8799 subsurface picks for the top of the Oldman Formation in the Alberta Plains was generated using geophysical well logs. Well data were screened for potential errors in KB and ground elevation values and for errors resulting from deviated wells. Local and global outliers were identified using statistical methods and either rejected or confirmed based on well-by-well examination. Additional picks were made to delineate local structure, where necessary. The modelled structure surface shows the regional structure on the top of the Oldman Formation within southern Alberta.

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