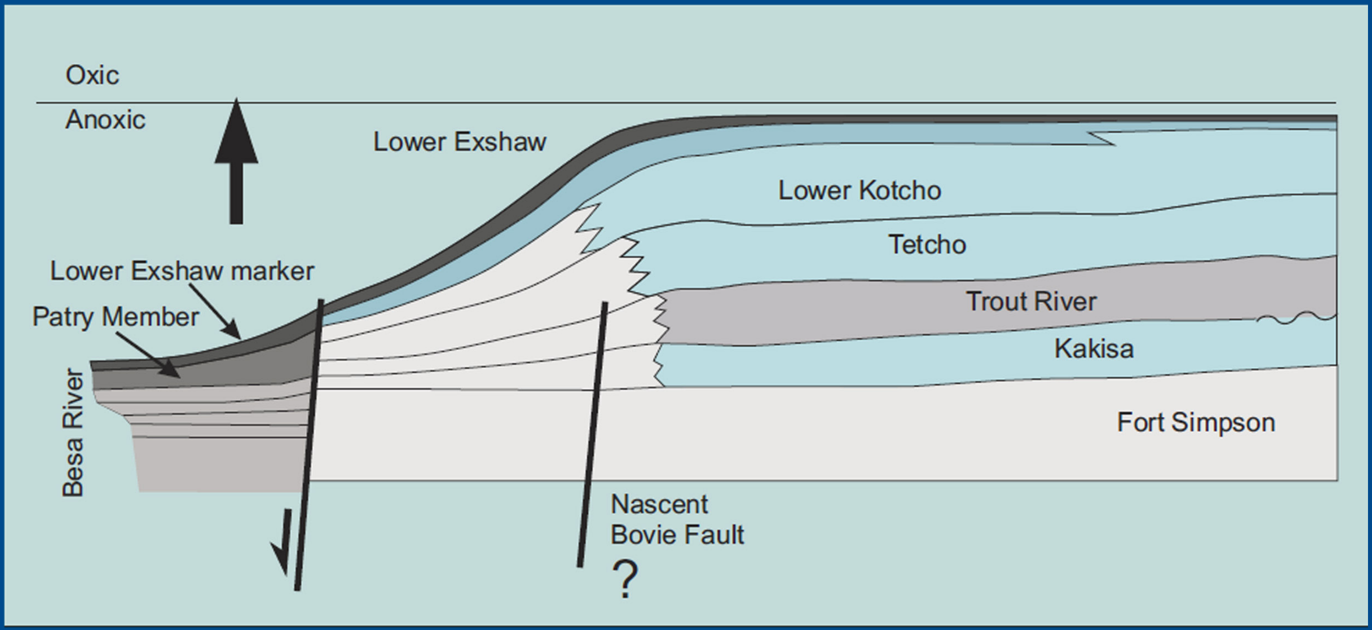
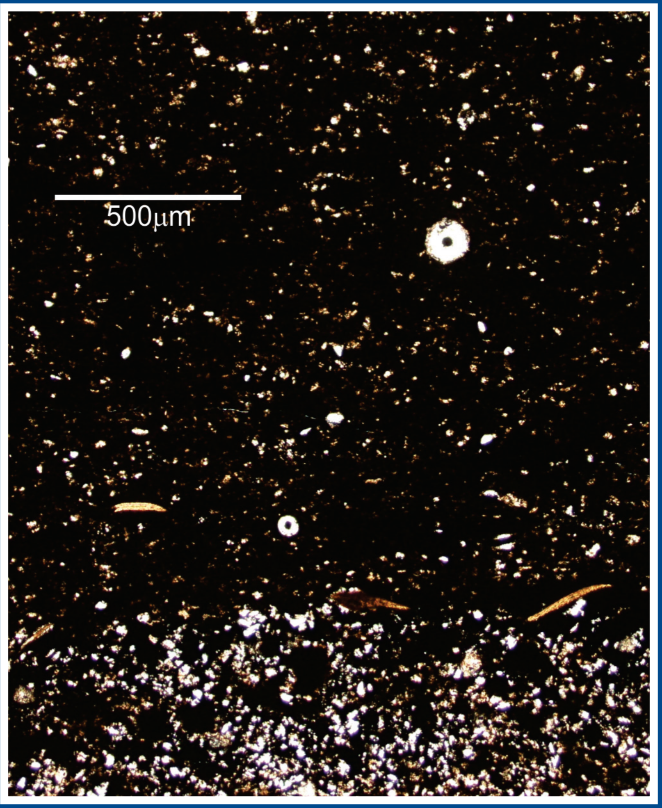
Oil and Gas Geoscience Reports 2015





Ministry of Natural Gas Development
Tenure and Geoscience Branch

Oil and Gas Geoscience Reports 2015

Front cover

Top: Model for the origin of organic-rich shales in the central part of Liard Basin. Organic-rich mudrocks of the Patry member were deposited in anoxic waters adjacent to a syndepositional, west-side-down normal fault sub-parallel to the Bovie Fault. At the stage of sedimentation depicted, sea level has risen and anoxic waters have flooded the shelf, depositing the lower part of the Exshaw Formation.

Left: Dark grey calcareous shale of the lower Patry member containing thin discontinuous light grey carbonate layers and a pyrite nodule (upper left), 3771.6 m level.

Bottom: Photomicrograph of dark grey, laminated and calcareous shale of the lower Patry member, 3775.2 m level. Calcareous laminae contain detrital carbonate grains such as crinoid ossicles and shell fragments.

See

Ferri, F., McMechan, M., and Creaser, R., 2015. The Besa River Formation in Liard Basin, British Columbia, pp. 1-27.

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Victoria, British Columbia
June, 2015

British Columbia
Ministry of Natural Gas Development
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Foreward

The 2015 volume of Geoscience Reports presents research from the Tenure and Geoscience Branch that continues the focus on unconventional resources.

The paper by Ferri, McMechan, and Creaser describes the regional setting and stratigraphic relationships of the Besa River Formation in Liard Basin. Although this unit host significant shale gas resources, it is poorly understood. The paper also examines and analyzes recently released data from core of the Apache b-23-K well, which was cut from the gas-rich zone of the Besa River Formation. This paper suggests possible correlations of the "pay zone" with known formations in other parts of the Western Canada Sedimentary Basin and proposes a depositional model for this sequence.

The second paper by Janicki and Balogun describes a thin, tight sandy to silty horizon in the upper part of the Fernie Formation that may be equivalent to the Rock Creek sandstone of southern Alberta. The stratigraphic proximity of this unit to underlying organic-rich shales of the Nordegg (Gordondale) Member of the Fernie Formation lends it to likely being charged with hydrocarbons.

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BRITISH COLUMBIA
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The Besa River Formation in Liard Basin, British Columbia

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Abstract
The Besa River Formation (Middle Devonian to Middle Mississippian) is a predominantly shale succession that was deposited in Liard Basin and now outcrops along the eastern slopes of the Rocky Mountains in northeast British Columbia. It contains the deep-water basin equivalents to carbonate and shale developed to the east, in the subsurface of the Western Canada Sedimentary Basin. In westernmost Liard Basin, the Besa River Formation is about 300 m thick whereas near the Bovie structure, the correlative carbonate and shale are over 2000 m thick. In central Liard Basin, the upper Besa River Formation contains a gas-saturated, silica- and organic-rich section equivalent to the Exshaw Formation and an underlying unit informally referred to herein as the Patry member. This succession has recently been the focus of shale-gas exploration and has proven to be quite prolific, with the initial development well producing over 6.5 billion cubic feet (184 x $10^6 m^3$) of natural gas since 2011. This organic-rich sequence is developed in central and western Liard Basin and is considerably thicker along its eastern limit where it defines a north to north-easterly trending section that is over 200 m thick. We propose a depositional model in which a west-side-down normal fault similar to the Bovie structure created the accommodation space for accumulation of a thick section of organic-rich rocks in anoxic bottom waters.

Keywords: Liard Basin, shale gas, Devonian-Mississippian, Bovie structure, Besa River Formation, Patry member, unconventional gas

1. Introduction

Significant mid-Paleozoic shale gas resources have been delineated in British Columbia's portion of the Western Canada Sedimentary Basin. These resources are in Devono-Mississippian shale sequences deposited in the Horn River Basin and related Cordova Embayment, and in Liard Basin (Figures 1, 2). Initial exploration and development activity focused on Middle to Late Devonian shales of the Horn River Formation in Horn River Basin. Published resource estimates for the Horn River Basin indicate 78 trillion cubic feet (Tcf; 2.2 x 10^6 m^3) of marketable gas and 442 Tcf (12.5 x 10^6 m^3) of gas-in-place (BC Ministry of Energy and Mines, 2011). Although published resource estimates for the Liard Basin are lacking, Apache Canada Ltd. suggested a resource of 48 Tcf (1.6 x 10^6 m^3) on its 174 000 hectare land holdings in Liard Basin based on initial production and drilling results (Macedo, 2012). This estimate, if extrapolated to the remaining parts of the basin, implies a resource potential rivaling that of the Horn River Basin.

Outside of the Foothills, the Liard Basin represents one of the most challenging regions for oil and gas exploration and development in British Columbia. As a result, only a few dozen wells have penetrated the Besa River Formation (Figures 2, 3), either targeting it directly or gas-prone formations in underlying mid-Paleozoic carbonate rocks. This report summarizes some of the initial regional mapping and data compilation undertaken as part of a broader unconventional resource assessment programme examining Devono-Mississippian shale sequences in Liard Basin. This programme is a collaboration with the National Energy Board, the BC Oil and Gas Commission, and the governments of the Yukon and Northwest Territories. Previous reports of the programme include an assessment of Horn River Basin (BC Ministry of Energy and Mines, 2011) and an evaluation of the Montney Formation (BC Ministry of Natural Gas Development, 2013). Work on the Cordova Embayment (Balogun, 2014) should be published late in 2015.

2. Regional Geology

The Besa River Formation occurs within the western half of the Liard Basin. The basin contains a thick succession of Cretaceous through Carboniferous sedimentary rocks and is bounded to the east by the Bovie structure (Figure 2), a north- to northeast-trending fault that was periodically active throughout the Paleozoic and Mesozoic, with both reverse and normal movement (McLean and Morrow, 2004; Leckie et al., 1991). Seismic and well data indicate over 1000 m of west side-down displacement on this fault. A broad anticline, cored by Mississippian carbonate rocks adjacent to the northern trace of the Bovie structure records shortening. Although Monahan (2000) and MacLean and Morrow (2004) suggested that movement younger than Late Carboniferous, thickness variations of Late Devonian to Early Mississippian units across the Bovie structure suggest it may have had earlier motion. Abrupt thickening and facies changes of the Fort St. John Group indicate the structure was active in the Early Cretaceous (Stott, 1982; Monahan, 2000; MacLean and Morrow, 2004).

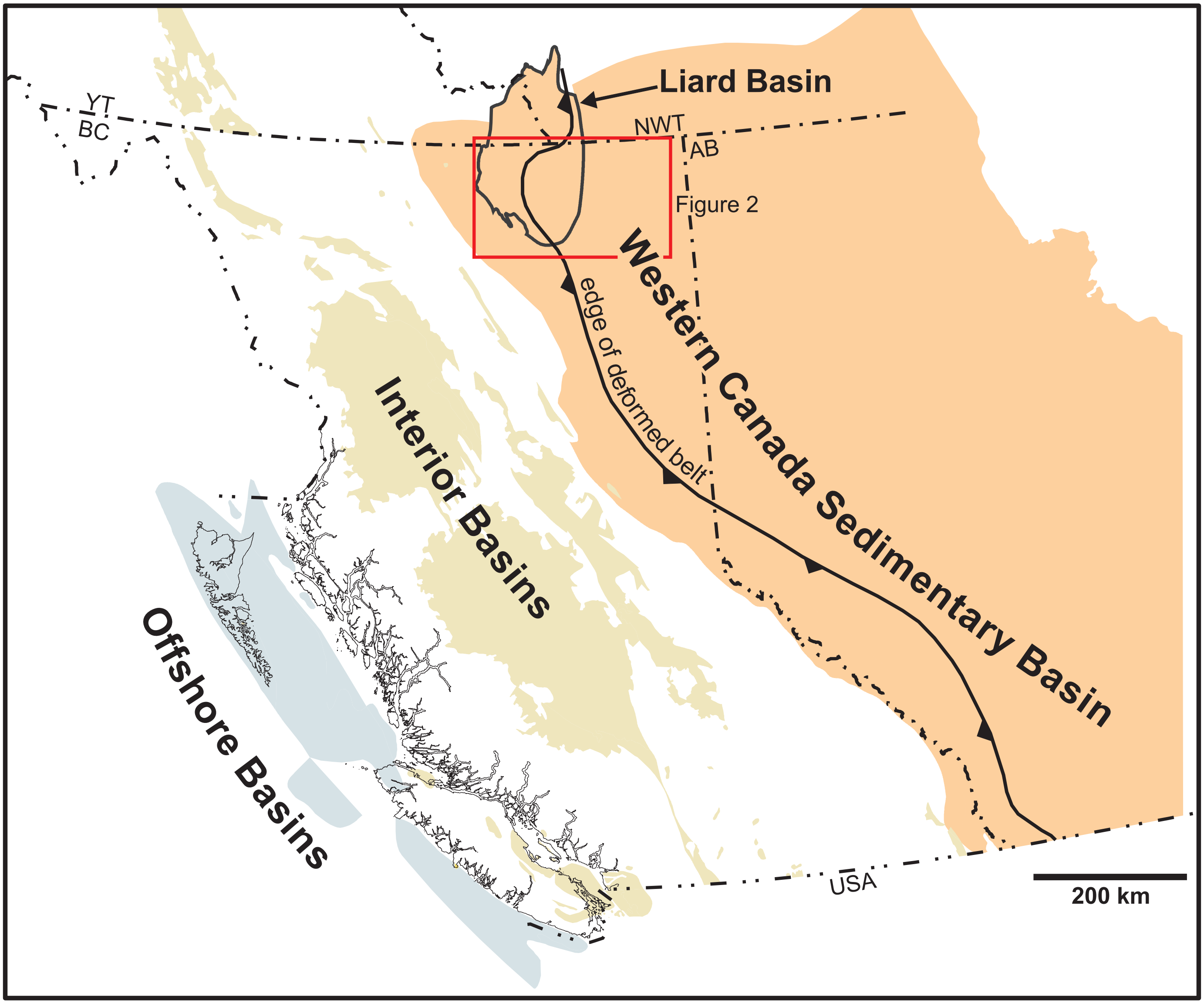

Figure 1: Generalized map of the western Canada showing the location of the Liard Basin with respect to the Western Canada Sedimentary Basin and British Columbia. Modified from Mossop et al. (2004).

Cordilleran folding and thrusting affected the western part of the Liard Basin. Within the Cordillera, the Liard area is unique as it marks the abrupt transition between northwest-trending structures of the northernmost Rocky Mountains and the north- to northeast-trending structures of the Franklin and Mackenzie mountains (Figure 4; Wheeler and McFeely, 1991). Most folds and thrusts in the Rocky Mountains verge east, whereas many structures in the Mackenzie and Franklin mountains verge west.

3. Exploration History

The first exploration targets in the Liard Basin were large, structurally controlled gas accumulations in hydrothermally altered carbonate rocks of the Nahanni Formation (Middle Devonian). Successful targets included the Beaver River and Crow River gas fields in British Columbia, the Kotaneelee field in Yukon, and the Pointed Mounted field in the Northwest Territories. In the 1990s and 2000s, the Chinkeh sandstone of the Maxhamish area of eastern Liard Basin was targeted. The Chinkeh also contains an oil lag in the southwest part of the Maxhamish area.

The unconventional gas potential of the Besa River Formation was first noted in a report of Devonian strata in northeast British Columbia (BC Ministry of Energy and Mines, 2005) and in a more regional paper by Ross and Bustin (2008). Although the Horn River Group is found within the Liard Basin, displacement on the Bovie structure has placed the unit at depths (Figure 5, 8) that pose challenges for economic development. As such, the stratigraphically higher organic-rich horizons within the Besa River Formation were the focus of exploration and development. Large tenure sales targeting shale gas development in Liard Basin began in 2008 and culminated in over $110 M worth of oil and gas rights being sold in 2010 (Adams, 2009, 2010, 2011). Subsequent drilling by Apache Canada Ltd., Paramount Resources, and Nexen

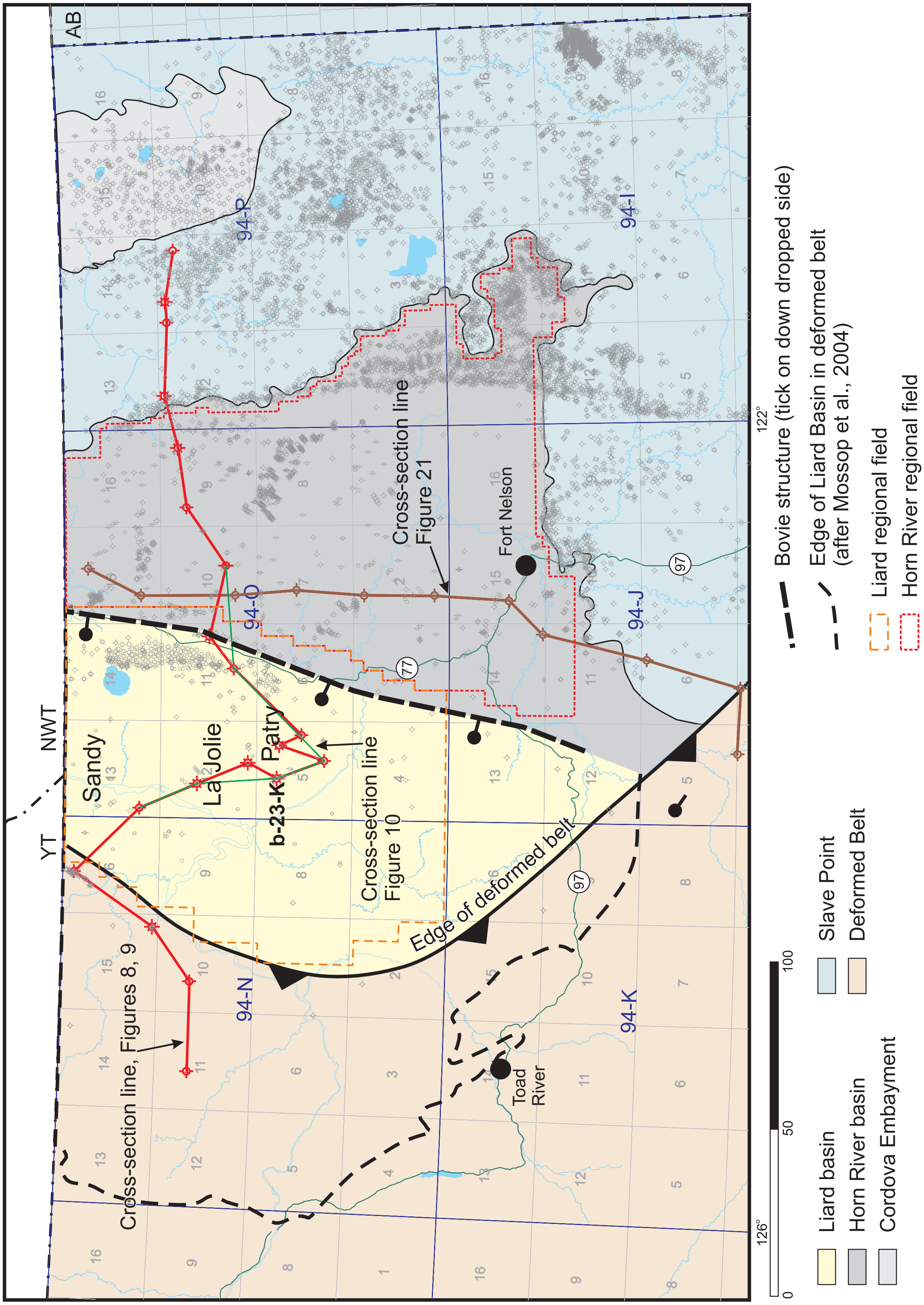

Figure 2: Regional context of the Liard Basin area showing the main mid-Paleozoic depositional and structural elements together with the two main unconventional regional gas fields, and the Patry and La Jolie areas. Also shown are the locations of the cross-sections shown in figures 6, 7, 8 and 19. The outline of the Liard Basin is taken from Mossop et al. (2004). The regional gas fields and Horn Basin outlines were obtained from digital downloads through www.bcogc.ca.

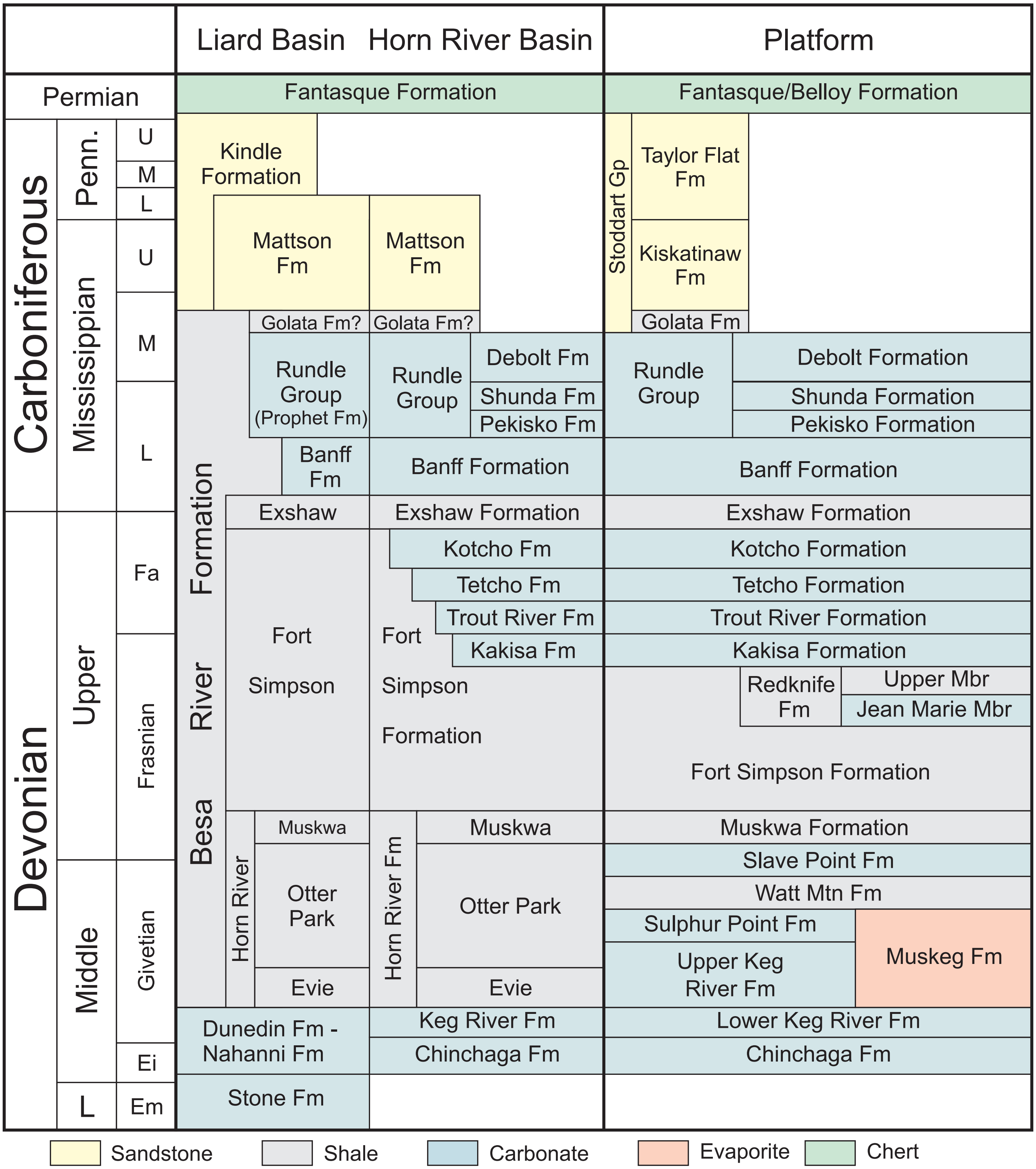

Figure 3: Time-stratigraphic chart showing the relationship of the Besa River Formation to other units in the Western Canada Sedimentary Basin.

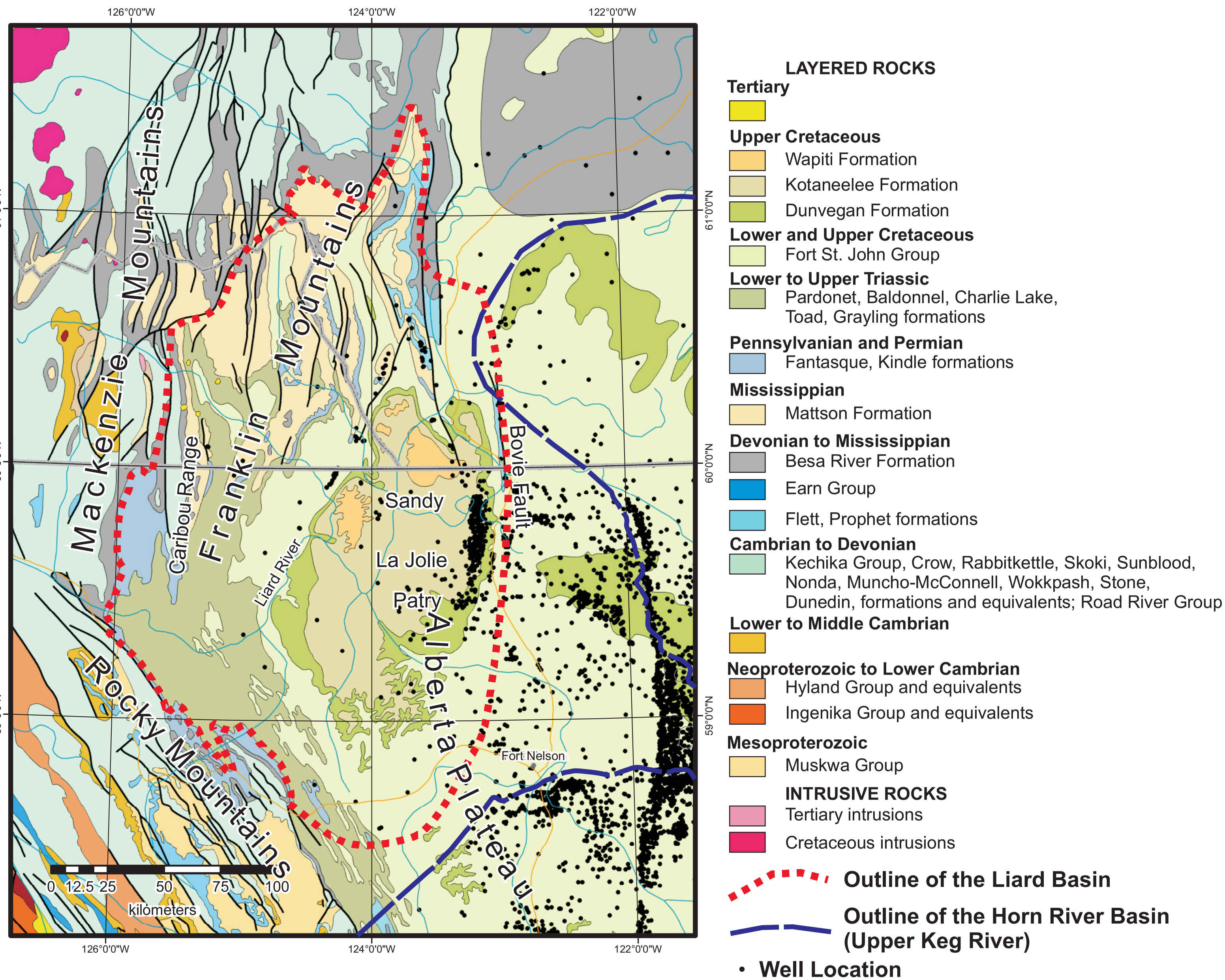

Figure 4: Bedrock geological map of the Liard Basin area. This diagram shows the relatively abrupt transition from the northwest- trending structures of the Rocky Mountains into the north- and northeast- striking faults and folds of the Mackenzie and Franklin mountains. Note that the northern Liard Basin area (between the Bovie Fault and Caribou Range) is at the southern end of the north- to northeast- trending structures. The geological base map is modified from Wheeler and McFeely (1991). The outline of the Liard Basin is from Mossop et al. (2004). The Horn Basin outline was modified from Meijer Drees (1994) and the physiographic regions are from Mathews (1986).

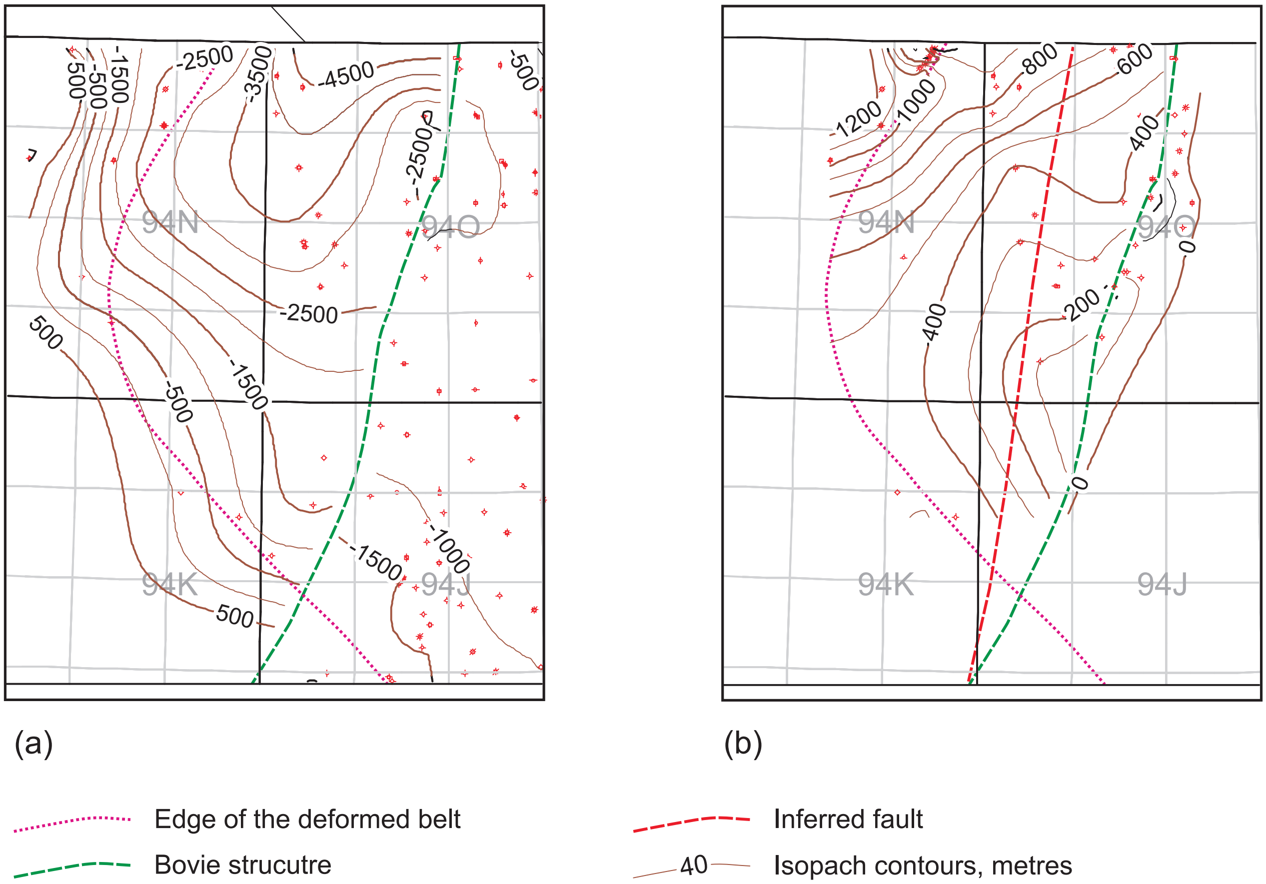

Figure 5: **(a)** Structure at the top of the Exshaw Formation or Exshaw Marker of the Besa River Formation. The depths of this horizon are between 3500 and 5000 m in the central and northern part of 94O. **(b)** Thickness of the Mattson Formation, Liard Basin. This thick, quartzose sandstone poses drilling challenges for deeper horizons in the Liard Basin. Contours in metres.

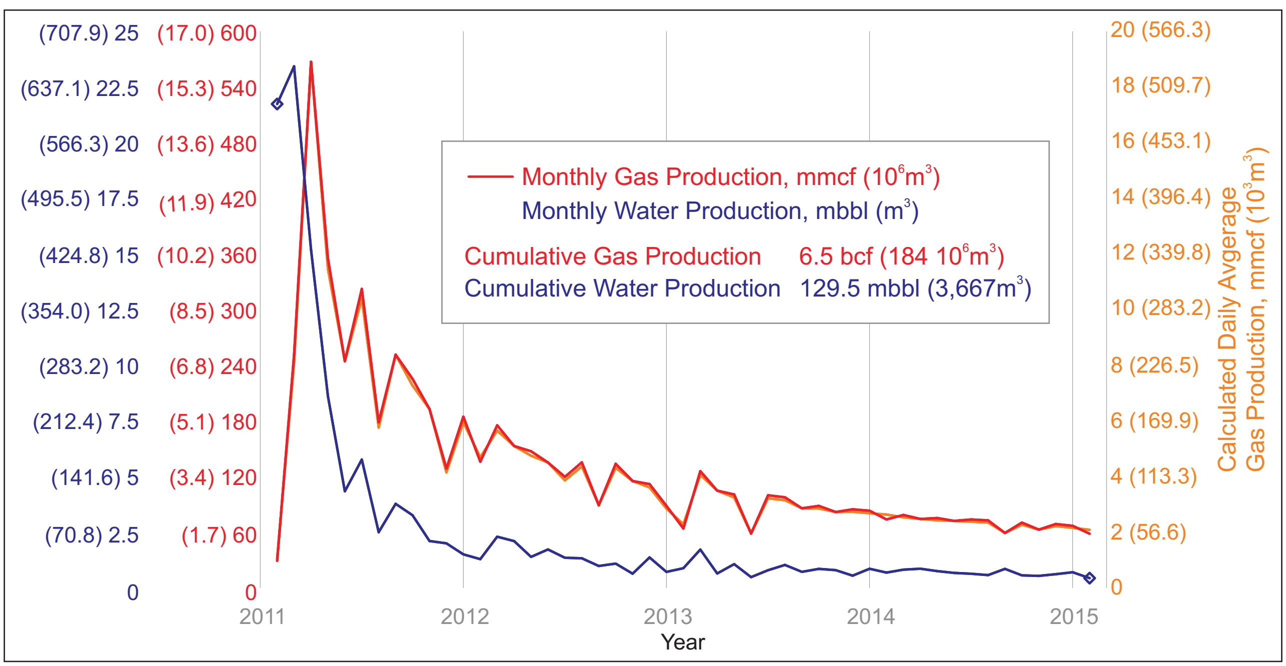

Figure 6: Monthly production statistics for the Apache Patry HZ d-34-K/94-O-5 well. Data from www.bcogc.ca.

Canada Ltd. tested the Besa River Formation for shale gas. This handful of wells provided the only modern public data sets available across this unit. The data from the Apache Patry d-23-K well are particularly robust as a significant section of core was acquired across the approximately 90 m thick pay zone.

Shale gas development of the Besa River Formation commenced with the Apache HZ Patry c-45-K/94-O-5 well consisting of a horizontal leg of approximately 800 m containing 6 zones that were hydraulically fractured (Apache Canada Ltd., 2012). Data available from the British Columbia Oil and Gas Commission (www.bcogc.ca) indicate an initial calculated daily average production for this well of 18.92 mmcf (535x10^{3}m^3) natural gas (Figure 6). Although production data captured over four years show an initial steep decline, cumulative production is approximately 6.5 bcf (184x10^{6}m^3) natural gas and production rates are still 2 mmcf/day (56.6x10^{3}m^3, Figure 6). The British Columbia Oil and Gas Commission (2013) indicates an average ultimate potential of 8 bcf (227x10^{6}m^3) natural gas per well within the Besa River Formation.

4. Stratigraphic analysis

4.1. Regional

The Besa River Formation is a uniform sequence of dark grey to black shale that outcrops along the eastern margin of the north-central Canadian Cordillera (Kidd, 1962, 1963; Pelzer, 1966, Bamber et al., 1968). The unit can be traced from near the Monkman Pass area of northeastern British Columbia into southern Yukon and Northwest Territories (Taylor and Stott, 1973, 1999; McMechan, 1994; Stott et al., 1983; Thompson, 1989; Stott et al., 1963; Stott and Taylor, 1968; Douglas and Norris, 1974; Douglas, 1976). Although the unit can be greater than 1600 m thick (Richards, 1989), it is about 300 m thick in western Liard Basin (Ferri et al., 2011, 2012, 2013). It represents a deep-water succession that is equivalent to 2000 metres of shelf shale and carbonate units in the subsurface to the east (Figures 3, 8). In the western Rocky Mountains and Mackenzie Mountains of northernmost British Columbia, basal rocks of Besa River Formation rest conformably on Middle Devonian (latest Eifelian to middle Givetian) carbonate rocks of the Dunedin Formation, which are equivalent to the lower part of the Keg River Formation farther east. In the upper part of the unit, shales are transitional with Middle to Late Mississippian sandstones of the Mattson Formation (Ferri et al., 2011, 2012). Farther west, in the western Rocky Mountains, rocks equivalent to the Besa River Formation are in the Earn Group, although the age span of these black shales is longer due to the shale out of Middle Devonian carbonates equivalent to the Dunedin and Stone formations (Figure 7; Ferri et al., 1999).

Some workers apply the term 'Besa River' to shales immediately west of where carbonate rocks of the Jean Marie member and Redknife Formation disappear (Morrow, 2012). Because rocks of the Redknife Formation pass into grey shales similar to those of the Fort Simpson Formation, the term 'Fort Simpson Formation' is retained herein. The upper contact of the Fort Simpson Formation shifts upwards farther west as carbonate rocks of the Kakisa, Trout River, and Tetcho formations shale out (Figures 8, 9).

The Kotcho Formation also becomes less calcareous to the west. Most of the Kotcho Formation like the underlying Tetcho to Kakisa carbonate rocks disappears into grey shales included in the Fort Simpson Formation. However, the upper Kotcho appears to transition into dark grey to black, organic-rich shales with characteristics similar to overlying rocks that are equivalent to the lower part of the Exshaw Formation (Exshaw marker). This horizon and overlying shales corresponding to rocks of the lower Exshaw Formation comprise targets for shale gas development, and together were designated the First Black Shale in wells drilled by Apache Canada Ltd. and other operators (Apache Canada Ltd., 2012; Poco Petroleums Ltd., 2000; BC Ministry of Energy and Mines, 2005). The

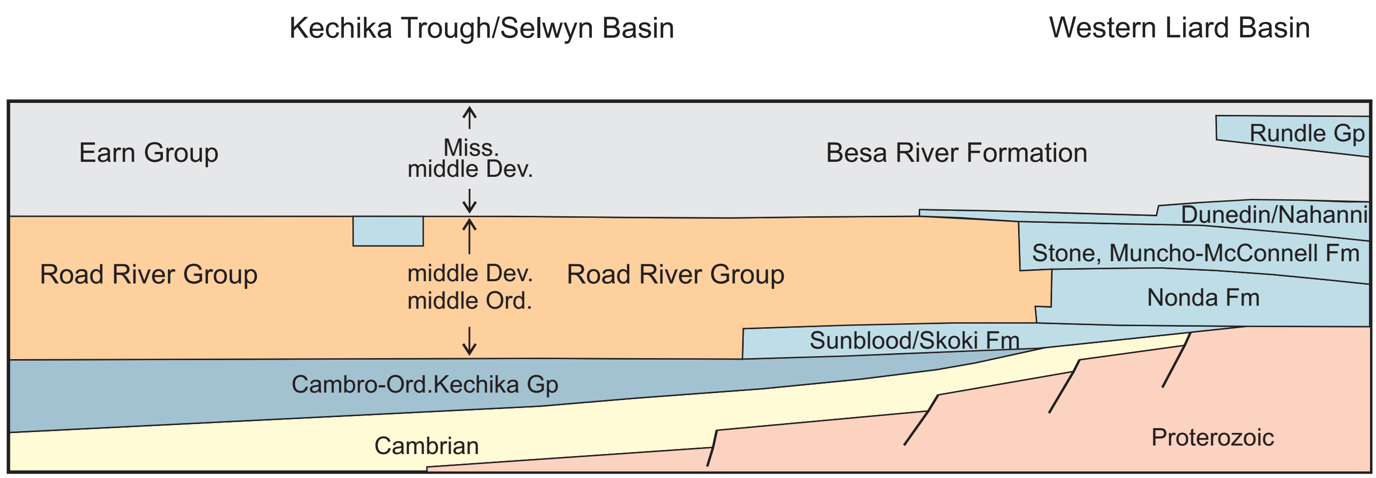

Figure 7: Schematic representation of westward shale-out of Lower Paleozoic carbonates into Road River siltstone and shales within the Kechika Trough and Selwyn Basin, and the relationship between the Besa River Formation and the Earn Group. Modified from Thompson (1989).

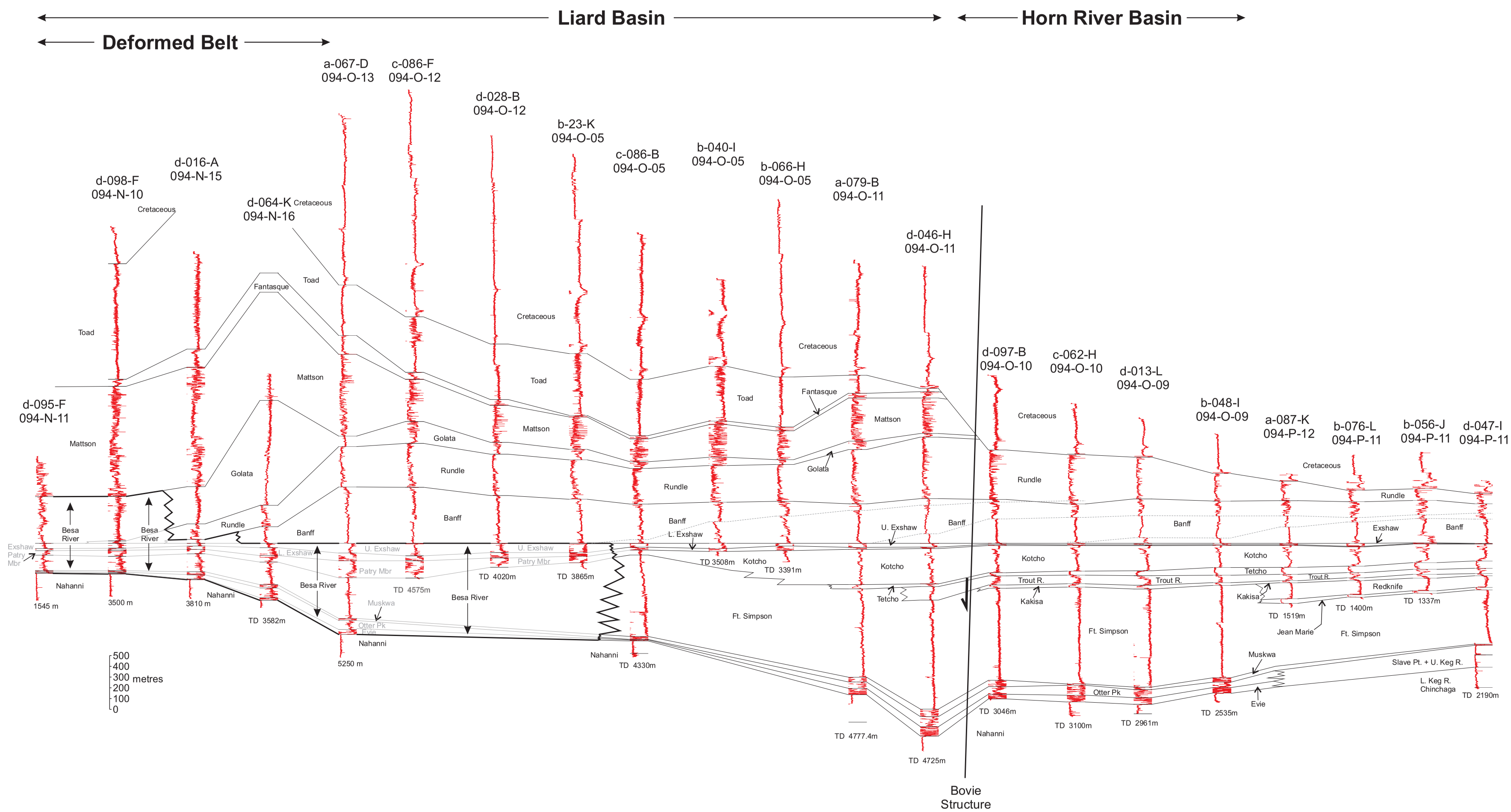

Figure 8: Regional correlation of subsurface units using gamma ray logs extending from the eastern margin of Horn River Basin to the central part of Liard Basin. The definition of sections equivalent to formations east of the transition to the Besa River Formation are shown by use of lighter grey text and correlation lines. The Besa River Formation thins to the west, but thickens again in its western extent due to the shale out of Rundle and Banff carbonate rocks and the incorporation of Golata shales. The formation thins to less than half the thickness shown in d-95-F in Caribou Range exposures. The excessive thickness of Golata shales in d-64-K is likely structural. The top of the Exshaw Formation is the datum; see Figure 1 for location.

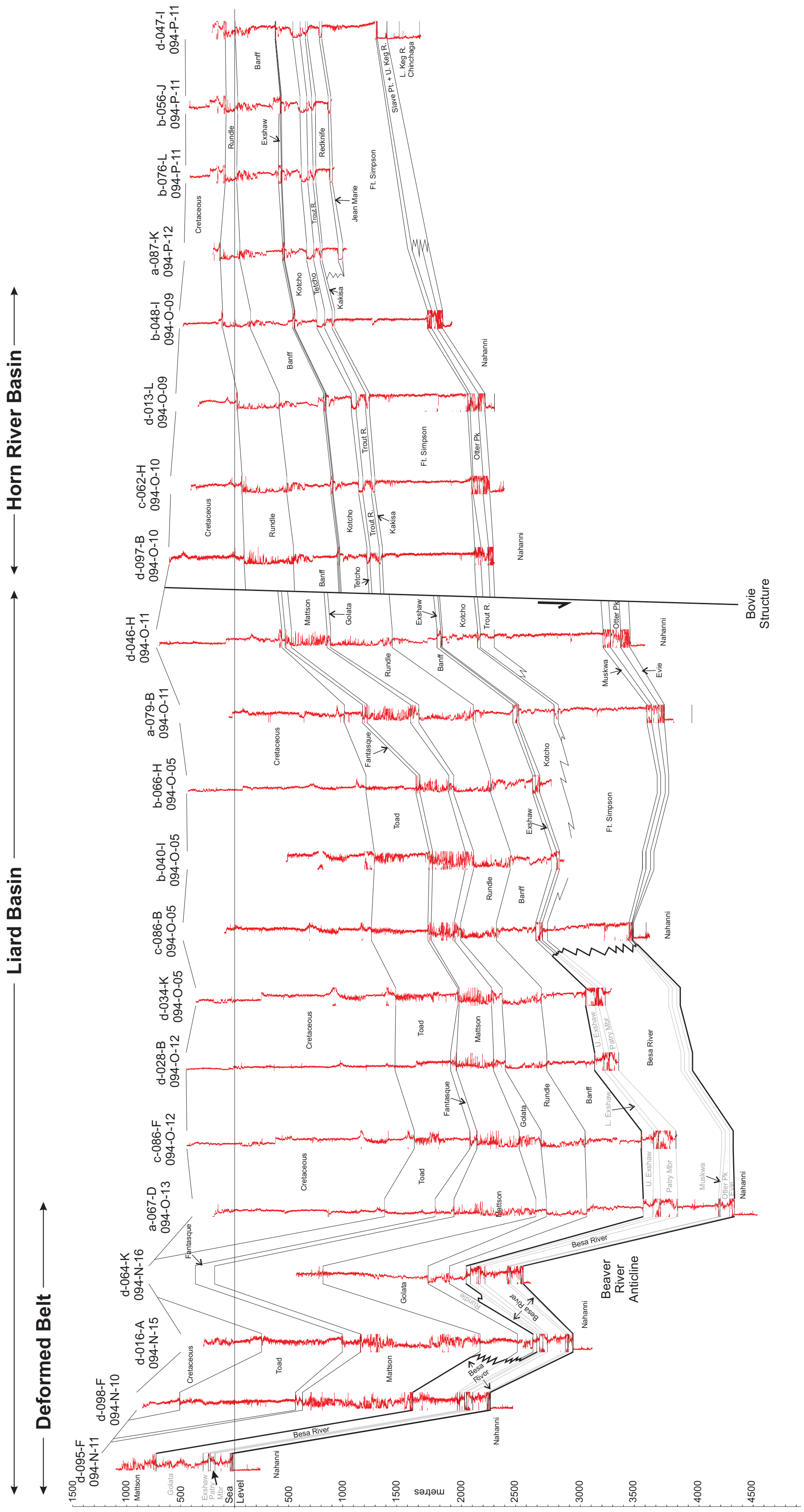

Figure 9: Sub-sea section using the same data as in Figure 4. This representation shows the displacement along the Bovie structure and uplift in the deformed belt. Also note the eastward bevelling of stratigraphy below the Cretaceous unconformity and the preservation of Triassic to upper Paleozoic stratigraphy in the Liard Basin. See Figure 1 for location.

Exshaw marker can commonly be separated from underlying organic-rich shales through use of logs, although the lithologic distinction is less clear (see below). As such, it is herein recommended that, as one moves to the west in the subsurface of Liard Basin, the first use of the term Besa River Formation be reserved for the shale succussion west of the last definitive Kotcho developed between carbonates of the Banff and Nahanni formations (Figure 8, 9). Markers equivalent to the Exshaw, Fort Simpson and Horn River formations can still be delineated within the Besa River Formation.

By virtue of its distinctive radioactive signature, the Exshaw Formation is another useful marker that can be correlated into Liard Basin. This unit is relatively thin to the east, but thickens west of the Bovie structure (Figures 8, 9, 10). It is less than 10 m thick near the Cordova Embayment but thickens to over 50 m in the region of shale gas development in the Liard Basin (NTS 94O/5, 12 and 13). In this study the Exshaw Formation/Member is subdivided into two parts: a lower unit of radioactive and resistive, organic-rich shale, and an upper unit of less radioactive dark grey shale, calcareous shale or limestone. The top of the Exshaw is commonly marked by a radioactive horizon.

Banff and Rundle formation carbonate rocks extend farther to the west, although the number of shale interbeds increases and carbonate beds thin. Also evident are clinoforms in the Banff Formation and Rundle Group (Figure 8). Where these formations thin and disappear, the Golata Formation thickens, and the horizon correlated with the Fort Simpson Formation thins markedly. The distinctive, mid-grey, soft nature typical of Fort Simpson shales is lost at sections in NTS 094N and instead, darker grey, more siliceous and organic-rich radioactive shales are encountered (Figure 8). In the subsurface of western Liard Basin, the Besa River Formation is approximately 600 m thick and is found between the base of the Mattson Formation and top of Dunedin carbonate rocks. Within the Besa River, radioactive markers equivalent to the Horn River and the Exshaw formations, together with radioactive zones between the two horizons can be distinguisged. In the outcrop belt farther west, the same section is about 300 m thick (Ferri et al., 2010, 2011, 2012). Based on the above correlations, this 300 m-thick section corresponds to over 2700 m of stratigraphy found near the Bovie structure.

The correlations displayed in Figures 8 and 9, particularly in the western part of Liard Basin, differ from those suggested by Ferri et al. (2010) who traced an outcrop section of the Besa River Formation in the Caribou Hills into the subsurface. The outcrop section equated with the Muskwa marker by Ferri et al. (2010) is likely a younger horizon in overlying rocks equivalent to the Fort Simpson marker. This would suggest the Horn River marker in Caribou Hills is condensed, consistent with the regional cross sections shown in Figures 8 and 9.

4.2. Patry – La Jolie – Birch areas

Initial success in developing shale gas resources in Liard Basin was in the Patry area, where the targeted horizon was referred to as the ‘First Black Shale’ of the Besa River Formation (Figure 11, Apache Canada Ltd., 2012). This horizon spans stratigraphy between the Exshaw Formation and units assigned to the Kotcho or Fort Simpson formations (Figure 11; Apache Canada Ltd., 2012; Poco Petroleums Ltd., 2000). Although the Banff Formation was recognized in the well, the contact with the Upper Besa River Formation was placed several hundred metres above their Exshaw Formation, resulting in the latter being placed in the middle of the Besa River Formation (Apache Canada Ltd., 2012).

The term “First Black Shale” was used to describe the first section of organic-rich, radioactive shales encountered while drilling through rocks assigned to the Besa River Formation (BC Ministry of Energy and Mines, 2005; Morrow, 2012; Amoco Canada Petroleum Ltd., 1974). The use of this term and other unit names have not been applied consistently in the Patry, La Jolie, and other areas of the Liard Basin. This inconsistency likely reflects proximity to the shale-out of units such as the Kotcho and Tetcho formations and increased shale content in the overlying Banff Formation. In addition, although the Exshaw marker can be recognized, it sits above another section of radioactive, organic-rich shale that occupies the same stratigraphic horizon as the Kotcho Formation to the east (Figures 10, 11), suggesting the latter has shaled-out into this succession. Although this interval has characteristics similar to the Exshaw Formation, it is much thicker and is much more calcareous relative to eastern sections.

As described above, for the purposes of this report, the term “Besa River Formation” is applied to the section extending from the top of the Exshaw member or marker as shown in the Apache Patry b-23-K well in Figure 9 and extending down to the top of the Nahanni Formation (Figures 8, 9, 10). The overlying calcareous shales more closely resemble the Banff Formation. The upward shift in the top contact of the Besa River Formation as one moves westward reflects the decrease in the dominance of calcareous material in the overlying Banff and Rundle sections. Ultimately, several reference sections of the Besa River Formation should be established to define the unit from the subsurface westward into the outcrop belt.

In the Patry area, the Exshaw marker appears to occupy the upper part of the Besa River Formation, extending down to the middle part of the radioactive zone originally designated as the “First Black Shale” (Figure 11). The radioactive section underlying the Exshaw marker does not have an equivalent in sections to the west, and occupies the same stratigraphic interval equivalent to the Kotcho Formation (Figure 10). The similarities between these lithologies and overlying rocks equivalent to the Exshaw (see below), suggest deposition under similar conditions. In this report, the term “Patry member” is applied to this organic-rich, radioactive zone below the base of the Exshaw marker.

4.3. Apache Patry b-23-K

The core and analyses obtained from the Besa River Formation in the Apache Patry d-23-K well represent an

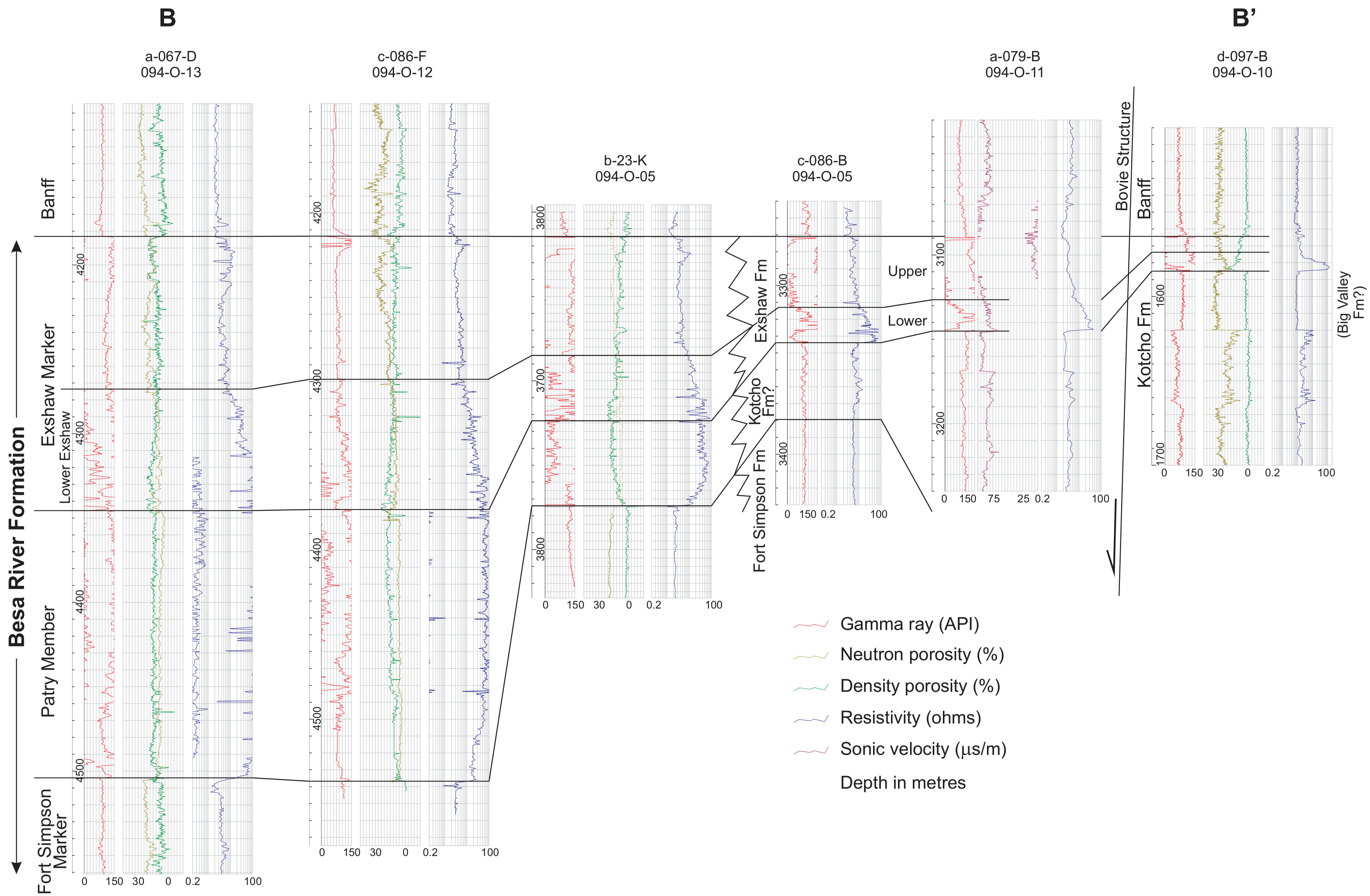

Figure 10: Stratigraphic correlation of the Exshaw Formation, and its equivalents, across the Bovie structure and into the Patry area. The Exshaw section thickens markedly across the Bovie structure and farther west into the Patry area. Note how the lithologies of the Kotcho Formation correlate into the organic-rich shales of the Patry member. The datum is the top of the Exshaw Formation or marker; see Figure 2 for location.

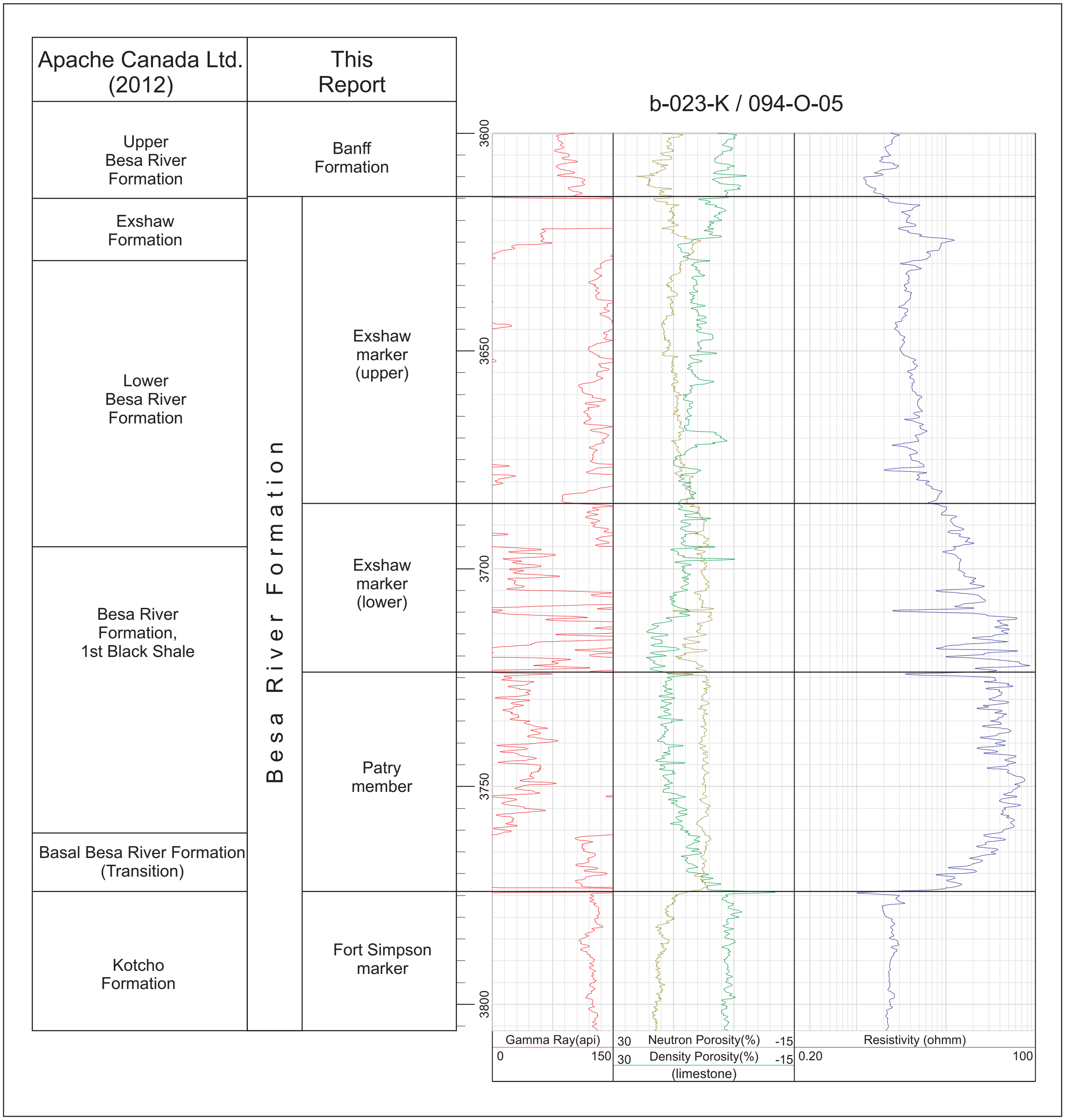

Figure 11: Gamma ray, density-neutron and resistivity profile across the bottom section of the Apache Patry b-23-K/94-O-5 well together with formation picks by Apache Canada Ltd. (2012) and those proposed in this report.

unparalleled public data set across this important shale gas sequence (Apache Canada Ltd., 2012). Over 80% of the interval was cored, and data were acquired from numerous analytical techniques including Rock-Eval, lithogeochemistry (ICP-MS and ICP-ES), X-ray diffraction, rock mechanics, porosity and permeability, adsorption isotherms, and cation exchange capacity. In addition, detailed pre-analysis core photographs were provided.

4.3.1. Lithology

Lithologically, the upper Exshaw marker is characterized by dark grey to black carbonaceous and siliceous mudstone to shale displaying poor partings and well-developed rhythmic laminations (Figures 12, 13, 14). The laminations are less than 2 mm thick and typically have sharp bases. Lighter grey laminations are richer in siliciclastic grains whereas the intervening darker layers have higher organic carbon contents. Locally, siliciclastic-rich layers appear to grade into those that are organic rich. The upper Exshaw marker also contains a breccia zone in which mudrock clasts are cemented by calcite (Figure 13b). The lower Exshaw marker is slightly paler in colour and characterized by better developed laminates. The upper part of the lower Exshaw marker is more fissile and displays sporadic, thin calcareous horizons in the lower part, some of which are graded. The upper part of the lower Exshaw marker also contains a 2 cm thick grey, tuffaceous horizon (Figure 12) which has been sampled for U-Pb geochronology.

The Patry member contains thin calcareous laminations up to a few millimetres thick that are locally graded and commonly display lensoidal bedding forms, which may be starved ripples (Figure 14a). These calcareous laminations can display sharp bases and locally grade into overlying darker, organic-rich layers. The carbonate material in these horizons appears to be detrital; some horizons contain coarse crinoid ossicles and shell fragments (Figure 14d). Most of the Patry member (i.e. inter-laminae material) is also calcareous. Lenses or thin horizons of finely crystalline pyrite are also common (Figure 14c).

Disseminated to nodular pyrite is common in the Patry member. The base of the unit is characterized by a 20 cm thick zone of bedded or disseminated pyrite corresponding to the gamma ray spike shown in Figures 12 and 15. The presence of this horizon is considered to be linked to the change in chemistry of the hosting lithologies together with the suggested anoxification of bottom ocean waters. Underlying grey shales are calcareous and less carbonaceous and outwardly resemble the Fort Simpson Formation, although the carbonate content (less than 5 %) would suggest they are distal equivalents of the Kotcho Formation.

The preservation of delicate lamination in the rhythmites indicates deposition below storm wave base and the absence of bottom-dwelling fauna capable of bioturbation, which supports anoxic bottom waters. The sharp basal contacts of many of these laminae in conjunction with graded bedding, possible starved ripples, and bioclastic detritus are consistent with deposition as distal turbidites, likely sourced from shallower shelf environments to the east.

4.3.2. Re – Os geochronology

Use of the Re – Os geochronometer in black shales is based on the realization that, under anoxic to sub-oxic conditions, Re and Os in seawater is incorporated in preserved organic matter. The resultant concentrations of these elements in anoxic sediments (up to 400 ppb Re and 4 ppb Os) are several orders magnitude greater than abundances in detrital constituents. Although the best error for the method is greater that modern U-Pb geochronology (± 10% absolute age), it is still useful in obtaining a relatively accurate age for a sedimentary sequence where biostratigraphic or other radiometric dating techniques are unavailable (e.g., Cohen et al., 1999; Creaser et al., 2002, Selby and Creaser, 2003, 2005, and Kendall et al., 2004, 2006, 2009).

Two sample series were acquired for Re – Os geochronology; 6 samples were taken every 15 cm between measured core depths of 3709.0 to 3709.75 m (corrected depth of 3707 to 3707.75 m) and 6 samples were taken every 15 cm between drilled core depths of 3762.0 to 3762.75 m (corrected depth of 3758.0 to 3758.75 m). The samples were acquired from the top and bottom of the gas-prone zone in stratigraphy with a high total organic carbon content so as to assure sufficient Re and Os were incorporated into the sediment. The upper sample is from the lower Exshaw marker, whereas the lower sample is from the base of the Patry Member (Figure 12).

Preliminary ages based on a 6 point regression returned an age of 357 ± 25 Ma for the upper sample (3709 m) and 354 ± 17 Ma for the lower sample (3762 m). The large errors are due to the scatter of several fractions in each sample suite. These sample fractions will be re-analyzed in hopes of improving the age and precision.

These preliminary ages and associated errors, are consistent with those obtained from sections of the Exshaw Formation in other parts of the Western Canada Sedimentary Basin (U-Pb monzonite, 363.3 ± 0.39 Ma, Richards et al., 2002; Re-Os, black shale, 358 ± 10 Ma, Creaser et al., 2002; Re – Os, black shale, 361.3 ± 2.4 Ma, Selby and Creaser, 2005). These data support correlation of the upper, more radioactive section of the gas-prone zone with the eastern lower Exshaw Formation.

4.3.3. Geochemistry and X-ray diffraction

Rock-Eval data trends from core analysis indicate total organic carbon (TOC) contents of 1.5 to 6 wt. % across the lower Exshaw marker and the Patry member, with an average of approximately 3 wt. % (Figure 16). Lithogeochemical data show silica contents (predominantly as quartz, based on X-ray diffraction data) range from 65 to 85 wt. % in this zone, which decreases into the Fort Simpson marker (Kotcho of Apache Corp report) (Figures 16, 17). Terrigenous content, measured by total Al_2O_3+K_2O+TiO_2, is highest in the upper Exshaw marker and Fort Simpson marker (corresponding to higher clay contents), and is lowest across the gas-prone part of the lower Exshaw marker and Patry member. This also corresponds to

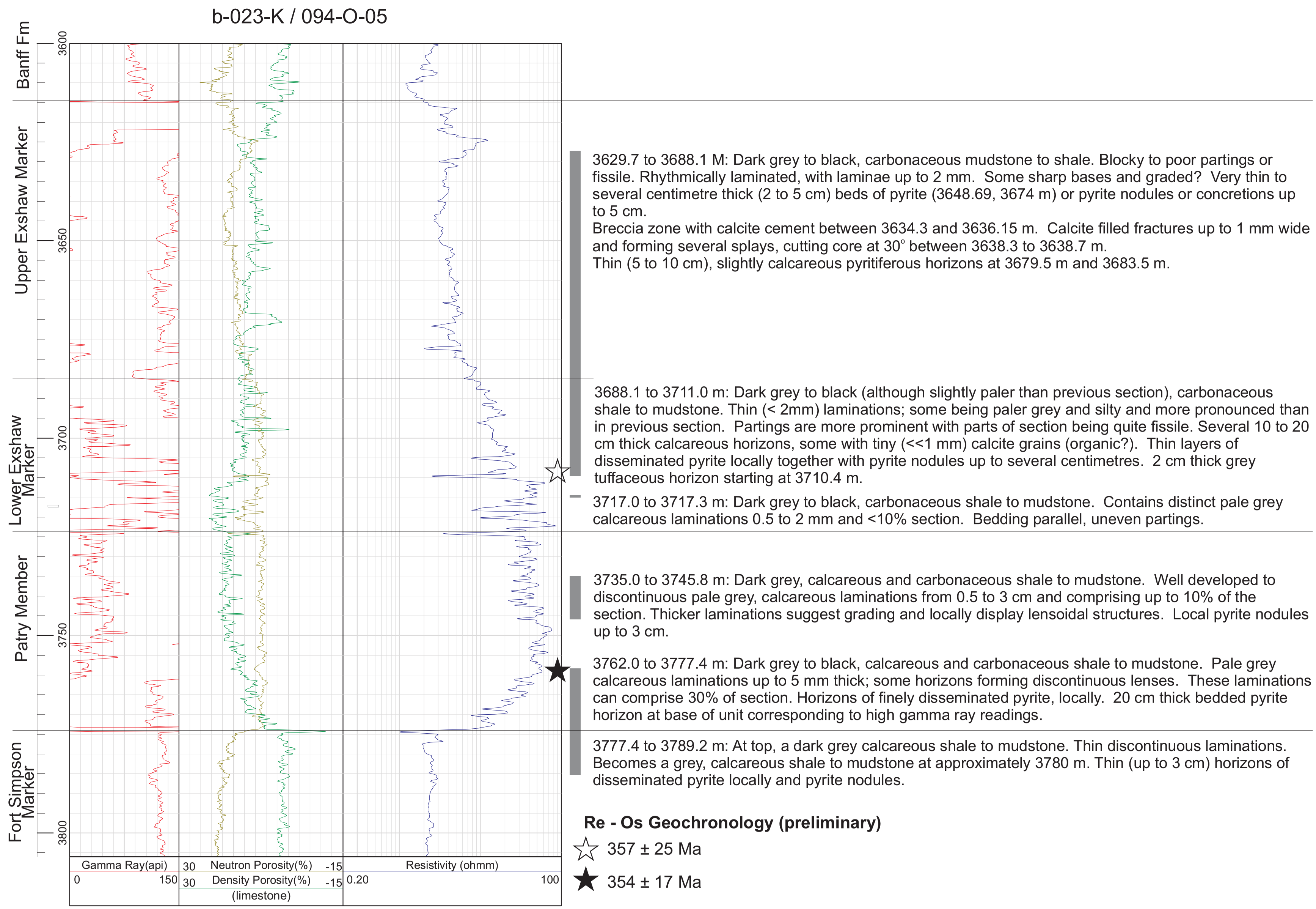

Figure 12: Lithologic description of core from the Apache Patry b-23-K well. Also shown are the stratigraphic positions of the Re – Os preliminary age determinations.

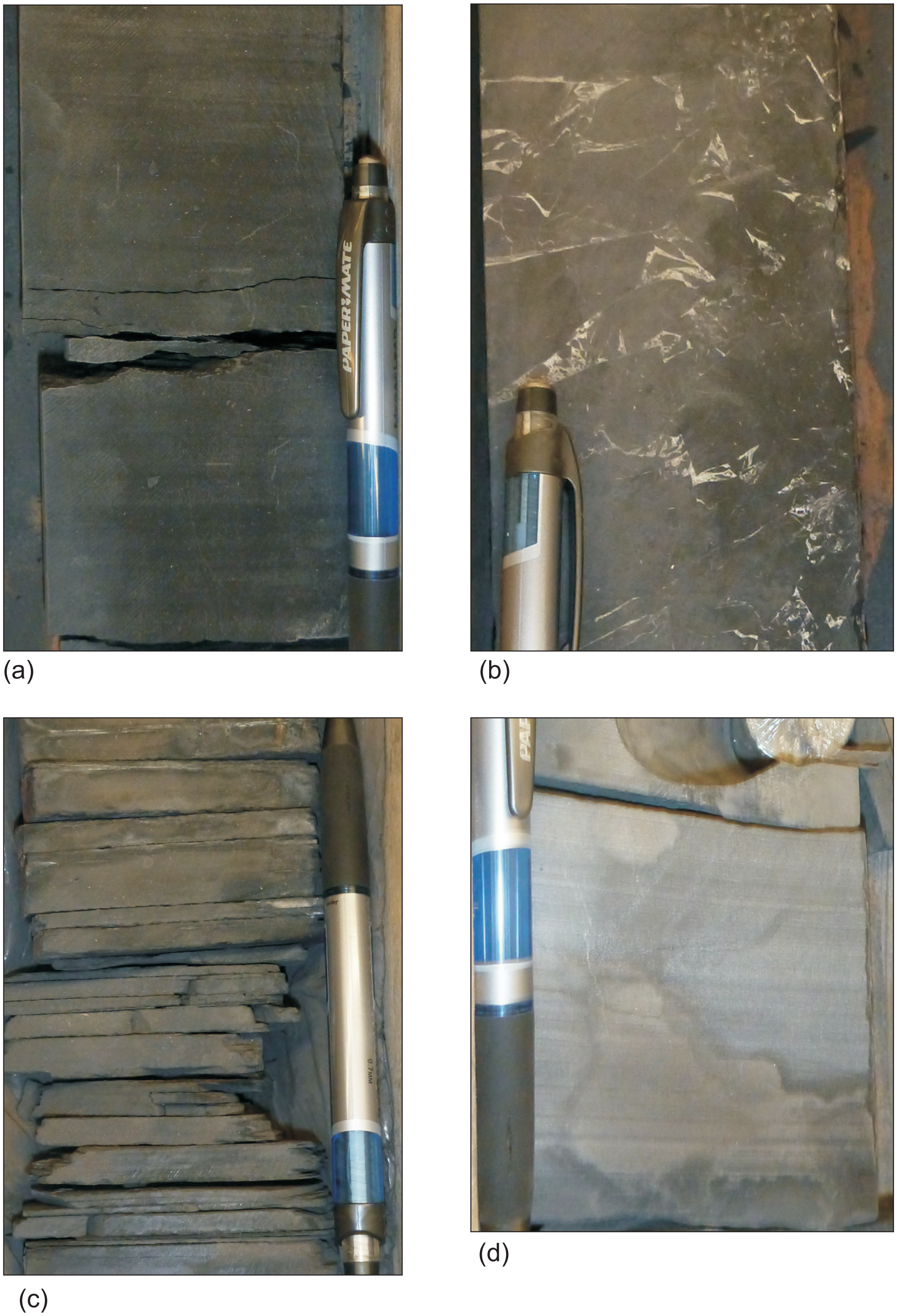

Figure 13: Photographs of core within the Exshaw marker of the Apache b-23-K well. **(a)** Photograph of the upper Exshaw marker at the 3657.75 m level. This is typical of the dark grey mudstone to shale in the upper Exshaw marker containing the thin rhythmites. These lighter grey horizons commonly show sharp bases and can grade into overlying darker grey and more organic-rich horizons. **(b)** Calcite-cemented breccia at the 3634.5 m level; upper part of upper Exshaw marker. **(c)** Laminated and fissile shale to mudstone, upper part of the lower Exshaw marker, 3692.3 m level. Note the more pronounced laminations (rhythmites) relative the Upper Exshaw marker in (a). These laminations are, for the most part, non-calcareous, although some (Figure 12) contain calcareous material. **(d)** Laminated and slightly paler grey shale to mudstone, lower Exshaw marker, 3699.5 m level.

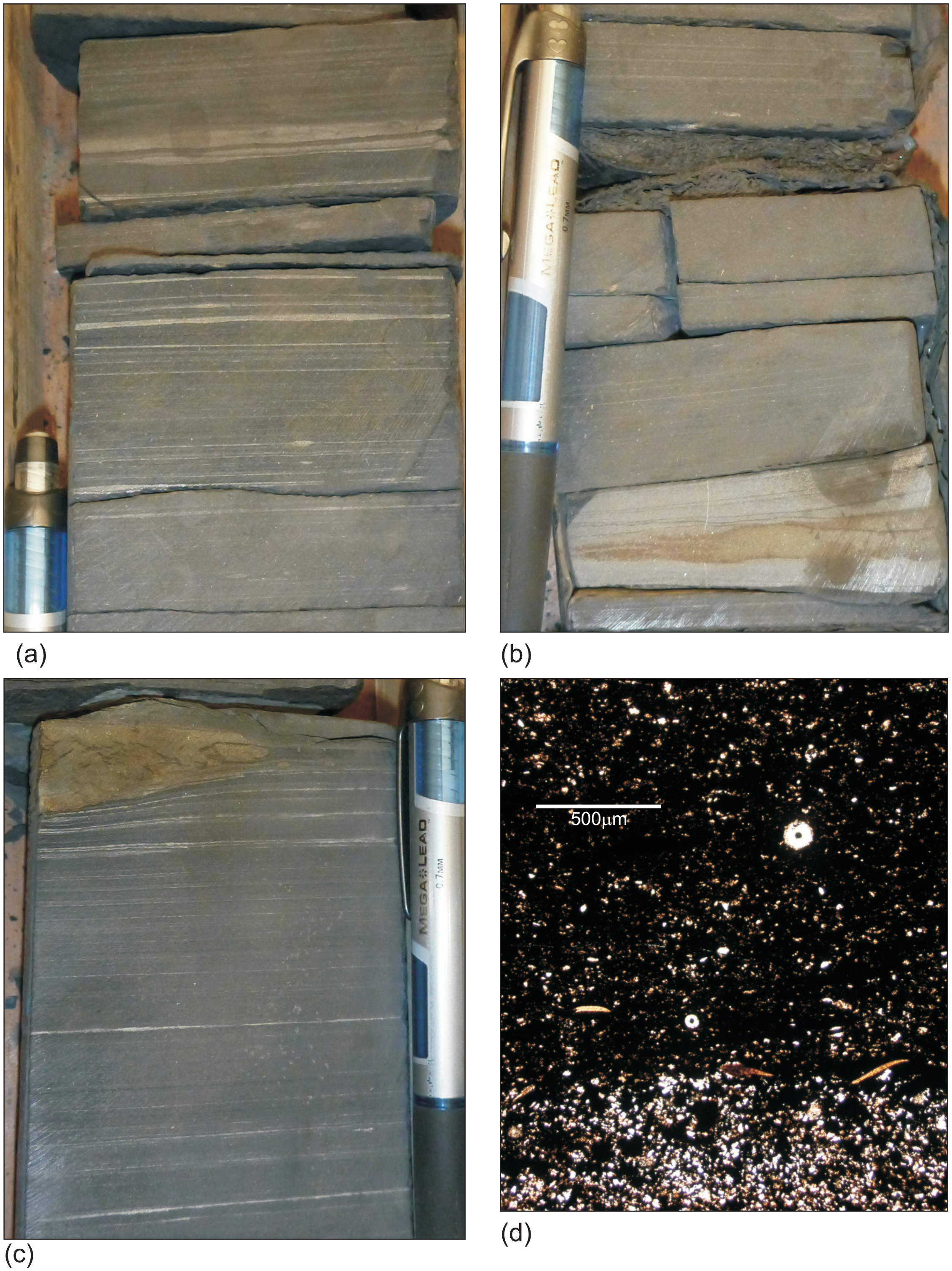

Figure 14: Photographs of Patry member core from the Apache b-23-K well. **(a)** Dark grey calcareous mudstone to shale of the upper Patry member containing light grey clastic carbonate layers that locally form discontinuous lenses, 3736.25 m level. The carbonate layers locally have sharp bases and appear to grade into dark grey shale or mudstone. Lensoidal calcareous layers, such as near the top of the core may represent starved ripples **(b)** At base, light grey, calcareous horizon several centimetres thick in the upper Patry member displaying inclined bedding, 3743.7 m level. There is pyrite in the core of this horizon and this inclination could be the result of compaction (see Figure 10c). **(c)** Dark grey calcareous shale of the lower Patry member containing thin, discontinuous light-grey carbonate layers and a pyrite nodule (upper left), 3771.6 m level. Note the similarity with the upper Patry member. **(d)** Photomicrograph of dark-grey, laminated, and calcareous shale of the lower Patry member, 3775.2 m level. Note crinoid ossicles and shell fragments.

Figure 15: Fine- to medium- crystalline bedded pyrite (buff) horizon about 20 cm thick (top at 3777.17 m). Based on the correlation of the core gamma ray log with the downhole gamma ray profile, this horizon corresponds to the large gamma ray excursion at 3774 m on the gamma ray log, at the contact between the Patry member and the Fort Simpson marker (Figure 12). This pyrite likely formed in situ and, developed at the boundary where geochemical data suggest an oxic to anoxic switch, probably records changing redox conditions in the water column.

the highest TOC contents. Silica is predominantly of organic origin as shown by the negative correlation of Zr versus SiO_2 (Figure 18f). Concentrations of elements such as Mo, U, V, and Mn indicate anoxic conditions throughout Exshaw marker and Patry member deposition (Sano et al., 2014; Algeo and Maynard, 2008). The abundance of fine laminae lacking evidence of any bioturbation supports the inference that the water column was low in oxygen and could not support multicellular organisms. These conditions would have enhanced preservation of organic matter.

The mineral composition of the core, based on X-ray diffraction data, displays trends similar to bulk compositions defined from lithogeochemical analysis (Figure 17). Clay contents follow Al_2O_3 levels, being lowest across the gas prone parts of the lower Exshaw marker and the Patry member. Quartz content increases across this zone and carbonate contents increase in the Party member and underlying shales of the Fort Simpson marker (Figure 17). Porosity averages between 4 and 9 %, being highest in the organic-rich horizon. Cross-plots of porosity versus major constituents show a slight positive correlation with total organic carbon contents (Figure 18) and very minor negative correlation with quartz and carbonate content. Clay content seems to have little effect on overall porosity (Figure 18). Not surprisingly, gas saturation correlates positively with total organic carbon and quartz contents (Figure 18), the latter likely reflecting the decrease in clay content (Figure 18). Although the cross-plot of gas saturation versus clay content shows a negative correlation (i.e. low gas saturations with high clay contents), the lack of correlation between porosity and clay content (and quartz and carbonate) suggests that the variation in gas saturation is tied primarily to organic carbon content.

5. Discussion

Although the Patry member of the Besa River Formation shares features with overlying lithologies of the Exshaw marker, it represents a section of stratigraphy not found east of the Patry area (Figure 19). This unit lies outboard of the shale-outs of Kakisa to Kotcho stratigraphy and its position immediately below rocks equivalent to the Exshaw Formation suggest it may be laterally time-equivalent to the upper Kotcho Formation. It is considerably thicker in the Patry and La Jolie areas suggesting fault motion may have occurred to create accommodation space. The sedimentary features displayed by Patry member (Figures 13, 14) are consistent with deposition as distal turbidites. Carbonate grain-rich laminae and bioclastic detritus support derivation from shelf carbonates of the Kotcho Formation farther east.

The Kotcho Formation is the upper unit of a transgressive-regressive succession which began with deposition of the Trout River Formation, the base of which is an unconformity towards the shelf (Morrow, 2012; Geldsetzer et al., 1993). Carbonate and shaly carbonate rocks of the Trout River-Kotcho interval were deposited in a broad shelf that transitioned into an outer shelf in eastern Liard Basin and ramp to deep-water basin

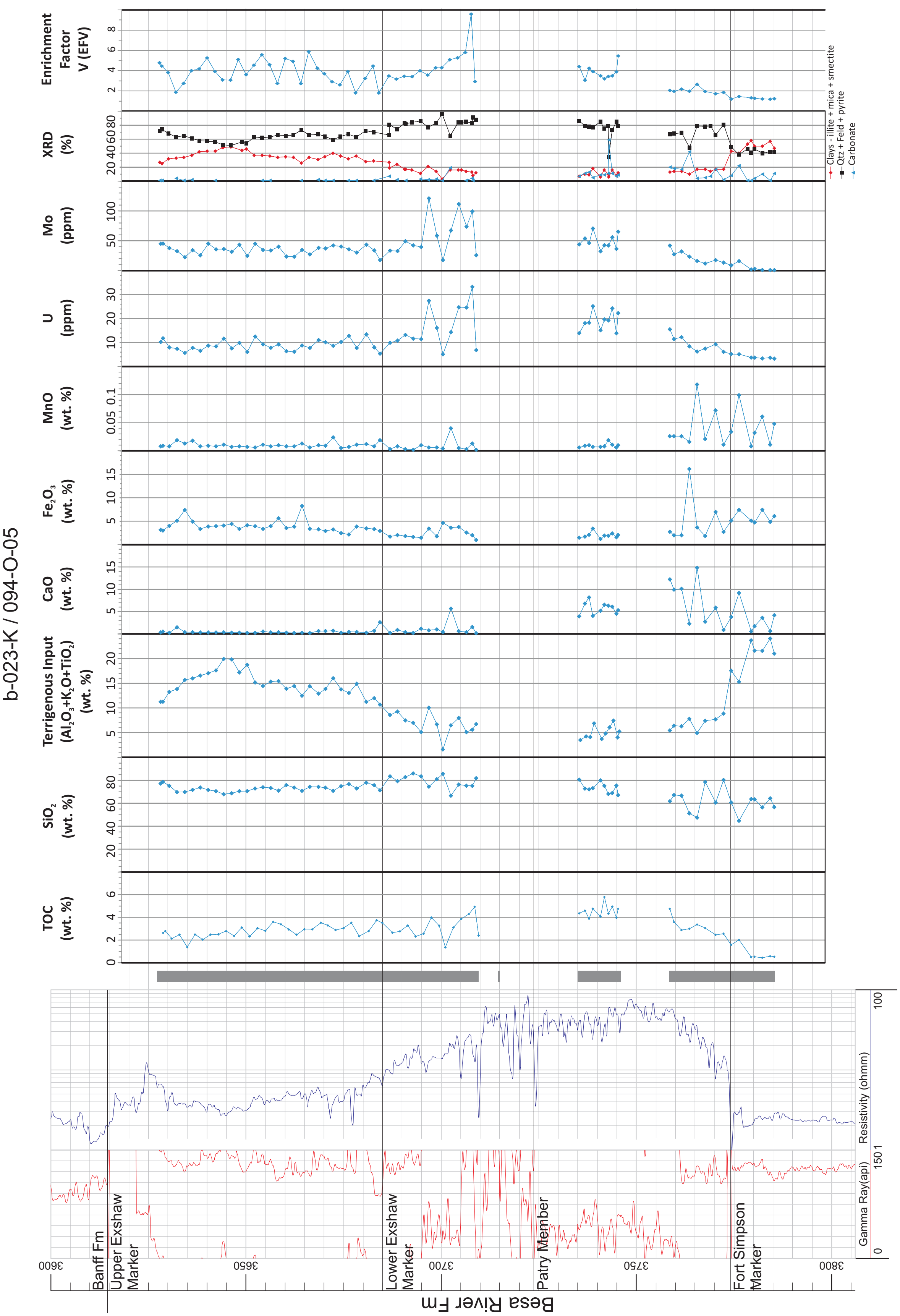

Figure 16: Comparison of gamma ray and resistivity logs across the upper Besa River Formation in the Apache Patry b-23-K well with variation in total organic carbon content from Rock-Eval analysis and selected major and minor element compositions acquired by ICP-MS and ICP-ES analysis (Apache Canada Ltd., 2012). Also shown is variation in major mineral constituents based on X-ray diffraction.

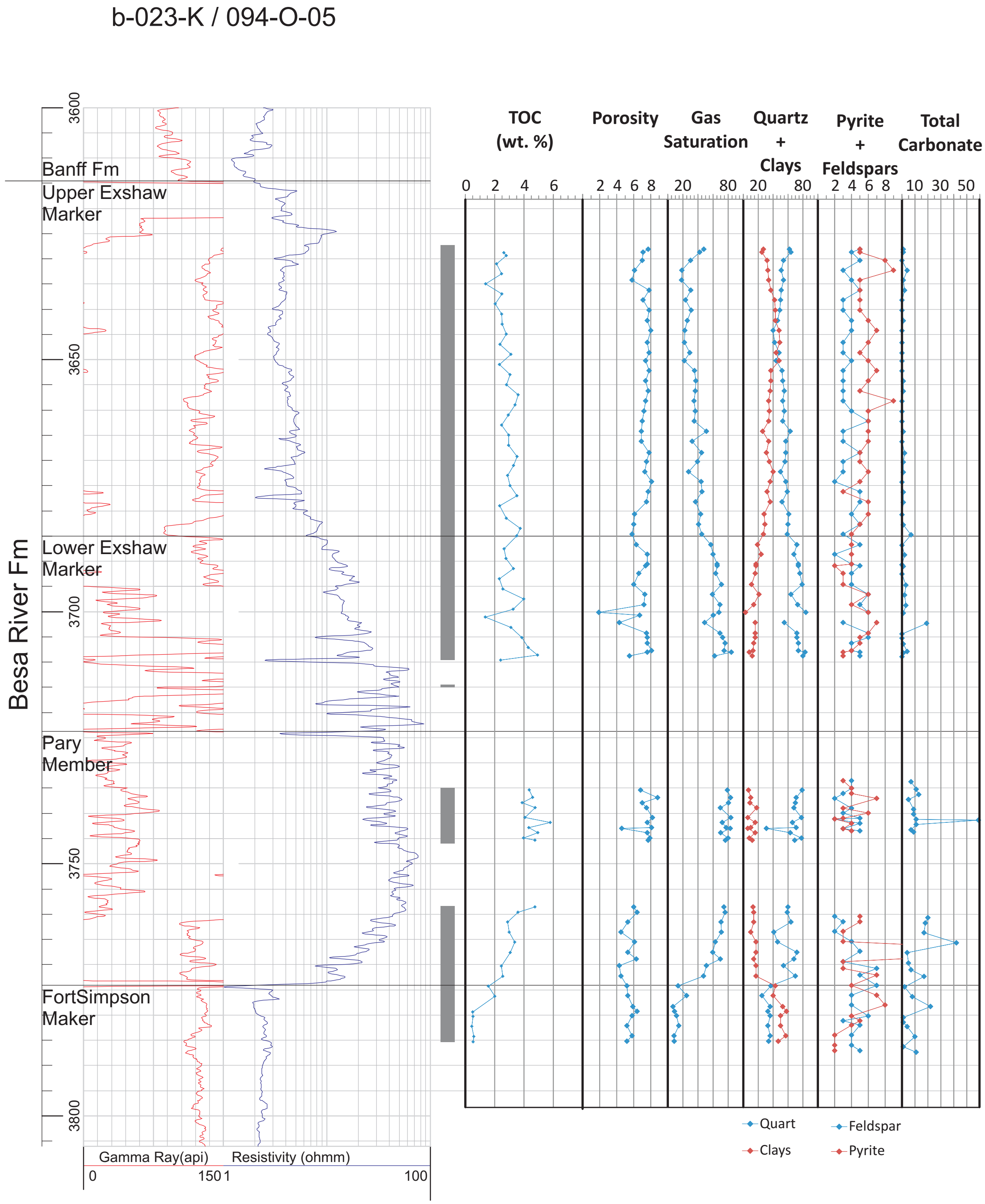

Figure 17: Comparison of gamma ray and resistivity logs across the upper Besa River Formation in the Apache Patry b-23-K well with variation in total organic carbon content from Rock-Eval analysis, porosity, gas saturation, and mineral composition (acquired by X-ray diffraction; Apache Canada Ltd., 2012).

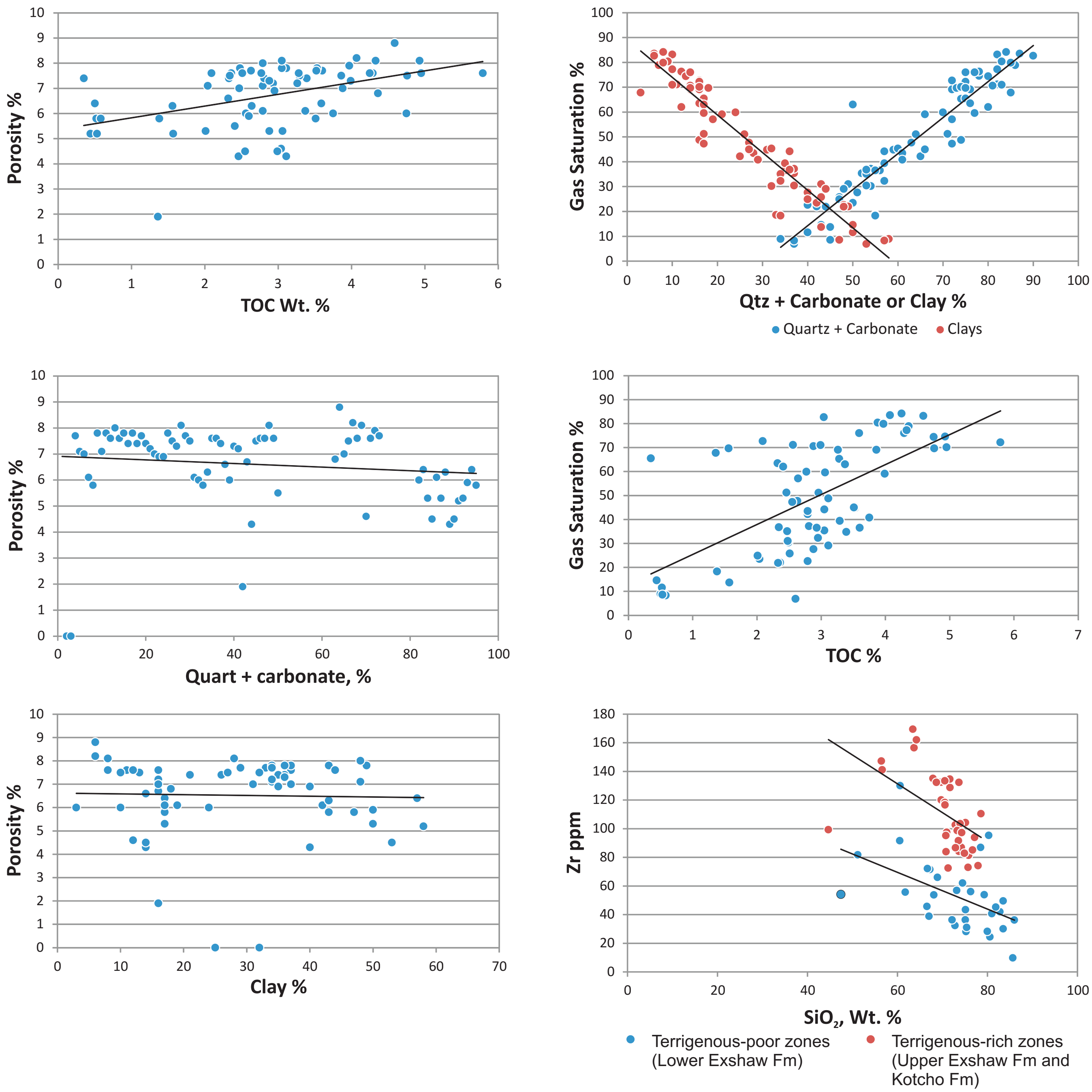

Figure 18: Apache Patry b-23-K core analysis. **(a)** to **(c)**, Variation of porosity with major mineral constituents (total organic carbon (TOC), quartz and carbonate and clay). **(d)** and **(e)** Variation of gas saturation and quartz-carbonate or clay content, and TOC. **(f)** Correlation between zirconium and silica content based on lithogeochemical analysis. Apache Canada Ltd. (2012).

settings in western Liard Basin (Halbertsma, 1994; Switzer et al., 1994).

The transition from predominantly carbonate shelf to outer shelf and deep-water basin for the Jean Marie, Kakisa and Kotcho carbonate rocks follows a north-south trend (Figure 20). For the Kakisa and Kotcho formations, this transition straddles and follows the trace of the Bovie structure (Figure 20). This suggests that the regional extensional tectonics represented by the initiation of the Bovie structure were likely active during Jean Marie to Kotcho sedimentation and localized the transition between shelf and off-shelf environments. Fault-controlled sedimentation during Kotcho and Tetcho sedimentation was interpreted in the Liard Basin area by Halbertsma (1994).

Although motion on the Bovie structure is thought to be no older than Late Mississippian (Monahan, 2000; MacLean and Morrow, 2004), thickness variations displayed by some Devonian units across the fault suggest Late Devonian movement (Figure 8). The Bovie structure was reactivated

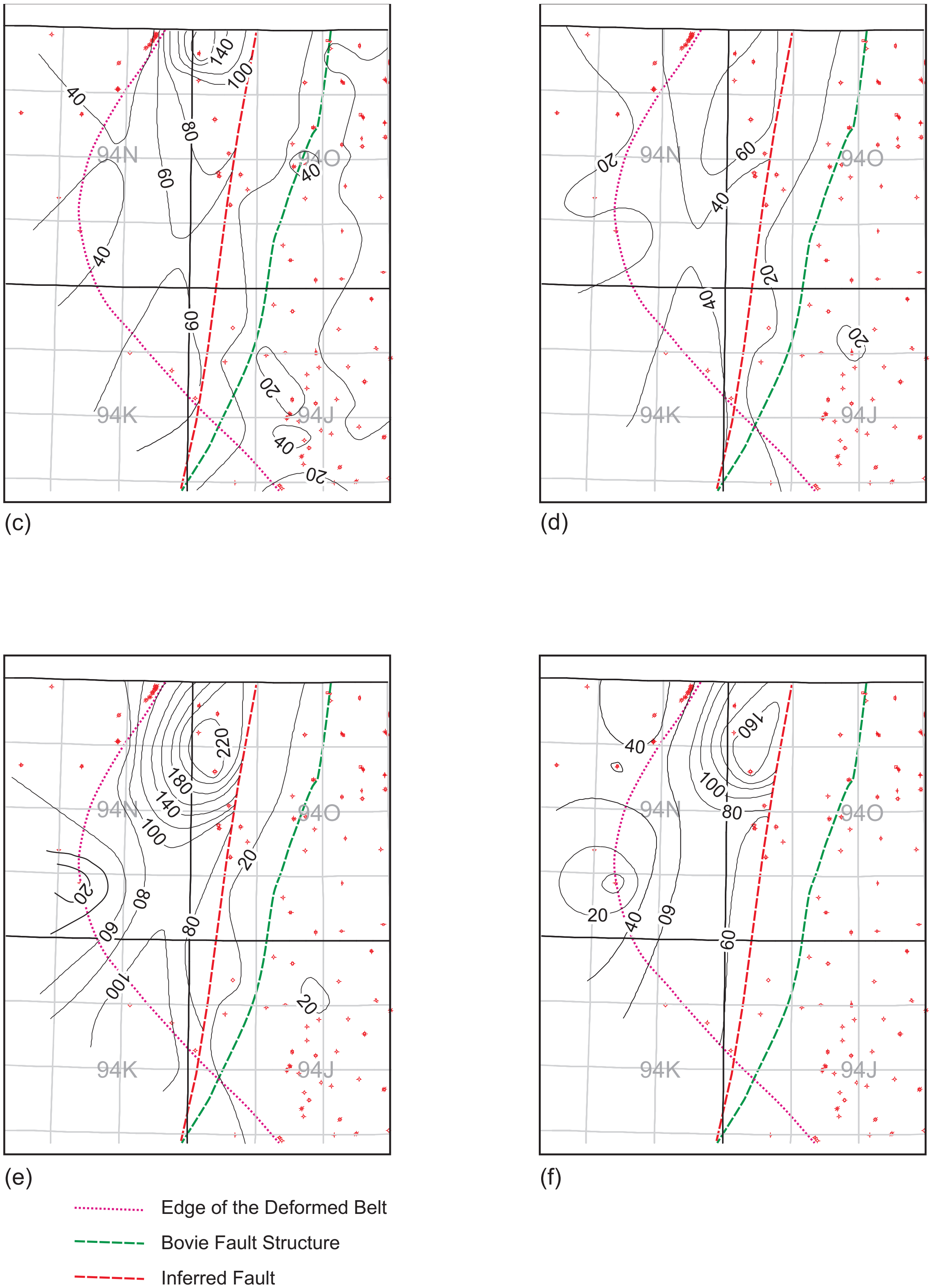

Figure 19: (a) Isopach map of the Upper Exshaw Formation and upper Exshaw marker. **(b)** Isopach map of the lower Exshaw Formation and lower Exshaw marker. **(c)** Isopach map of the lower Exshaw marker and the Patry member. **(d)** Isopach map of the Patry member. Shown in red is the inferred fault that is theorized to control the eastern limit of Patry Member deposition and lower Exshaw Marker deposition. Control wells are shown in red.

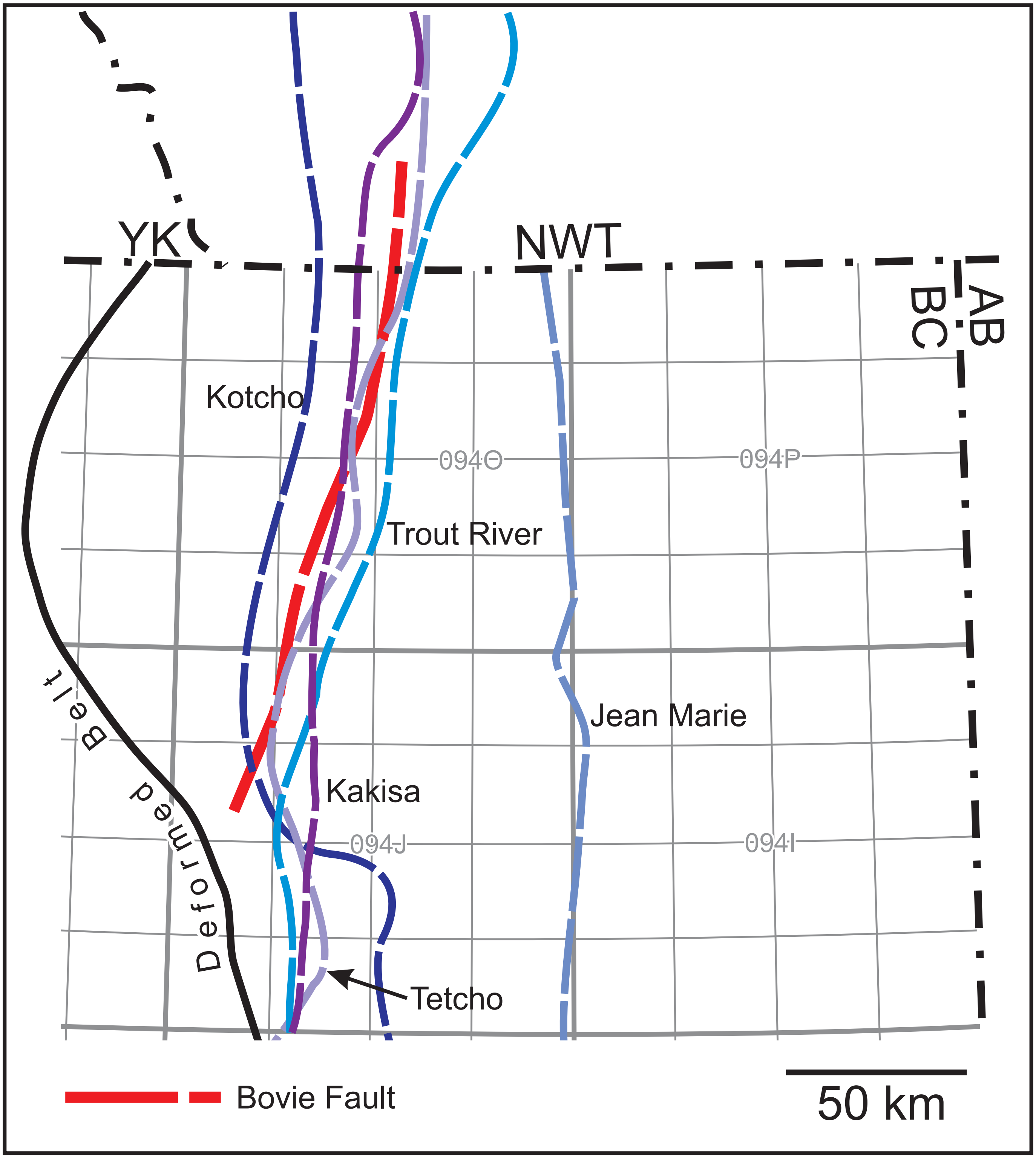

Figure 20: Map showing shale-out of Jean Marie, Kakisa, Trout River, Tetcho and Kotcho carbonates in relation to the Bovie fault structure. The southern departure in the north-south trend with respect to the Kotcho and Tetcho carbonates is due to the sub-Exshaw unconformity. Note the similar trend between these shale-outs and the trace of the Bovie fault structure.

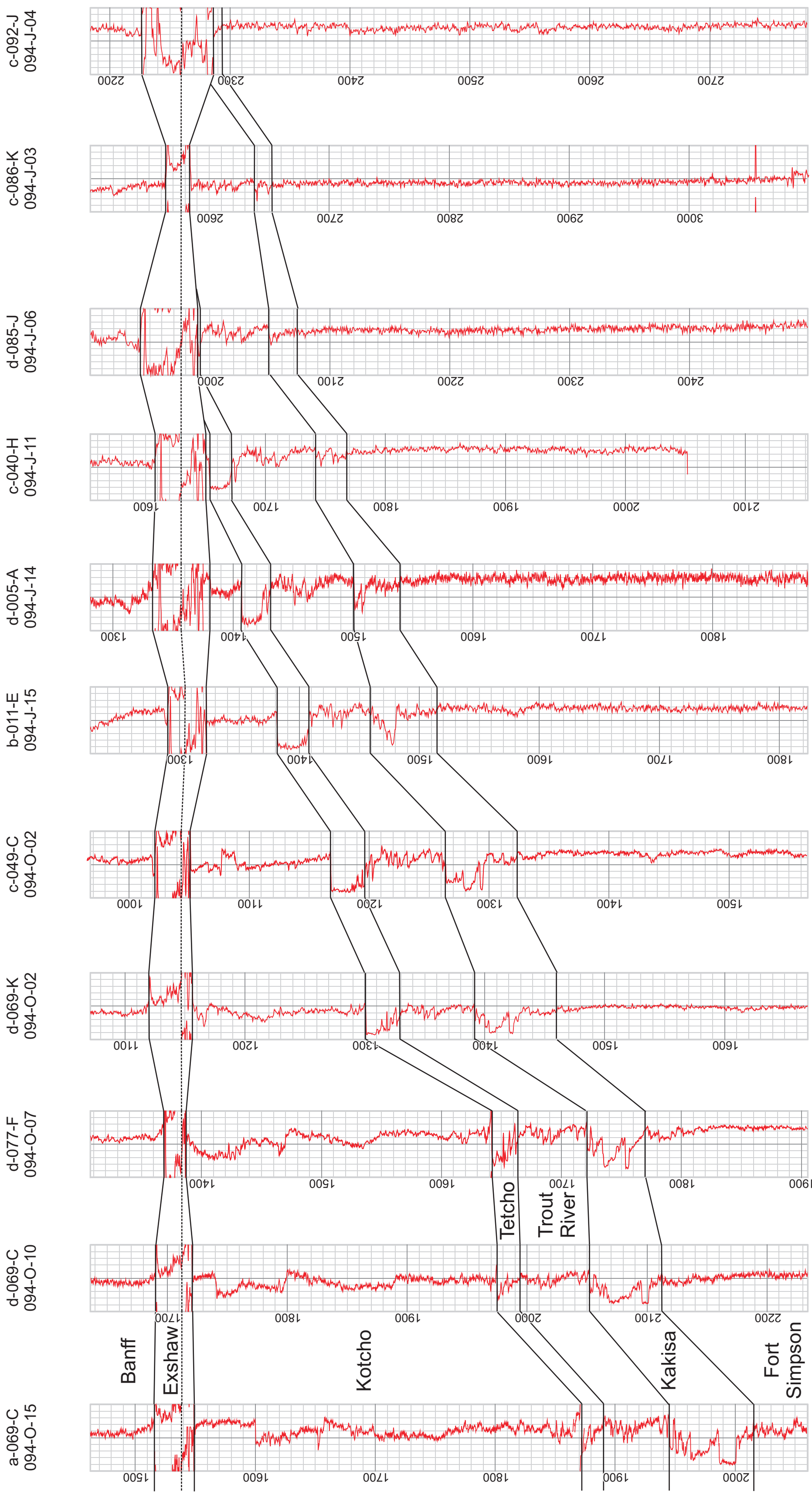

Figure 21: North – south cross-section along the east side of the Bovie fault structure illustrating the southward bevelling of Kotcho to Kakisa stratigraphy below the Exshaw Formation. Datum is the base of the upper Exshaw. See Figure 2 for location.

as a thrust fault during Cordilleran orogen deformation (MacLean and Morrow, 2004). The Bovie fault is parallel to and has similarities with steep reverse faults developed in the Mackenzie and Franklin mountains. We suggest that some or many of these structures represent reactivated normal faults that initiated in the early Paleozoic or mid to Late Devonian. Although few of these structures have surface expressions in British Columbia, we postulate that they extend southward into the La Jolie and Patry areas (Figure 4), where isopachs of the Patry member (Fig. 19) suggest local fault control.

The Exshaw Formation not only represents the beginning of a major, continent-wide transgression, it also contains the boundary between the Devonian and Mississippian systems, a major extinction event (Caplan and Bustin, 1999; Richards et al., 2002). The base of the Exshaw Formation is also an unconformity that bevels over 450 m of the underlying section southward along the east side of the Liard Basin (Figure21; Richards, et al., 1994). An unconformity at the base of the Exshaw marker is not currently recognized in the Liard Basin. The Patry member in Liard Basin could in part represent rocks preserved below the sub-Exshaw unconformity whose correlatives were removed in the east.

In Alberta, the base of transgressive-regressive sequence containing the Exshaw Formation lies within shale of the Big Valley Formation (Richards et al., 2002). Shale at the top of the Kotcho Formation west of the Bovie structure may be equivalent to the Big Valley Formation in Alberta (Halbertsma, 1994) and the base of the transgressive-regressive sequence is placed at the base of this shale. The maximum flooding surface is expected to occur within the peak gamma ray zone of the lower Exshaw Formation; the following regressive sequence is represented by the lower radioactive shales of the Upper Exshaw Formation (Figure 22). The base of the radioactive zone in the upper Exshaw Formation represents the beginning the next transgressive-regressive sequence, which encompasses most of the Banff Formation (Richards et al., 2002). Using these assumptions, the base of the Patry member would represent the deep-water basin equivalent to the lower boundary of the transgressive-regressive sequence encompassing the Exshaw Formation; i.e. part of the same system tract. The difference here is that instead of this system tract forming typical clinoforms that thin into the basin, the Patry member is considerably thicker due to synsedimentary faulting.

Rocks in the Exshaw marker and the underlying Patry member record anoxic to euxinic bottom waters, as indicated by elevated organic carbon contents and high levels of elements such as Mo and V, which are sensitive to redox conditions (Sano et al., 2014; Algeo and Maynard, 2008). This contrasts with shales of the underlying Besa River Formation, which are equivalent to the Fort Simpson Formation, that record normal marine oxygenated waters. Thus the widespread anoxic conditions represented by the Exshaw Formation may have already been established in the deeper parts of the Liard Basin during Patry sedimentation, while normal marine conditions prevailed on the ramp and shelf. Furthermore, the westward appearance of other radioactive shales in the Besa River Formation below the Patry member indicates similar conditions occurred in deeper western waters during the Late Devonian.

The model favoured here for development of the shale gas sequence in the upper part of the Besa River Formation of the Patry – La Jolie area envisages that anoxic bottom waters were established at or near the beginning of the transgressive sequence represented by the Patry member. Concurrently, one or more west side-down normal faults initiated on the eastern boundary of this area, sub-parallel to the Bovie structure. These structures allowed formation of the accommodation space required to accumulate the greater thickness of organic-rich Patry member strata. Fault motion continued during deposition of the lower Exshaw, and likely waned during upper Exshaw deposition. Although anoxic conditions existed within the basin at the initiation of the transgressive sequence, normal marine conditions were present farther east on the ramp and outer shelf. As transgression progressed, maximum flooding conditions were achieved, resulting in anoxic waters transgressing to the east and deposition of black shales of the lower Exshaw Formation across much of the shelf.

Although black, organic-rich shales of the Patry member and overlying lower Exshaw marker are developed throughout the central and western Liard Basin, the thickest sections occur in the inferred fault basin extending from the Patry – La Jolie area southward to the edge of the deformed belt (Figure 19). These relationships indicate that the most prospective area for shale gas resources in the upper Besa River Formation is smaller than the current outline of the Liard Basin, which may have implications on the ultimate potential of this shale gas resource.

6. Conclusions

Shale of the Middle Devonian to Middle Mississippian Besa River Formation in western Liard Basin is correlative to carbonate rocks and shales spanning the Horn River to Rundle intervals in the subsurface of the Western Canada Sedimentary Basin.

The upper Besa River Formation contains a gas-saturated, silica and organic-rich section equivalent to the Exshaw Formation, and an underlying unit informally named the Patry member in central and western Liard Basin.

This organic-rich succession has recently been the focus of shale-gas exploration, and initial horizontal production wells have proven successful, with initial daily rates upwards of 18 million cubic feet per day (510 x $10^3 m^3$) and with cumulative production of 6.5 billion cubic feet (184 x $10^6 m^3$) of natural gas since 2011.

This organic-rich sequence is thickest along its western extent (094O/5, 12 and 13) where it forms a north- to north-easterly trending trough over 200 m thick in its northern part.

We propose that these units were deposited in deep anoxic waters in the downdropped block of a syndepositional west-side-down normal fault. This postulated fault, subparallel and likely related to the Bovie structure, provided the accommodation

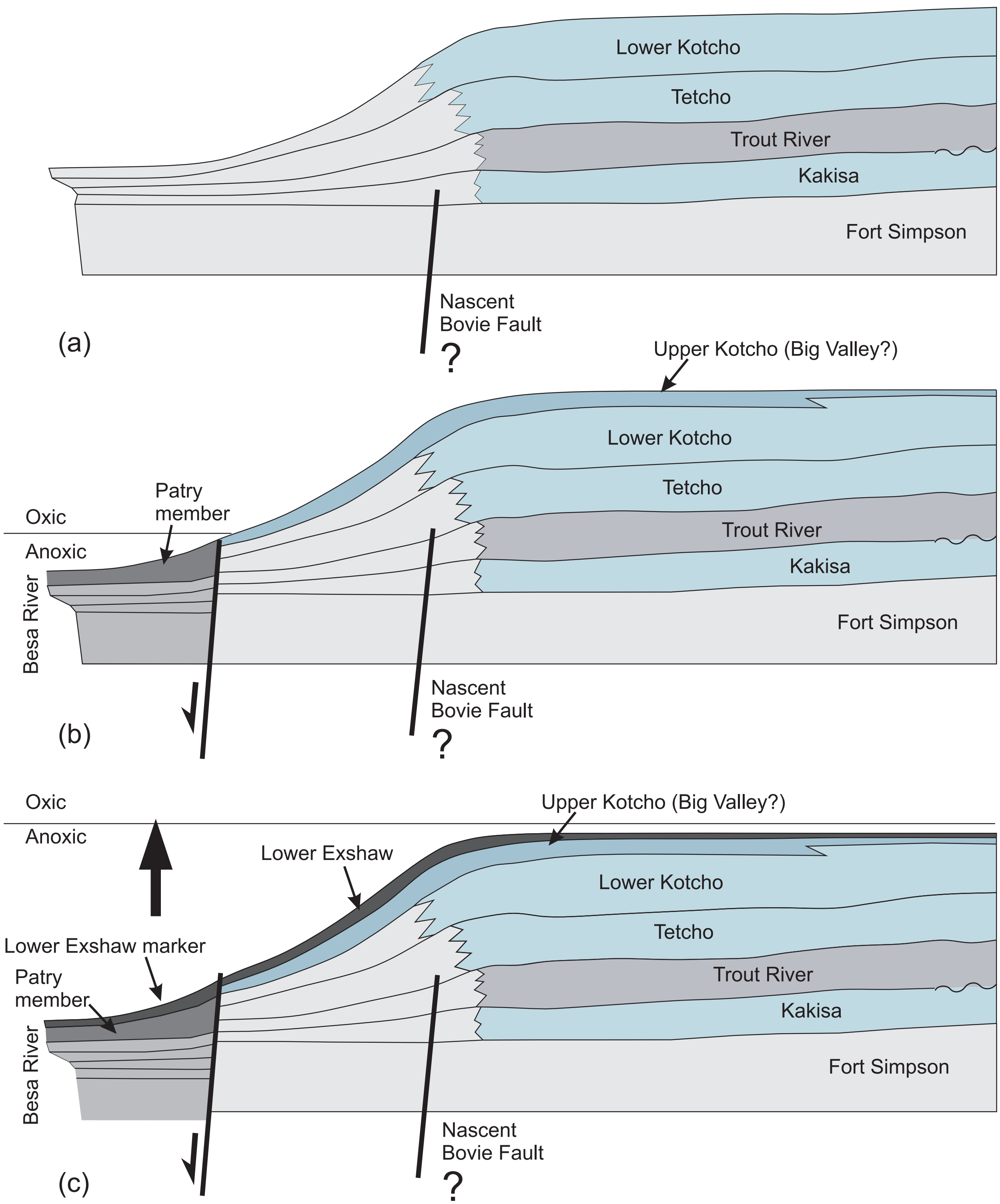

Figure 22: Proposed model for development of organic-rich shales in the central part of Liard Basin. **(a)** Deposition of Trout River to lower Kotcho succession as part of transgressive-regressive sequence. These carbonate rocks transition basinward into shales typical of the Fort Simpson Formation. Motion on the Bovie fault begins, helping to localize the shelf-slope break. **(b)** Beginning of the next transgressive-regressive sequence at the top of the Kotcho Formation. This is accompanied by faulting along a structure west of, and sub-parallel to, the nascent Bovie fault. The rise in sea level also saw anoxic conditions established in the deeper parts of the basin. **(c)** Sea-level rise continues, reaching maximum flooding during deposition of the lower part of the Exshaw Formation and anoxic waters flood the shelf. Faulting continues along the western structure, leading to a thicker section of deep-water rocks equivalent to the lower part of the Exshaw Formation.

space for deposition of a thickened Patry member section consisting of fine-grained, organic-rich sediment.

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