BESA RIVER FORMATION, WESTERN LIARD BASIN, BRITISH COLUMBIA (NTS 094N): GEOCHEMISTRY AND REGIONAL CORRELATIONS

Filippo Ferri[1], Adrian S. Hickin[1] and David H. Huntley[2]

ABSTRACT

The Besa River Formation in the northern Toad River map area contains correlatives of the subsurface Muskwa Member, which is being exploited for its shale gas potential. In the Caribou Range, more than 285 m of fine-grained carbonaceous siliciclastic sediments of the Besa River Formation were measured along the northwestern margin of the Liard Basin (the upper 15 m and lower 25 m of the section are not exposed). The formation has been subdivided into six informal lithostratigraphic units comprised primarily of dark grey to black, carbonaceous siltstone to shale. The exception is a middle unit comprising distinctive pale grey weathering siliceous siltstone. A handheld gamma-ray spectrometer was used to produce a gamma-ray log across the section, which delineated two radioactive zones that are correlated with the Muskwa and Exshaw markers in the subsurface. Rock-Eval geochemistry indicates that there are several zones of high organic carbon, with levels as high as 6%. Abundances of major oxides and trace elements show distinct variability across the section. The concentration of major oxides generally correlates with lithological subdivisions, whereas some of the trace-element abundances display a relationship with organic carbon content, suggesting that these levels are tied to redox conditions at the time of deposition.

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[1]Geoscience and Natural Gas Development Branch, Oil and Gas Division, BC Ministry of Energy and Mines, Victoria, BC; Fil.Ferri@gov.bc.ca

[2]Geological Survey of Canada, Natural Resources Canada, Vancouver, BC

Key Words: Liard Basin, Horn River Basin, Liard River, Toad River, Caribou Range, Besa River Formation, Horn River Formation, Muskwa Member, Fort Simpson Formation, Exshaw Formation, Mattson Formation, geochemistry, gamma ray, Rock-Eval, total organic content, oil, gas, sulphides

INTRODUCTION

The Geoscience and Natural Gas Development Branch of the British Columbia Ministry of Energy and Mines, in conjunction with the Geological Survey of Canada, undertook an examination of outcrop exposures of Middle Devonian to early Mississippian siltstone sequences of the Besa River Formation, which are equivalent, in part, to rocks currently being exploited for natural gas resources in the Horn River Basin and to sections being examined for similar potential in the Liard Basin (Figures 1 and 2). The main objective of this examination was to delineate shale gas–equivalent horizons in outcrop so that they could be used as potential reference sections to aid in understanding the subsurface geological setting in the Horn River Basin. Characterization of the section was accomplished through lithological description and collection of samples for lithological, organic geochemical and geochronological analysis. In addition, a gamma-ray spectroscopic survey of the outcrop was performed for use in correlating the section with subsurface sequences in the Liard and Horn River basins.

This study is part of a collaborative program between the Geological Survey of Canada and the British Columbia Ministry of Energy and Mines, and is under the umbrella of the federal government's Geo-mapping for Energy and Minerals program (GEM), which is examining petroleum-related geoscience of the Liard and Horn River basins. A major focus of this program has involved mapping resources associated with surficial geology that will assist with operational aspects of resource development (infrastructure, surface engineering, drilling and completion; Huntley and Hickin, 2010; Huntley and Sidwell, 2010; Huntley and Hickin, 2011; and Huntley et al., 2011).

LOCATION AND REGIONAL GEOLOGY

The Liard Basin is located in northeastern British Columbia, straddling the British Columbia–Yukon–Northwest Territories border (Figures 1 and 2), spanning NTS map areas 094N and O, and 095B and C. It is traversed by the Liard River and defines a relatively high plateau between the southern Selwyn Mountains and the northern Rocky

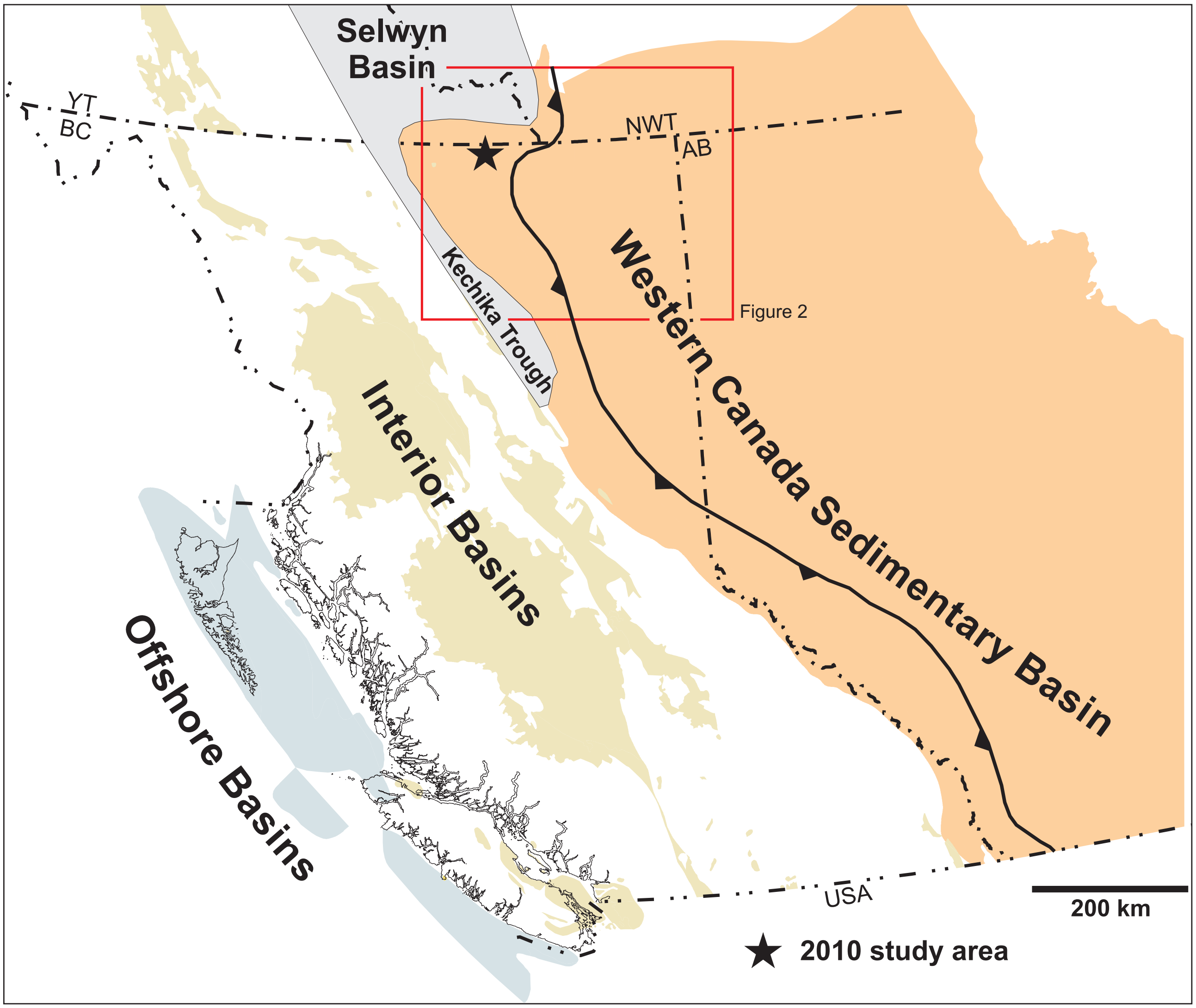

Figure 1. Location of the Liard Basin with respect to the primary sedimentary basins of Western Canada. Also shown are the Early Paleozoic offshelf depocentres of the Selwyn Basin and the Kechika Trough. The red box outlines the area shown in Figure 2. Basin outlines are from Mossop et al. (2004).

Mountains. Highway 77 runs along the eastern half of the basin and joins with the Alaska Highway, which cuts across the southern margin. Numerous petroleum activity roads and forestry access roads extend from these two main highways across the basin. Vehicle access across the Liard River is provided by a barge that originates at Fort Liard, NWT and terminates south of the confluence of La Biche River, where a road connects to the Beaver River gas field (Figure 3).

The Liard Basin is defined on the basis of its thick Late Paleozoic succession (Gabrielse, 1967; Figures 4 and 5). The Bovie Lake structure marks the eastern margin of the basin, west of which is an anomalously thick section of the Mississippian Mattson Formation (Figure 4). Subsequent Late Cretaceous movement on this fault has also preserved a thick sequence of Early to Late Cretaceous rocks (Leckie et al., 1991). Although the development of the Liard Basin had no influence on depositional facies and thicknesses of shale gas units within the older Horn River Basin (i.e., Horn River Formation), its initiation effectively marked the current western limit of shale gas development in the Horn River Basin. Prospective shale horizons in the eastern Horn River Basin, west of the Bovie fault (Figure 2), have been dropped deeper by approximately 2000 m (Figure 4), imposing drilling and completion challenges. A consequence of this has been a shift to the exploitation of the stratigraphically higher Exshaw Formation within the Liard Basin, which is at a depth that can be potentially economically developed for its shale gas resources.

The Middle Devonian to mid-Mississippian Besa River Formation represents the western basinal equivalents of predominantly carbonate successions between the Upper Keg River and Debolt formations (Figures 4 and 5). Farther west, in the Selwyn Basin and Kechika Trough, these rocks correlate with the Devono-Mississippian Earn Group (Figure 6). The Selwyn Basin and the Kechika Trough are

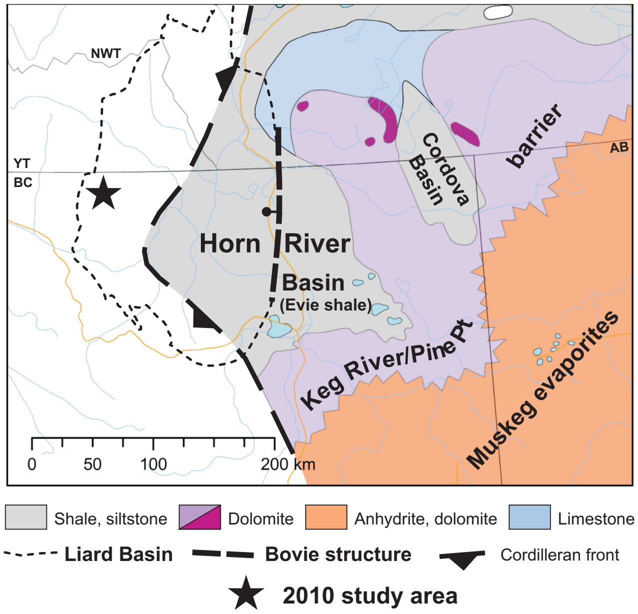

Figure 2. Schematic representation of the Horn River Basin (and Cordova Basin) during upper Keg River times (Givetian). Superimposed on this is the outline of the Liard Basin. This reef–carbonate–shale basin configuration persisted until the end of Slave Point times (end of Givetian; modified from Meijer Drees, 1994). Liard Basin outline is from Mossop et al. (2004).

deep-water equivalents to Early Paleozoic carbonate shelf deposition along the Western Canada Sedimentary Basin (MacDonald Platform; Ferri et al., 1999) and are filled primarily by shale and siltstone of the Kechika and Road River groups.

In the study area, Besa River shale and siltstone sit above carbonate rocks of the Middle Devonian Dunedin Formation, which can be traced westward into the subsurface where it is equivalent to parts of the Chinchaga and Lower Keg River formations (Figure 5; Meijer Drees, 1994). During Upper Keg River and Slave Point deposition, a well-defined barrier reef complex was developed, which marked the eastern limit of the Horn River Basin (Figures 2 and 3; Oldale and Munday, 1994). West of the barrier edge, shales of the Horn River Formation include a stratigraphically lower radioactive, bituminous shale assigned to the Evie Member, overlain by shale of the Otter Park Member (Figures 4 and 5). A transgression followed the Slave Point deposition and pushed the shallow carbonate edge eastward (Leduc facies), leading to deposition of the highly bituminous shale of the Muskwa Formation (Duvernay equivalent; Switzer et al., 1994). Carbonate conditions were re-established to the west during Frasnian and Famennian times, resulting in deposition of Kakiska to Kotcho formations along a broad shelf (Figures 4 and 5). A major transgression occurs across the Devono-Mississippian boundary, represented by deposition of the highly radioactive and bituminous shale of the Exshaw Formation. Carbonate deposition again migrated westward in Early Carboniferous times, with the deposition of the Banff Formation and the succeeding Rundle Group.

In the subsurface, the shale of the Fort Simpson Formation encompasses the westward shale-out of the carbonate units above the Muskwa Formation. Carbonate rocks of the Banff Formation and the Rundle Group disappear into basinal shale above the Exshaw Formation and finally into the Besa River Formation (Figures 4 and 5). Approximately 300 m of Besa River siltstone and shale equates to more than 2000 m of the carbonate and siltstone section along the Keg River barrier edge.

The upper part of the Besa River Formation interfingers with the Middle to Late Mississippian sandstone, siltstone and minor carbonate rocks of the Mattson Formation. These exceed 1000 m in thickness within the Liard Basin west of the Bovie fault structure. This fault has been interpreted as a Late Paleozoic extensional structure that was later reactivated during the Laramide compression (Wright et al., 1994). This is based on the preservation of thick Mattson sandstone and the succeeding Kindle Formation below the Permian Fantasque Formation west of the Bovie fault, whereas only a thin Mattson section occurs below the Fantasque Formation east of the fault (Monahan, 2000; MacLean and Morrow, 2004). In addition, the westerly directed thrust associated with the Bovie fault structure is likely related to compressional reactivation of this graben structure (McClay and Buchanan, 1992). This pre-existing fault allowed compressional structures to form outboard of major Laramide structures (Figure 3). Using seismic data, MacLean and Morrow (2004) interpret the Bovie fault as having Late Paleozoic and Mesozoic compressional tectonics followed by extension during the Cretaceous.

Mattson clastic rocks are part of a slope-to-delta plain and shallow marine sandstone succession that was sourced from the north (Bamber et al., 1991). These rocks correlate with similar deposits of the Carboniferous Stoddart Group, which was deposited within the Late Paleozoic Dawson Creek graben complex (Barclay et al., 1990). Deltaic deposits of the Mattson Formation disappear westward and are replaced by the upper Earn Group siltstone and shale within the Kechika Trough.

To the west, within the Kechika Trough and the Selwyn Basin, the Besa River shale and siltstone correlate with the Middle Devonian to Early Mississippian Earn Group (MacIntyre, 1998; Paradis et al., 1998; Ferri et al., 1999). These deeper-water siliciclastic strata overlie Middle Ordovician to Middle Devonian siltstone, shale and minor carbonate rocks of the Road River Group, representing basinal equivalents of coeval carbonate of the MacDonald Platform (Figure 6).

Besa River rocks examined during the 2010 field season are located within the northern part of the Caribou Range, part of the southern Hyland Highlands, occupying the southernmost extent of the Mackenzie Mountains (Mathews, 1986). The broad highland represented by the

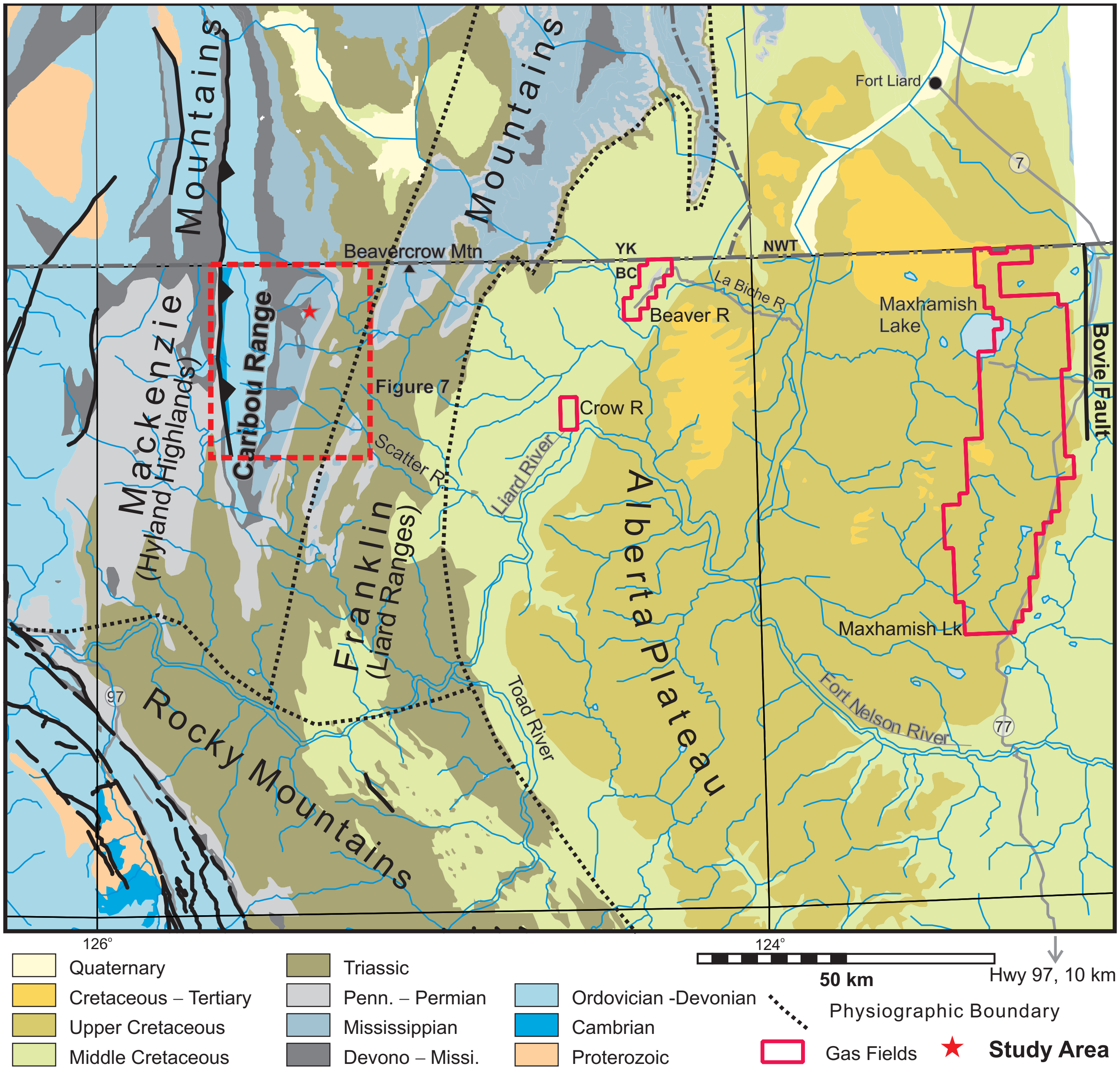

Figure 3. Geology of the western portion of the Liard Basin. The red box outlines the geology depicted in Figure 7. Geology is from MapPlace.ca (BC Geological Survey, 2011).

Caribou Range is underlain by a westwardly directed thrust panel of gently east-dipping Paleozoic rocks (Figures 2 and 7). These north- to northeast-striking rocks follow the general trend of structures within the Mackenzie and Franklin mountains and are at almost right angles to the northwest structural grain of the Rocky Mountains, resulting in the large bend in the trace of major structures across the Liard River (Figure 3). Furthermore, the southern portion of the Mackenzie and Franklin mountains represents a portion of the Foreland Belt dominated by west-verging structures, compared to overall northeast vergence seen within the Rocky Mountains (see Fallas et al., 2004).

Rocks as old as Cambrian are mapped within the Caribou Range, although these can be traced northward into the Yukon Territory where they are assigned a Proterozoic age (Taylor and Stott, 1999; Fallas et al., 2004). Generally, rocks of the Besa River Formation overlie the Dunedin Formation, although in the north, all of the Dunedin and parts of the upper Stone formations shale out and are included in the Besa River Formation (Figure 7; Taylor and Stott, 1999).

In British Columbia, the regional geological database in the vicinity of the section includes mapping within the Toad River (Taylor and Stott, 1999), the Tuchodi Lakes (Stott and Taylor, 1973) and the Rabbit River (Gabrielse, 1963; Ferri et al., 1999) map areas. In the Yukon and Northwest Territories, La Biche River (NTS 095C) has been compiled at 1:50 000 (Fallas, 2001; Fallas and Evenchick,

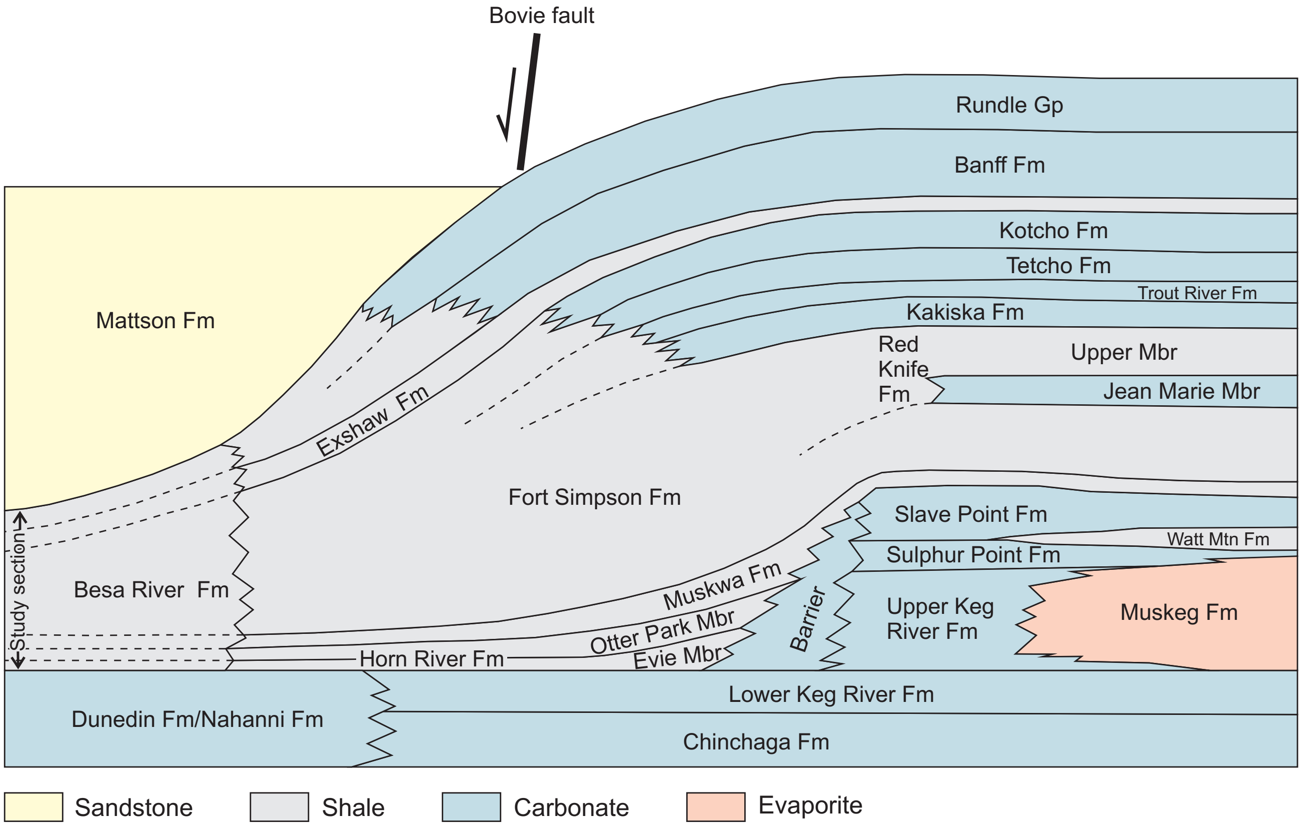

Figure 4. Schematic diagram showing relative thickness variations between Middle to Upper Paleozoic shelf and offshelf sequences depicted in Figure 2.

2002) and 100 000 scales (Fallas et al., 2004). The Besa River Formation was first defined by Kidd (1963) north of the Muskwa River; later, Pelzer (1966) further described its mineralogy and broad stratigraphy. The organic petrography and thermal maturity of similar rocks in the Yukon and Northwest Territories were described by Potter et al. (1993) and Morrow et al. (1993). A recent subsurface evaluation of Devono-Mississippian fine clastic sequences was published by Ross and Bustin (2008), which included Besa River rocks within the Liard Basin area. An assessment of the conventional hydrocarbon resources of the Liard Basin was produced by Monahan (2000).

METHODOLOGY AND RESULTS

A nearly complete section of the Besa River Formation was measured and described through the use of a 1.5 m staff along a west-facing valley, some 22 km southwest of Beavercrow Mountain (base of section: UTM 367107E, 6643192N; top of section: 367496E, 6642948N; zone 10, NAD 83; Figure 7). Representative chip samples were acquired across 2 m intervals along the entire section. Samples were split, with one group being analyzed for whole-rock, trace- and rare earth element abundances by inductively coupled plasma–emission spectroscopy (ICP-ES) and inductively coupled plasma–mass spectrometry (ICP-MS) via a lithium metaborate-tetraborate fusion at Acme Analytical Laboratories (Vancouver, BC), and a second group, at 4 m spacing, for Rock-Eval analysis at the Geological Survey of Canada (GSC) laboratories (Calgary, Alberta). A smaller subset of these samples will also be analyzed by X-ray diffraction (XRD) at the GSC laboratories for semi-quantitative determination of mineral abundances. Another subset will be processed for their potential to contain palynomorphs for biostratigraphy. Separate samples were collected for thermal maturity determination at the GSC laboratories in Calgary through reflected light microscopy. Data not presented or discussed in this paper will be presented in later publications. In addition, a handheld gamma-ray spectrometer (RS-230 by Radiation Solutions, Inc.) was used to measure natural gamma radiation every 1 m during a 2 minute time interval allowing the calculation of K (%), U (ppm), Th (ppm) and total gamma-ray count. The resulting diagram shows the variation in total natural radiation along the section and is approximately equivalent to conventional gamma-ray readings collected from boreholes in the subsurface. Results of this exercise were used to assist in the correlation of the outcrop section with equivalent rocks in the subsurface.

Approximately 285 m of siltstone and shale of the Besa River Formation were measured (Figure 8). The upper and

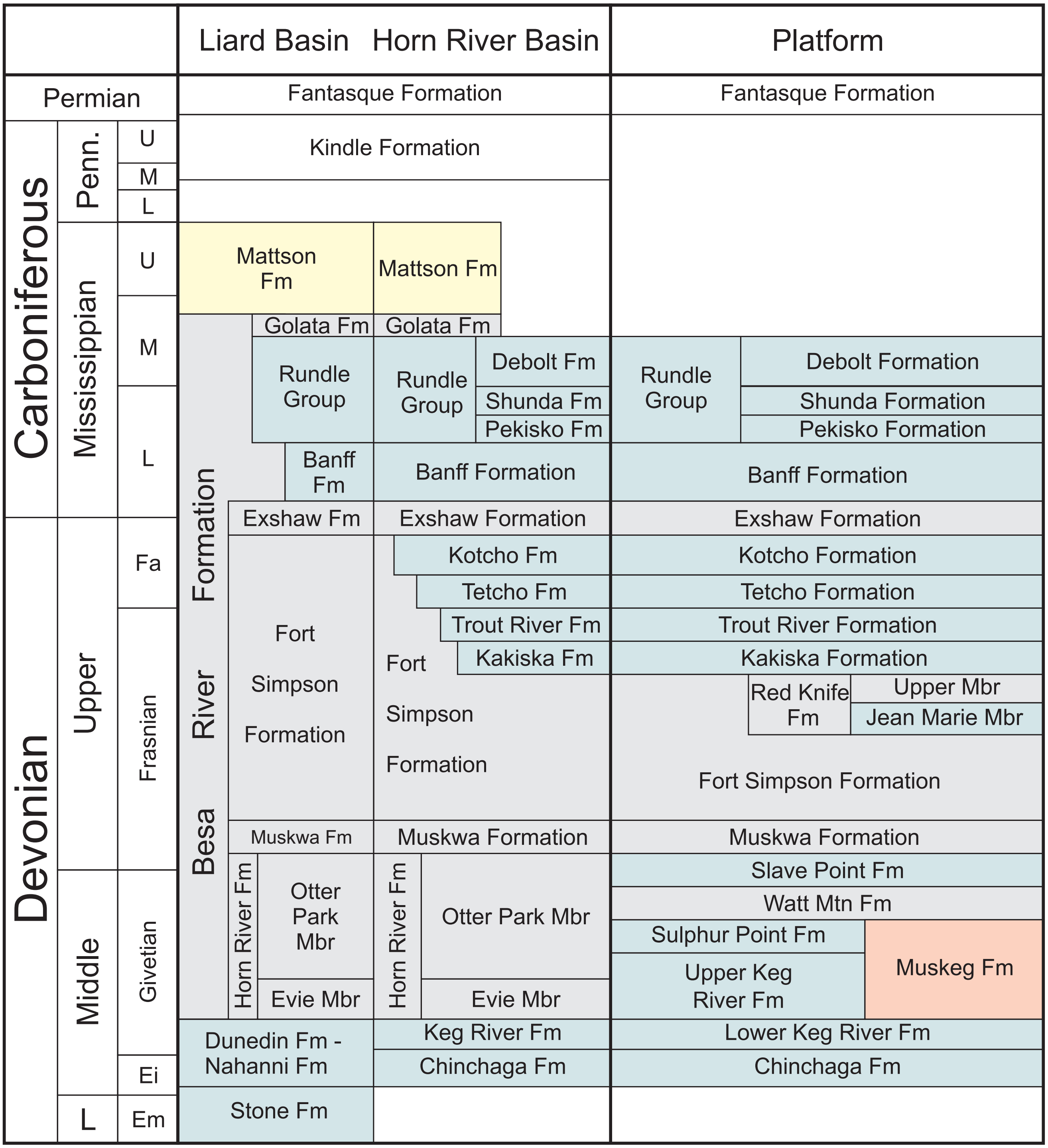

Figure 5. Time stratigraphic chart of the Middle to Upper Paleozoic showing the main stratigraphic units along the northwestern part of the Western Canada Sedimentary Basin within northeastern British Columbia and the relationship between shelf and offshelf sequences. The legend for this figure is shown in Figure 4.

lower parts of the Besa River Formation were not exposed, but examination of rocks to the north indicate approximately 15 m of missing Besa River rocks are below the base of the Mattson Formation, and a structural section suggests approximately 25 m of covered rocks are above the Dunedin Formation.

Broadly, the Besa River Formation consists of dark grey to black, carbonaceous siltstone and shale (Figure 8). Besa River Formation rocks along the measured section can be subdivided into six lithostratigraphic units consisting of, from the base (Figure 9): 1) dark grey to black carbonaceous siltstone to blocky siltstone with shale partings, showing tan to orange-brown or beige weathering (34 m thick, Figure 10a); 2) dark grey to black, fissile to blocky carbonaceous siltstone showing dark grey to beige weathering (34 m thick, Figures 10b, c); 3) dark grey to black

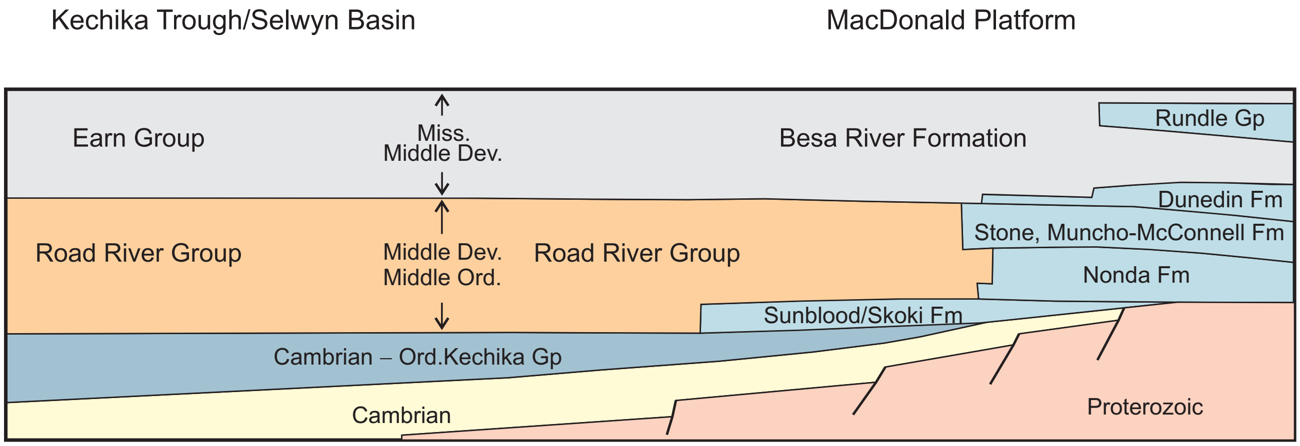

Figure 6. Schematic representation of the westward shale-out of Lower Paleozoic carbonate rocks into Road River siltstone and shale within the Kechika Trough and the Selwyn Basin, and the relationship between the Besa River Formation and the Earn Group.

carbonaceous blocky siltstone and shale, showing rusty to grey or dark grey weathering (32 m thick, Figures 10c, d); 4) rusty to light grey weathering, grey to light grey, blocky to platy and laminated siliceous siltstone showing rusty to light grey weathering (34 m thick, Figure 10e); 5) dark grey to black, blocky to platy and laminated, carbonaceous and siliceous siltstone showing rusty to dark grey weathering (51 m thick, Figures 10f, g); 6) dark grey to black crumbly siltstone to shale showing dark grey to rusty weathering with uneven partings, and with lesser blocky siltstone in the lower and middle parts (100 m thick, Figures 10g, h).

Exposures of the Besa River Formation in the Caribou Range display the distinctive light grey weathering of unit 4 together with the recessive, crumbly nature of the upper part of unit 6 (Figures 8 and 10h). Distinctive rusty to ochre-coloured run-off channels emanating from exposures of unit 6 are also observed within the central part of the Caribou Range.

The upper part of the section contains several thin horizons (5–20 cm) of disseminated and massive pyrite, together with a horizon containing barite nodules of more than 30 cm in diameter (Figure 9). These occurrences are more fully described by Ferri et al. (2011).

Comparison of the broad lithological composition; total gamma-ray counts; K, Th and U contents; and total organic carbon (TOC) contents from Rock-Eval analysis along the section are shown in Figure 11. Values of other elements based on lithogeochemistry are shown in Figure 12. Total organic carbon levels are quite high across several portions of the formation, reaching more than 6% by weight in some parts and they are consistently more than 2% for the upper half of the section. The S2[1] values across the section are less than 0.1 mg HC[2] /g rock, with corresponding hydrogen index (HI) values averaging approximately 2 mg HC/g TOC. These values indicate that the rocks are mature to overmature and contain little to no generative capacity. Although the low S2 values calls into question the reliability of Tmax[3] in determining thermal maturity (Peters, 1986), some of the higher S2 values have corresponding Tmax values in the range of 480 to 500oC, suggesting the upper wet gas window. This is consistent with HI levels within organic matter. This data also suggests that these organic-rich horizons were likely two to four times richer in organic matter prior to the expulsion of hydrocarbons during maturation (Jarvie, 1991).

There is excellent correlation between relative abundances of U and organic carbon content, suggesting either syngenetic precipitation of U during periods of higher anoxia or diagenetically within horizons rich in organic material. Although U concentrations appear to generally decrease towards the upper part of the section, Th shows an increase in abundance. The concentration of K does not appear to correlate with the abundances of the other elements, and is probably tied to the mineralogy of the sediments being deposited.

The carbonaceous (i.e., organic-rich) nature of these sediments is a reflection of the reducing conditions present during deposition. These very low oxygen conditions did not permit any aerobic organic activity, which led to the preservation of organic matter (Fowler et al., 2005). In these anoxic waters, bacteria that respire through the reduction of sulphur became abundant, producing a large amount of reduced sulphur that was used in the precipitation of metal sulphides from metalliferous brines expelled on the seafloor (Goodfellow and Lydon, 2007). Even if these brines had sufficient reduced sulphur, this anoxic environment favoured the preservation of any precipitated sulphides. Oxygenated bottom waters, as in today's oceans, would have led to the oxidation of sulphides in the water column or along the seafloor, negating or eliminating any sizable sulphide accumulations (Force et al., 1983).

1 Represents the amount of hydrocarbons resulting from the cracking of sedimentary organic matter in the sample.
2 Hydrocarbons
3 Temperature of maximum S2 production

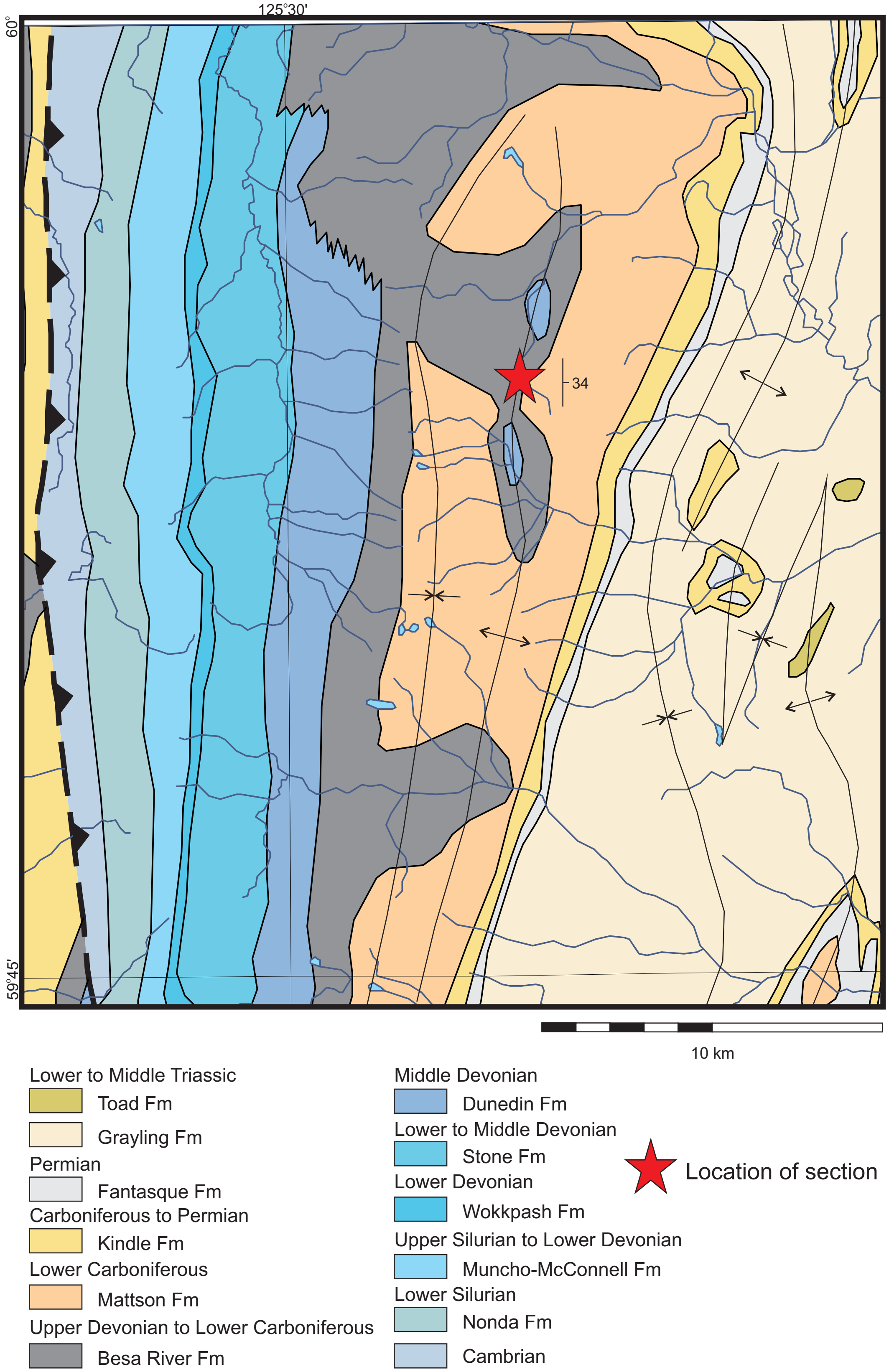

Figure 7. Geology of the Caribou Range, showing the location of the measured section. Geology is from MapPlace.ca (BC Geological Survey, 2011).

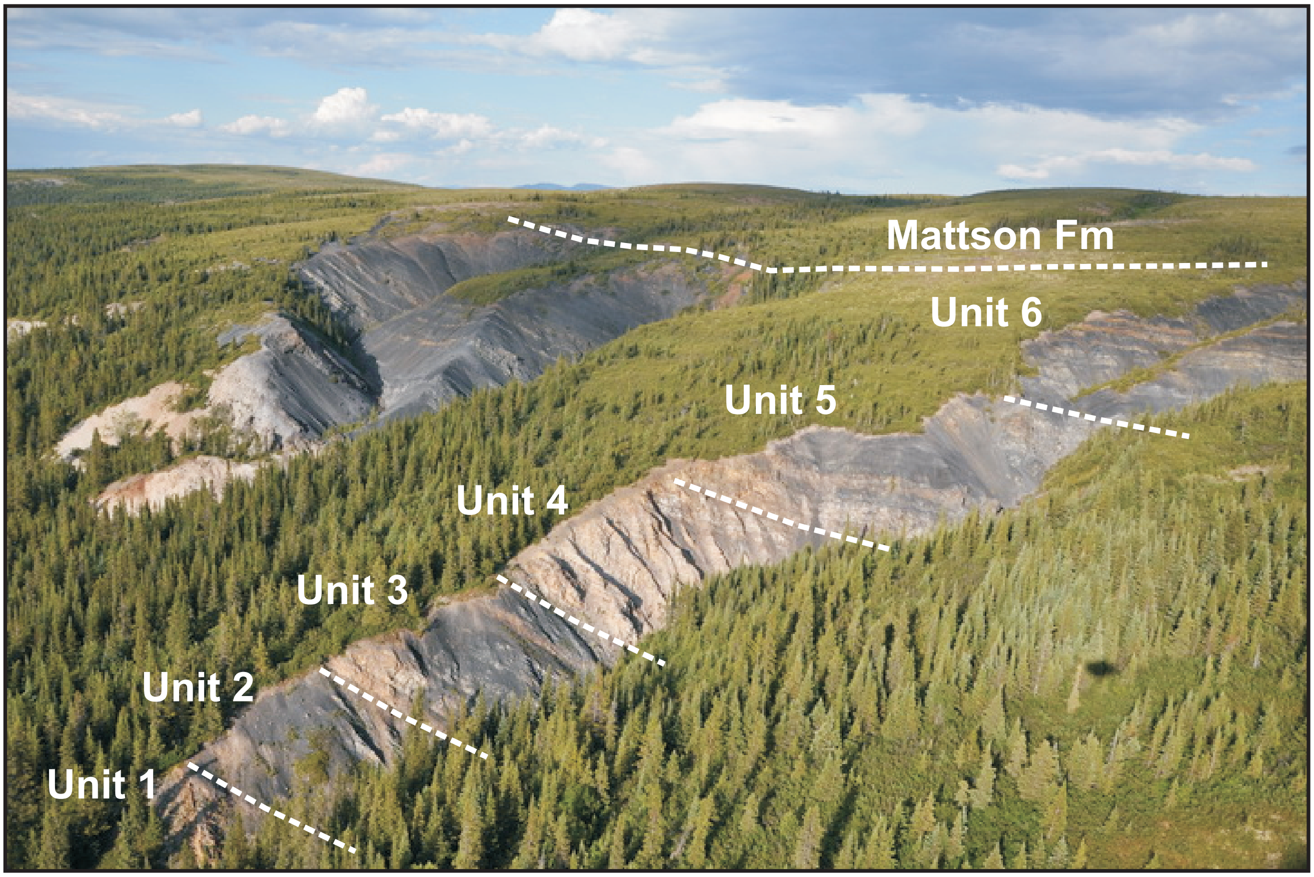

Figure 8. Photograph of the measured section of Besa River Formation showing the character of exposed rock. The light-coloured material is produced by the more siliceous siltstone of unit 4. The upper Besa River siltstone (unit 6) appears somewhat more recessive than the siltstone of unit 5.

Lithogeochemical abundances of select major oxides and trace elements are shown in Figure 12 in comparison to the main units defined during the logging of the section. Several of the units, particularly units 4, 5 and 6, show distinct elemental concentrations. Unit 4 is elevated in SiO_2 and depleted in Al_2O_3, K_2O and MgO, which contrasts with the other units. Unit 6 also shows a general decrease in SiO_2 contents towards its upper part. The concentration of Al_2O_3 shows an inverse relationship to SiO_2, suggesting that clay increases in abundance at the expense of silica. There is also a general increase in MgO, CaO and Na_2O towards the top of the Besa River Formation. Although the concentration of Fe_2O_3 remains at approximately 1–2% across much of the formation, it increases substantially in the upper part, as reflected lithologically by the presence of disseminated to bedded pyrite mineralization. In general, it is likely that major oxide concentrations reflect the mineralogy of the sediments being deposited, although the chemistry of the waters during deposition (i.e., redox conditions) could affect the concentrations of certain elements (e.g., Fe_2O_3 and MnO; see following sections).

Abundances of several trace elements appear to correlate with organic carbon concentrations, suggesting a genetic link (Figures 11 and 12). This is particularly true for U, Mo, V and to some extent Pb. As with U, there is a suggestion of either syngenetic precipitation of U during periods of higher anoxia or diagenetically within horizons rich in organic material. The elemental logs in Figure 12 indicate that Mo, V, and to a lesser extent Pb, may be good inorganic proxies for the relative abundance of organic carbon and the reducing nature of the water column during the deposition of the sediments. Nickel, zinc and to some extent lead have higher concentrations in the upper and lower parts of the Besa River section and correspond to higher concentrations of Fe_2O_3. The higher level of these elements may be tied to either changes in reducing conditions, or, as inferred in the case of Fe_2O_3 and Ba, higher input from metalliferous brines that were active during this time.

The preservation of organic matter in these sediments attests to the reducing environment during deposition. The concentration of Mn in sedimentary rocks is suggested by Goodfellow (2000) and Quinby-Hunt and Wilde (1994) to be related to redox conditions of the water column. Quinby-Hunt and Wilde (1994) have shown that in low-calcic shale (CaO <0.6%), under specific pE and pH conditions, MnO concentrations of less than 0.1% signify anoxic conditions.

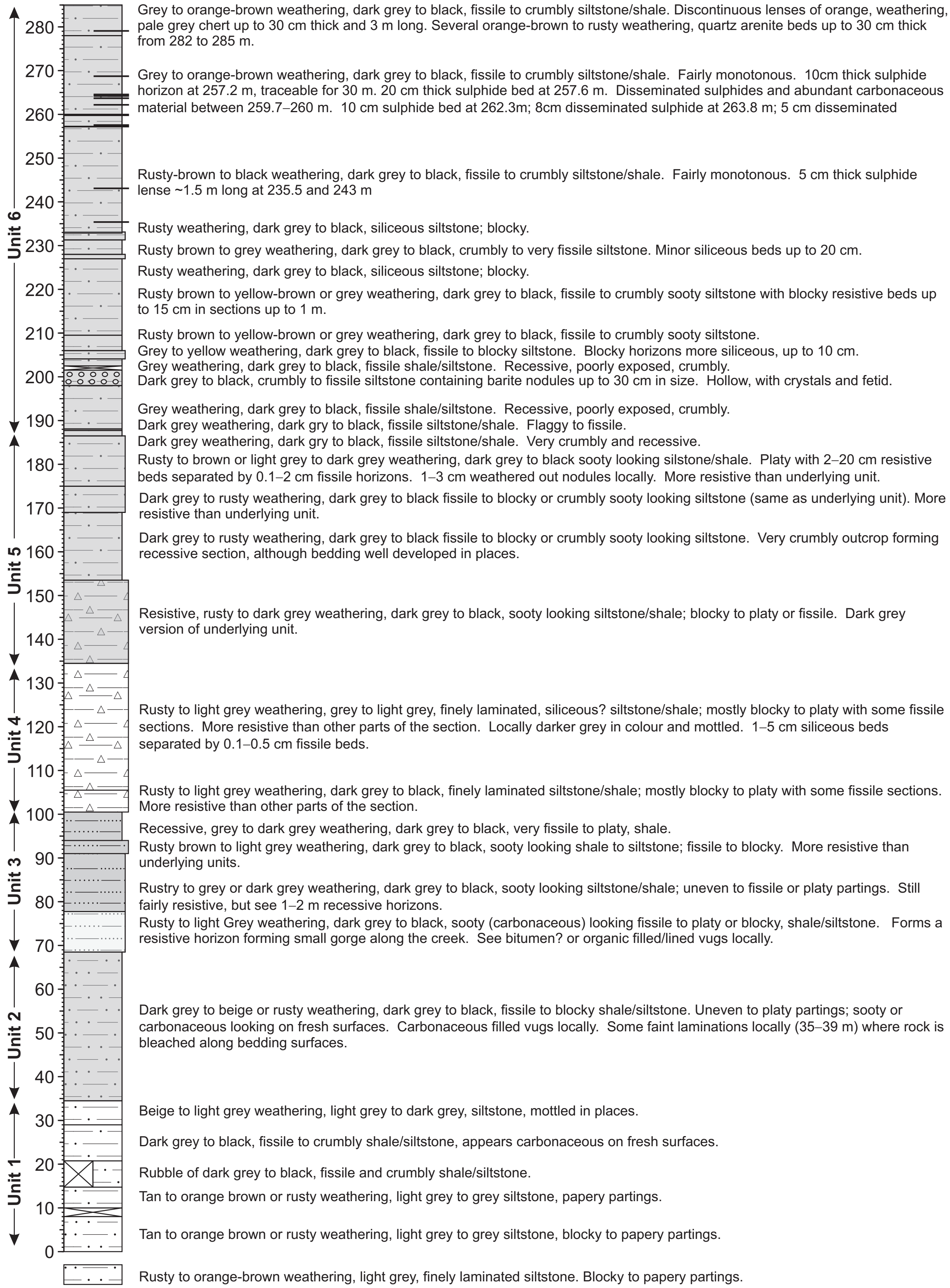

Figure 9. Lithological section of the Besa River Formation measured along the eastern part of the Caribou Range.

Figure 10. a) Rusty weathering siltstone of unit 1 at the 5 m level; b) beige to grey weathering, dark grey siltstone of unit 2 between 37 and 41 m; c) contact between units 2 and 3, showing the slightly more resistive nature of the siltstone in unit 3; d) general shot of grey to dark grey weathering siltstone of unit 3 at the 80 m level; e) light grey and rusty weathering siltstone of unit 4, 116 m level; f) dark grey and resistive siltstone with shaly partings within unit 5 at the 150 m level; g) transition from more resistive ribs of siltstone in unit 5 into more recessive siltstone of unit 6; h) crumbly dark grey siltstone of unit 6, 238–250 m level.

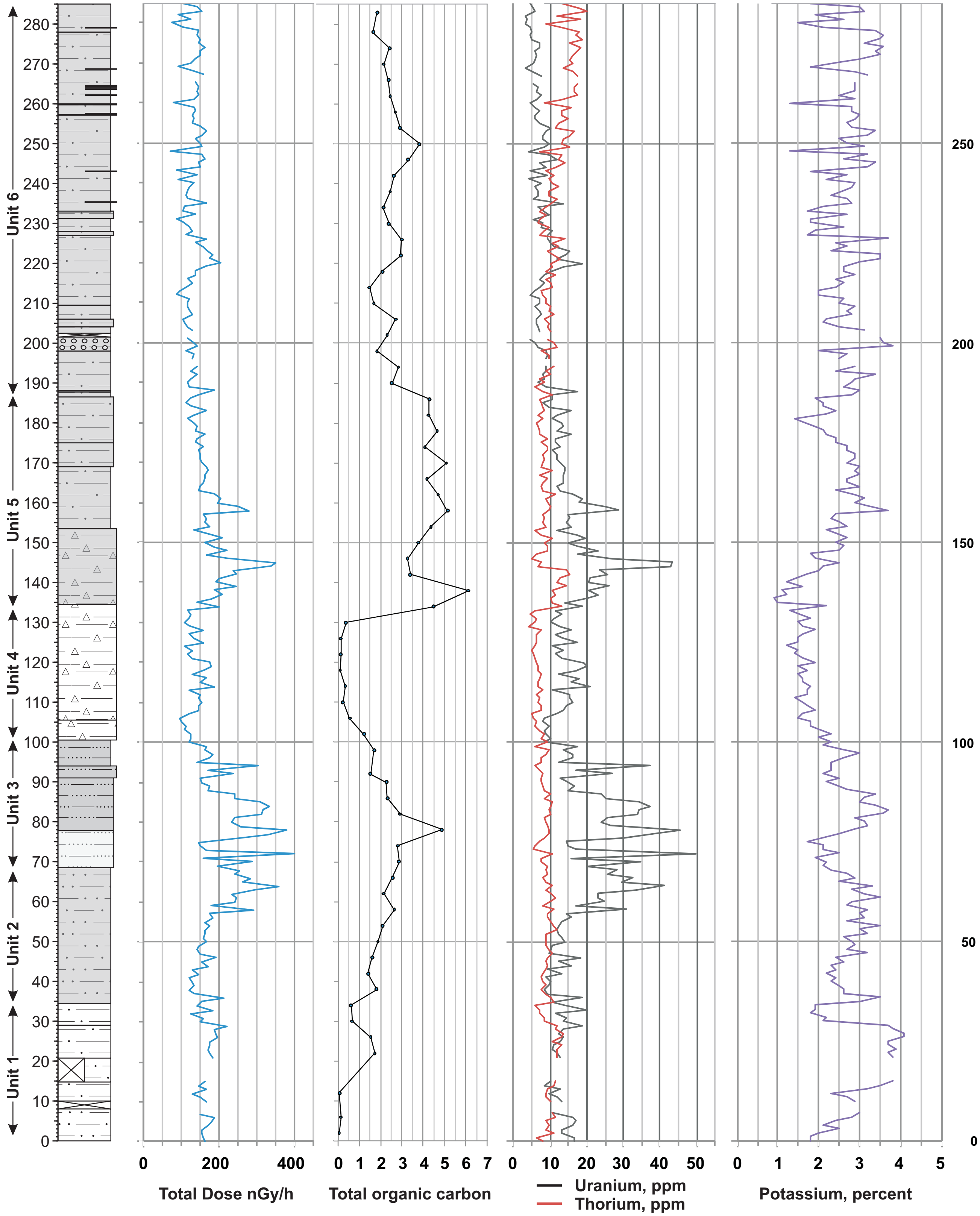

Figure 11. Comparison of main lithological units of the measured Besa River Formation section with measured levels of total gamma-ray counts, U, Th, K and total organic carbon.

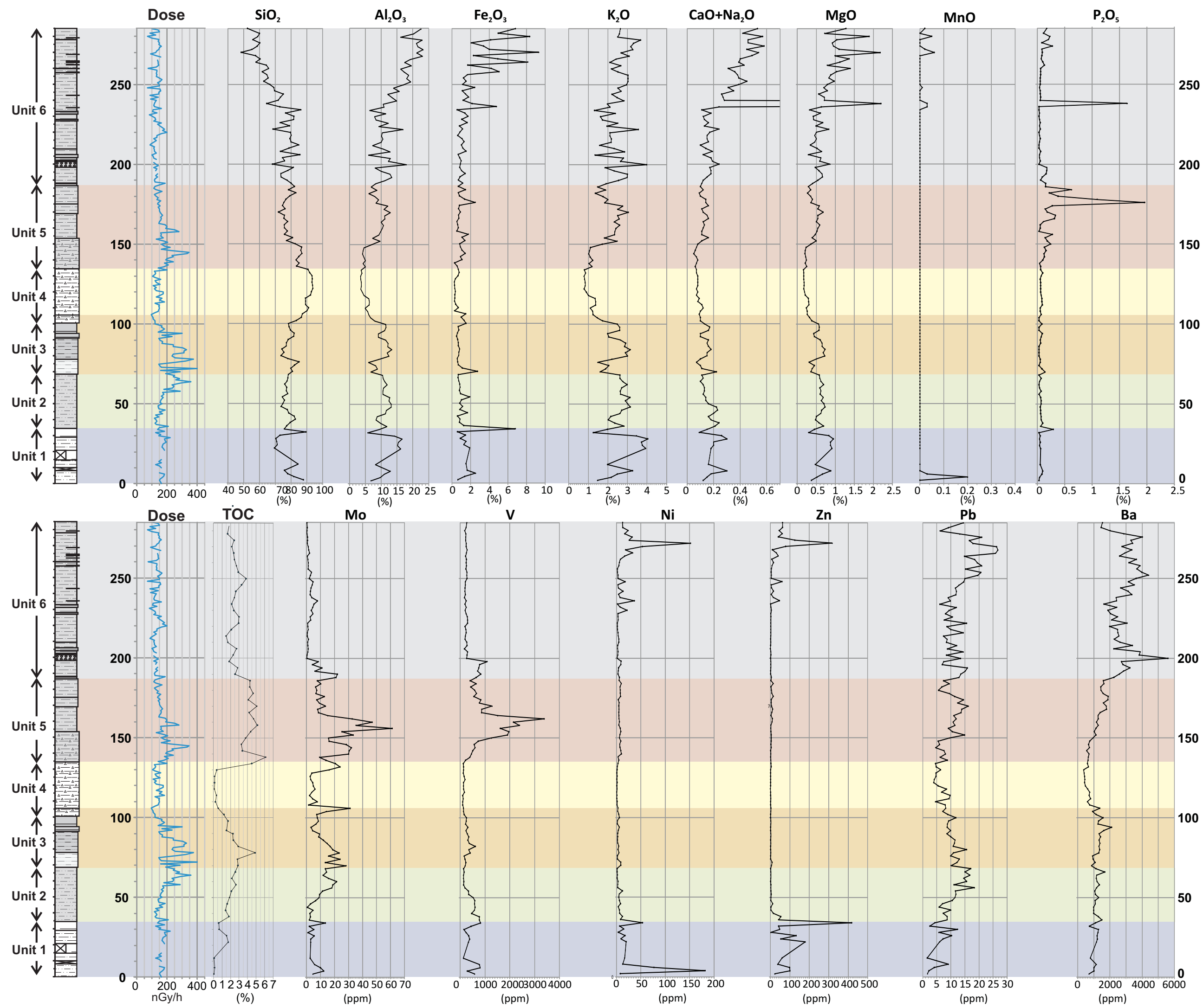

Figure 12. Abundances of select major oxides and trace elements within rocks of the Besa River Formation within the study area. The lithological log with units is shown on the right. The colour banding is provided as a guide to the unit boundaries.

Furthermore, these authors have further subdivided shales deposited within the anoxic environment based on the relative abundances of V and Fe. In the least-reducing environment (less anoxic), Fe is found as oxides (less insoluble) and will occur in rocks in concentrations greater than 3.75%. Under these conditions, V levels are low (<320 ppm). Where Eh conditions are lower (more anoxic), Fe is reduced, soluble concentrations in rocks will fall below 3.75%, and MnO concentrations average approximately 0.02%. Under the most reduced conditions, MnO concentration is approximately 0.01% and V concentration averages 1500 ppm.

Lithogeochemistry (and the carbonaceous nature of the sediments) of the Besa River rocks suggests deposition under anoxic conditions. High V, low Fe and corresponding elevated levels of organic matter within parts of the section also suggest reducing conditions during deposition.

Quinby-Hunt and Wilde (1994) also note that the concentration of V can be used as an inorganic indicator of the organic content of the shale. Vanadium in the water column can form organic compounds that are best preserved under low pH and highly reducing conditions. It is clear that the concentrations of Mo and U relative to those of C shown in Figure 12 suggest a similar origin.

CORRELATIONS

Besa River rocks in the study area can be broadly correlated with the Earn Group of the Kechika Trough (Figure 5). Units 1–5 most likely correlate with cherty argillite, carbonaceous siliceous shale, and lesser black carbonaceous siltstone and shale of the Middle to Late Devonian Gunsteel Formation (MacIntyre, 1998). The succeeding more recessive and crumbly siltstone and shale of unit 6 are probably correlative to recessive dark grey siltstone of the Akie Formation, postulated to be Late Devonian to Early Mississippian in age (MacIntyre, 1998).

Correlation of the outcropping Besa River Formation with subsurface formations to the east is suggested based on the total gamma-ray trace across the measured section (Figures 13 and 14). In the subsurface, as the Keg River reef and successive Devonian and Mississippian carbonate successions shale-out westward into fine clastic rocks of the Horn River, Fort Simpson and Besa River formations, the distinctive radioactive shales of the Evie, Muskwa and Exshaw successions can be traced across into the thick, monotonous siltstone sequence. The Exshaw Formation can be traced with confidence because it forms a regional marker horizon throughout a large part of the Western Canada Sedimentary Basin. The Evie shale above the Lower Keg River carbonate also defines a distinctive package, and together with the succeeding Muskwa horizon, they characterize a recognizable sequence.

Correlations of the outcrop section with several wells west of the Liard River are depicted in Figure 14. To the east of these wells, the Fort Simpson Formation increases in thickness to more than 400 m. The Exshaw Formation can be traced into the strongly radioactive central part of the Besa River section and the lowermost radioactive zone equates with the Muskwa Formation. Approximately 25 m of basal Besa River Formation siltstone is covered; they are assumed to represent the Evie Member of the Horn River Formation. The siltstone below Muskwa-equivalent rocks would be equivalent to the Otter Park siltstone, and those between the Muskwa and Exshaw horizons to the Fort Simpson Formation. These correlations also correspond broadly to the main lithological units described previously: unit 1 corresponds to the Otter Park Member, units 2 and 3 to the Muskwa Formation, unit 4 to the Fort Simpson Formation and unit 5 to the Exshaw Formation (Figure 14). Note that the distinctive light grey weathering panel within the Besa River Formation exposures in the Caribou Range,

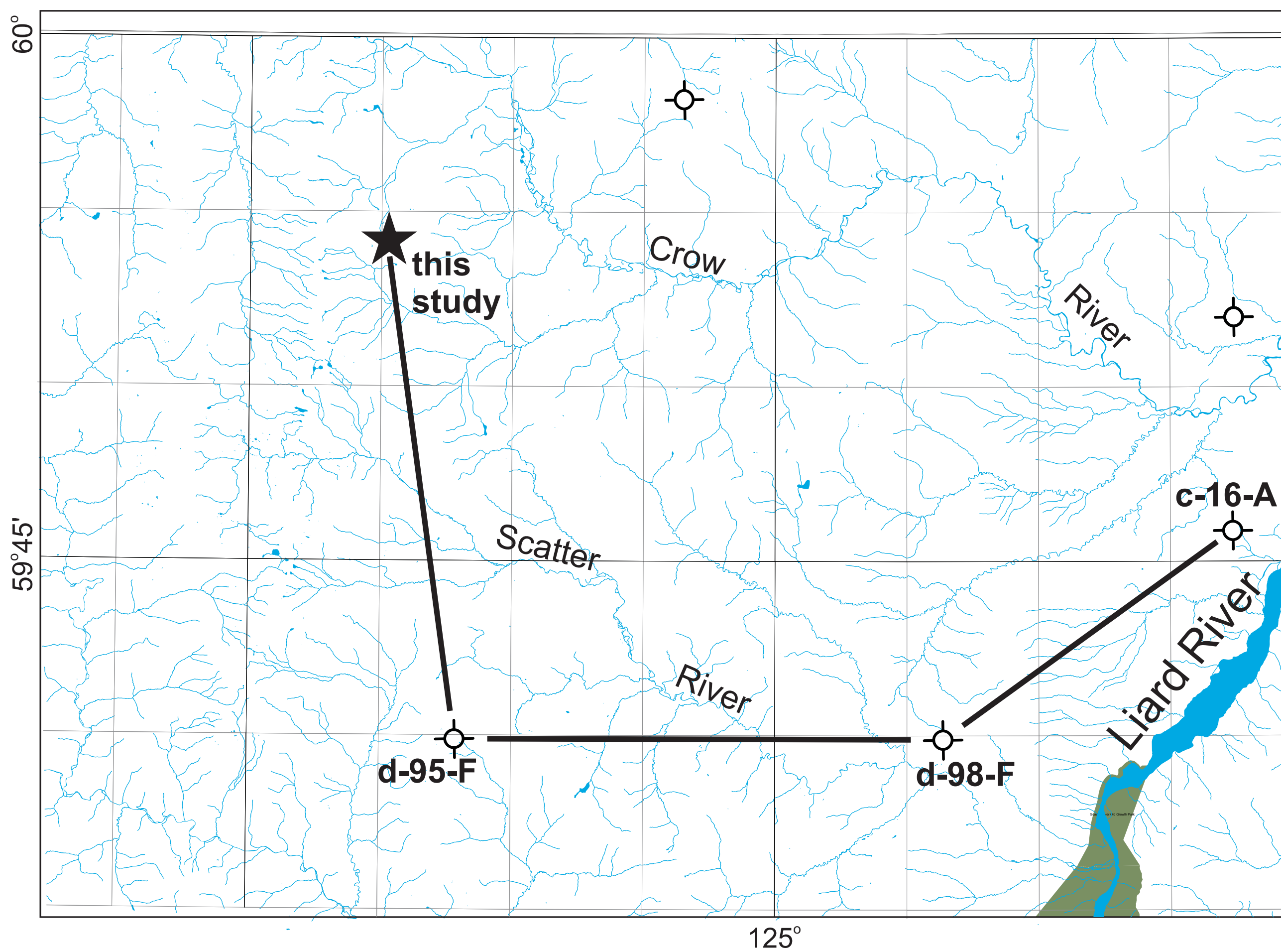

Figure 13. Map showing well locations used in the correlations depicted in Figure 14. The study area is shown by a star.

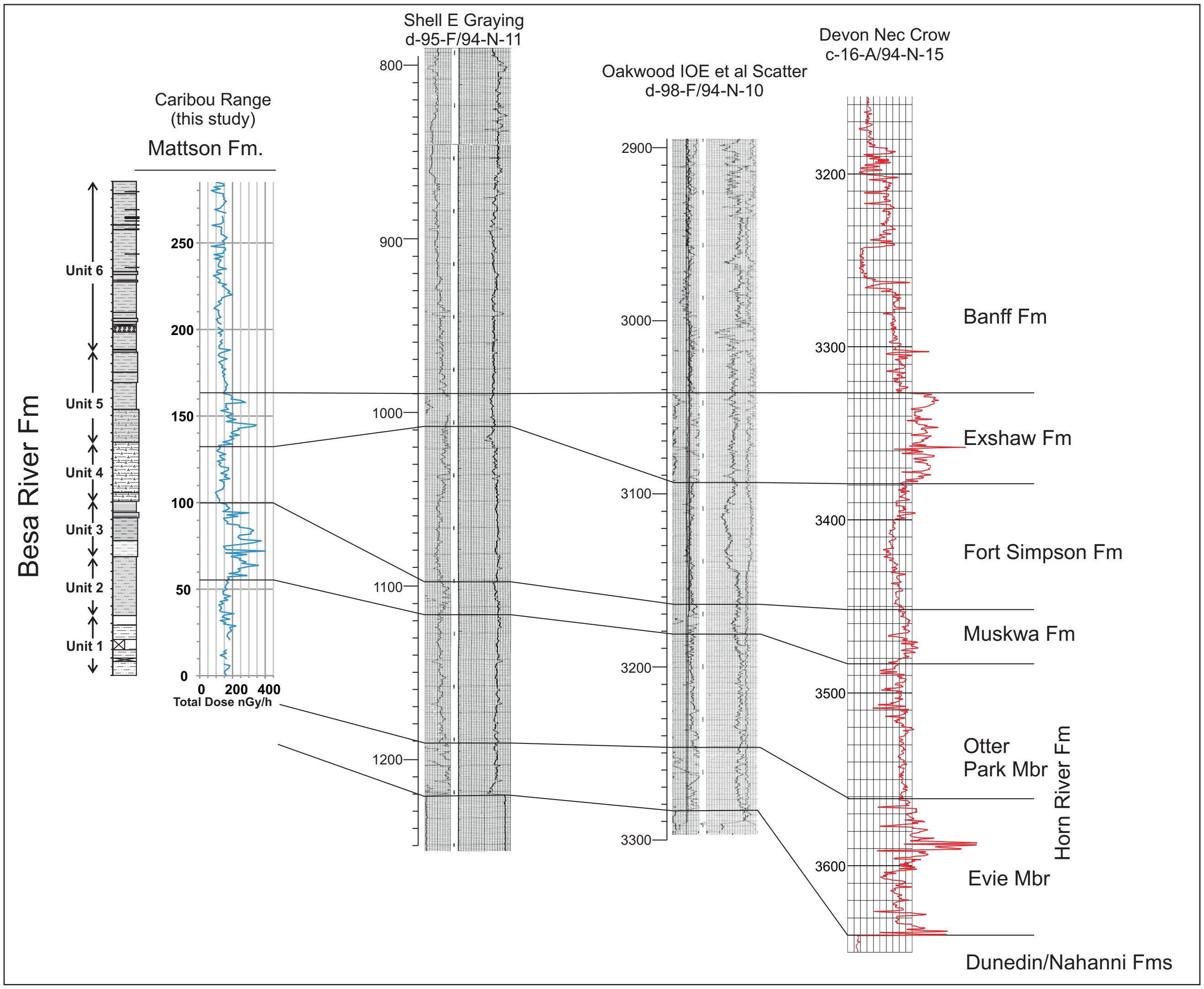

Figure 14. Correlation of the measured Besa River section, using the trace of total gamma-ray counts, with several subsurface sections, the locations of which are shown in Figure 13. Only the gamma-ray log is shown for the c-16-A well. The bulk density is shown for the d-98-F well and the acoustic log for the d-95-F well.

which corresponds to the Fort Simpson–equivalent horizon, is only approximately 25–35 m in thickness, attesting to the extremely condensed nature of this section, compared to the previously mentioned Fort Simpson interval with a thickness of more than 400 m. In outcrop, the section above unit 4 that correlates with the Exshaw Formation appears as siliceous as the underlying Fort Simpson–equivalent strata, but is considerably darker and more carbonaceous. This is confirmed by lithogeochemistry (Figure 12).

Although the overall trace of the gamma-ray log across the outcrop is very similar to subsurface gamma-ray logs, the unit boundaries defined by this methodology do not necessarily correspond to those defined within the lithological log (Figures 11 and 14). The relatively sharp contacts of unit 4 correlate with breaks in the gamma-ray trace (Fort Simpson Formation equivalent, Figure 11). The upper boundary of the Exshaw marker, as defined by the gamma-ray trace, falls within the upper part of unit 5. This unit is also defined by high organic contents and higher U concentrations than the base of unit 6 (Figure 11), suggesting that this may be the upper contact of the Exshaw marker.

The contact between units 2 and 3 occurs within the lower part of the Muskwa marker. Furthermore, the contact between units 1 and 2 is not distinctive on the gamma-ray trace, although total organic carbon contents are higher in unit 2 and K levels are higher in unit 1. There is an increase in organic content (and U levels) in unit 2 up-section, whereas its overall lithological character stays relatively uniform.

It is not surprising that unit boundaries of these fine-grained sediments defined within outcrop do not conform precisely to radioactive marker boundaries delineated in the subsurface or with radioactive zones in the outcrop. The high levels of radioactivity (i.e., U content) within specific sedimentary sections appear linked to reducing conditions during deposition and preservation of produced organic matter, and may not necessarily correlate to the lithological composition of sediments being deposited. A change in redox conditions and/or organic production during otherwise uniform deposition will lead to concentration of organic matter within the bulk inorganic composition, thus altering its gamma-ray signature. This is evident between units 4 and 5; the base of unit 5 is still fairly siliceous (as in unit 4) but is more carbon-rich than unit 4, thus more radioactive. In some horizons, the production and preservation of organic matter will correlate very well with other lithological compositions (i.e., unit 4), suggesting a link between mineralogical input and organic productivity.

CONCLUSIONS

- Approximately 285 m of the Besa River Formation outcrops along the western margin of the Liard Basin and consists of light grey to black weathering carbonaceous siltstone to siliceous siltstone. The lower 25 m and upper 15 m of the unit are not exposed.
- The Besa River Formation has been subdivided into six informal lithostratigraphic units based on overall outcrop composition.
- Rock-Eval analysis of representative samples on 4 m spacing across the outcrop indicate two zones of high organic carbon content, with levels reaching 6% by weight. Little generative capacity remains in these rocks as peak thermal maturities are inferred to be in the upper wet gas window.
- A gamma-ray spectroscopic log across the outcrop defines several zones of higher radiation that correlate to higher concentrations of U and organic carbon.
- Lithogeochemistry across the section displays distinct variability with respect to major oxides and trace-element abundances. Generally, the concentration of major oxides correlates with lithological subdivisions, whereas some of the trace-element abundances show a relationship with organic carbon content, suggesting that these levels are tied to redox conditions during deposition.
- Correlation of the gamma-ray trace with subsurface sections to the east suggests that the lower and upper radioactive zones in the outcrop correlate with the Muskwa and Exshaw markers, respectively.

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