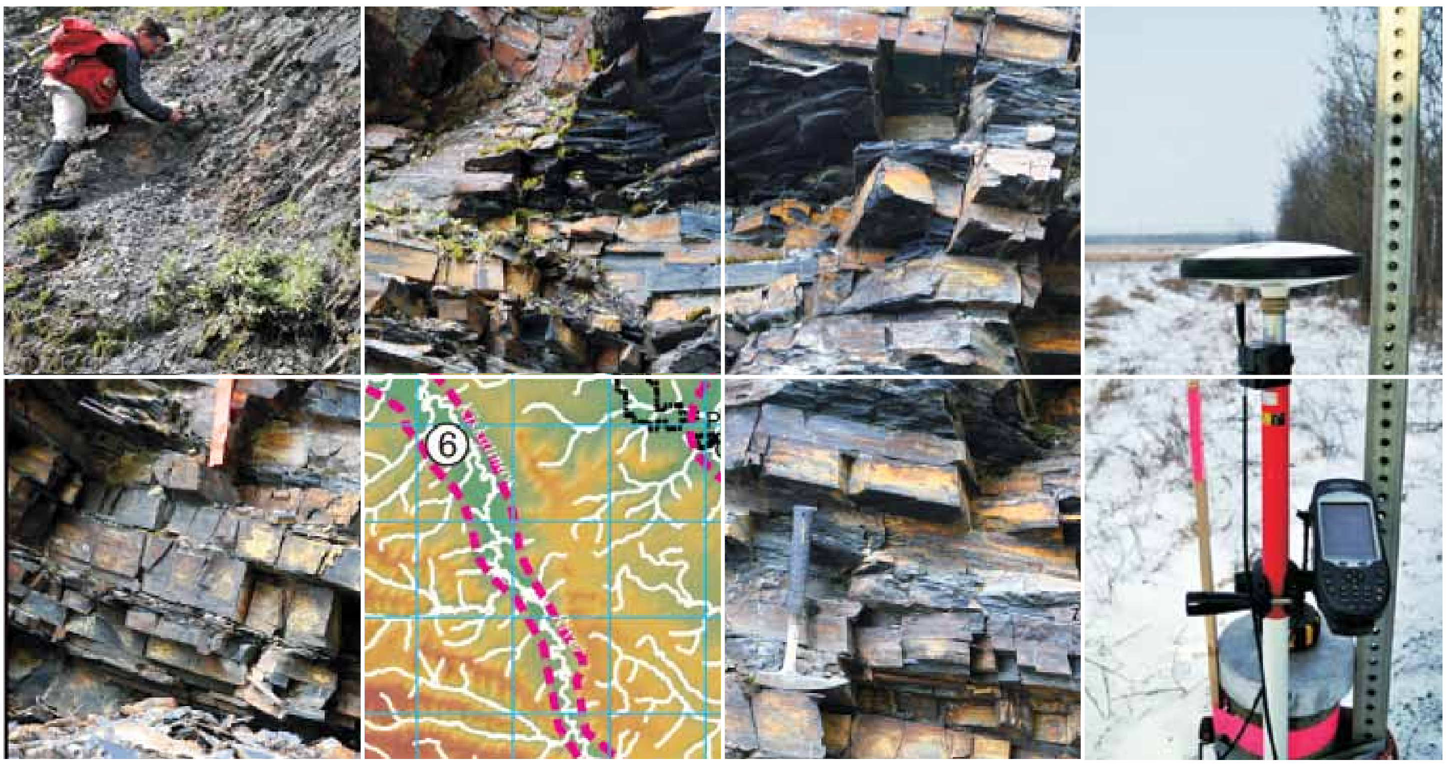
Oil And Gas
Geoscience Reports 2012



BC Ministry of Energy and Mines
Geoscience and Strategic Initiatives Branch

BRITISH COLUMBIA

Oil and Gas Division
Geoscience and Strategic Initiatives Branch
Victoria, British Columbia, April 2012

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FOREWORD

Geoscience Reports is the annual publication of the Geoscience Section of the Geoscience and Strategic Initiatives Branch (GSIB) in the Oil and Gas Division, BC Ministry of Energy and Mines. This publication highlights petroleum related geosciences activities carried out in British Columbia by ministry staff and affiliated partners. The Geoscience Section of the Strategic Initiatives Branch provides public geoscience information to reduce exploration and development risk and promote investment in British Columbia's natural gas and other petroleum resources. The studies produced by staff and partners encourage responsible development and provide technical expertise to better aid policy development. Public Geoscience is identified as an important component of the British Columbia Natural Gas Strategy, announced in February 2012 (www.gov.bc.ca/ener/natural_gas_strategy.html).

Geoscience Reports 2012 includes six articles that focus on two themes; geological studies in the Liard region of northeast British Columbia and water studies related to oil and gas development. The first two articles describe mapping and thematic studies in the Liard Basin. These studies investigate rocks that are currently being targeted for shale gas development in the Liard and Horn River basins. The subsequent four articles focus on water, an important resource in northeast British Columbia, where it is critical for the petroleum industry, agriculture and domestic activities.

The first article in this year's volume is by Filippo Ferri and Adrian Hickin of the GSIB and Julito Reyes of the Geological Survey of Canada (GSC). They present results from the 2011 summer field program that is part of a multi-year project evaluating the shale and siliceous siltstone of the Besa River Formation from measured sections of outcrop. The evaluation includes lithological description, a gamma-ray spectrometry (U, Th and K) survey and Rock-Eval™ and lithogeochemical analysis of samples. The second study, by Margaret McMechan (GSC), Filippo Ferri (GSIB) and Larry MacDonald (GSC), is a regional mapping project. This article reports on summer fieldwork in 2011 within the Toad River map area (NTS 094N) and incorporates published and unpublished geological studies in the Liard River area. Rocks in this map sheet span the Mesoproterozoic to Upper Cretaceous, which have been effected by tectonic activity during the Middle Cambrian, Ordovician to Silurian, Mississippian to Permian, and Jurassic to Early Cretaceous (pre-Albian). Hydrocarbon resources occur within Middle Devonian carbonates involved in large, structural culminations (e.g. Beaver River and Crow River gas fields). In addition, the Paleozoic and Mesozoic successions contain several organic-rich horizons (Besa River Formation, Toad/Grayling formations and Garbutt Formation) that are stratigraphically equivalent to sequences being developed for shale gas resources elsewhere within the Western Canada Sedimentary Basin.

The first of the series of papers related to water resources is by Elizabeth Johnson of GSIB and Laura Johnson, an independent consultant. Their contribution investigates industry water consumption during hydraulic fracturing operations in northeast British Columbia. The paper looks at the relationships around fracture type, stimulation volume, well location and the number of fractures per well. Another contribution is a compilation of potential freshwater aquifers hosted in shallow bedrock formations by Janet Riddell, formerly with the GSIB, but now with the British Columbia Geological Survey. She notes that the most important prospective regional aquifer units are the coarse clastic Cenomanian Dunvegan and Campanian Wapiti formations. Some of these aquifers are well known in the Peace River valley, but outside that region hydrogeological data are sparse and many aquifers are not formally identified or delineated. This work indicates that new data will significantly improve our knowledge about the hydrostratigraphy of Cretaceous clastic units across northeast British Columbia.

The final two papers introduce a multi-year, inter-agency program initiated in September of 2011. This program is directed at gaining an understanding of the groundwater resources in the rural area around Dawson Creek. The principle objective of this ongoing work is to provide science based information (characterization of groundwater aquifers and water) that will benefit water resource management. The paper by Wilford et al. includes 15 authors from 10 agencies that are participating in this multi-year program. This paper describes two projects; the first is the Northeast British Columbia Aquifer Project with components that include: 1) a private water well sampling survey; 2) expansion of the British Columbia Observation Well Network; 3) an evaluation of the geological framework for the Groundbirch Paleovalley; and 4) an update to the Groundwater Level Interface database. The second project involves surface water hydrology modelling and the development of a decision-support tool for water allocation in northeast British Columbia. The final paper in the volume, by Adrian Hickin (GSIB) and Melvyn Best (Bemex Consulting International), describes the geophysical techniques that were employed to construct the geological framework of the Groundbirch Paleovalley, a feature known to host an unconsolidated groundwater aquifer. In their paper, they provide some preliminary results from the Coldstream River, where incision by the river has allowed direct observation of the paleovalley-fill secession.

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HORN RIVER BASIN–EQUIVALENT STRATA IN BESA RIVER FORMATION SHALE, NORTHEASTERN BRITISH COLUMBIA (NTS 094K/15)

Filippo Ferri[1], Adrian S. Hickin[1] and Julito Reyes[2]

ABSTRACT

In the summer of 2011, approximately 310 m of shale and siliceous siltstone of the Besa River Formation was measured in the Stone Mountain area of northeastern British Columbia (NTS 094K/15). In addition to a lithological description, a gamma-ray spectrometry (U, Th and K) survey was conducted and Rock Eval™ samples were collected across the section. Results show similarities between this section and a section of the Besa River Formation measured in the Caribou Range along the northern border of the Toad River map area (NTS 094N) in 2010. Although a comparison of U, Th and K logs from each section are in general agreement, absolute levels, particularly with respect to U, are higher within the Caribou Range. Comparison of the gamma-ray log with similar subsurface sections shows good correlation and indicates the presence of the Evie and Muskwa markers of the Horn River succession, and the Exshaw Formation within the Besa River section. Total organic carbon levels are high (up to 7 wt.%) within Evie-, Muskaw- and Exshaw-equivalent strata. There is also a zone with high total organic carbon (up to 8 wt.%) above the Exshaw marker, in the upper part of the Besa River Formation.

Ferri, F., Hickin, A.S. and Reyes, J. (2012): Horn River basin–equivalent strata in Besa River Formation shale, northeastern British Columbia (NTS 094K/15); in Geoscience Reports 2012, *British Columbia Ministry of Energy and Mines*, pages 1–15.

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Key Words: Liard basin, Horn River basin, Liard River, Toad River, Caribou Range, Stone Mountain, Besa River Formation, Horn River Formation, Evie Member, Muskwa Member, Evie Member, Fort Simpson Formation, Exshaw Formation, Mattson Group, Stoddart Group, geochemistry, gamma ray, rock Eval, total organic content, oil, gas, sulphides

INTRODUCTION

This report summarizes preliminary results from the 2011 field season, part of an ongoing project examining surface exposures of Horn River basin–equivalent strata within the Besa River Formation in northeastern British Columbia (Ferri et al., 2011). The main objective of this project is to delineate units in outcrop that are equivalent to shale gas–producing horizons in the subsurface, thereby providing potential reference sections for understanding the geological setting of the strata in the Horn River basin. The rationale for investigating the 2011 section was primarily its proximity to the Slave Point–Keg River carbonate edge (Fig. 1, 2). Characterization of the section was accomplished through lithological description and collection of samples for lithological and organic geochemical and geochronological analysis. In addition, a gamma-ray spectroscopic survey of the outcrop was performed and used to correlate the section with subsurface sequences in the Liard and Horn River basins.

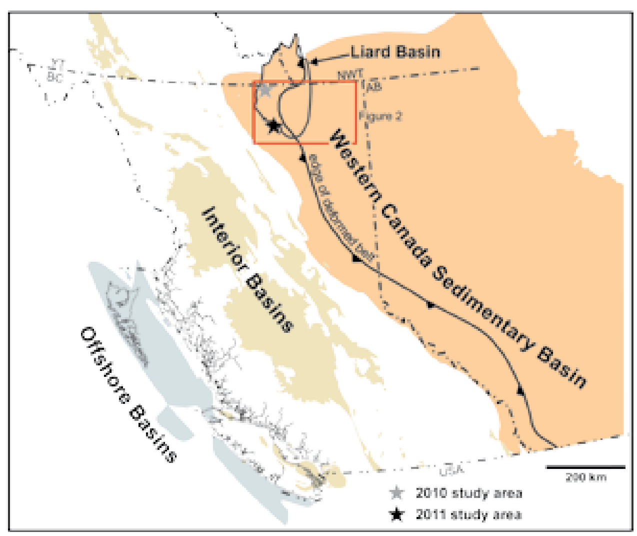

Figure 1. Location of the 2011 study area. Outline of basins adapted from Mossop et al. (2004).

This study is part of a collaborative program between the Geological Survey of Canada (GSC) and the British Columbia Ministry of Energy and Mines. It is part of the Liard and Horn River basins projects, which fall under the umbrella of Natural Resources Canada's Geo-mapping for Energy and Minerals program (GEM). These projects are focused on examining petroleum-related geoscience data for these basins, a regional bedrock mapping project in the Toad River map area (NTS 094N) to update the regional geological database (McMechan et al., 2012) and mapping the surficial geology resources that are relevant to operational aspects of oil and gas resource development (e.g., infrastructure, surface engineering, drilling and completion; Huntley and Hickin, 2010; Huntley and Sidwell, 2010).

LOCATION AND REGIONAL GEOLOGY

The 2011 Besa River Formation section is located along the southwestern margin of the Liard basin, 80 km northwest of the Slave Point carbonate edge (Fig. 2). It is found within the northern part of the Tuchodi Lakes map area (NTS 094K/15) approximately 10 km east of the small community of Toad River and 5 km east of the Alaska Highway (Fig. 2, 3). This section was first recognized by Bamber et al. (1968) as part of a regional study examining Carboniferous and Permian strata. More than 300 m of Besa River Formation shale and siltstone are exposed on the western limb of a large, northwest-plunging, faulted anticline that is cored by carbonates of the Dunedin and Stone formations (Fig. 4). Diagrammatic representations of the time and lithostratigraphic relationships of the Besa River Formation to other units in the study area and to units in the subsurface are shown in Figures 5 and 6. Horn River basin strata correlate with the lower parts of the Besa River Formation. Ferri et al. (2011) provided a brief summary of the regional geology of the study area.

The age of the Besa River Formation is mid-Middle Devonian to Early Carboniferous. Nadijwon (2001) reported conodont collections from the top of the Dunedin Formation and lowermost Besa River Formation in the Stone Mountain area as latest Eifellian to mid-Givetian age. Although Besa River rocks are shown to be capped by the Kindle Formation in the map area (Taylor and Stott, 1973), sandstone observed at the top of the section likely

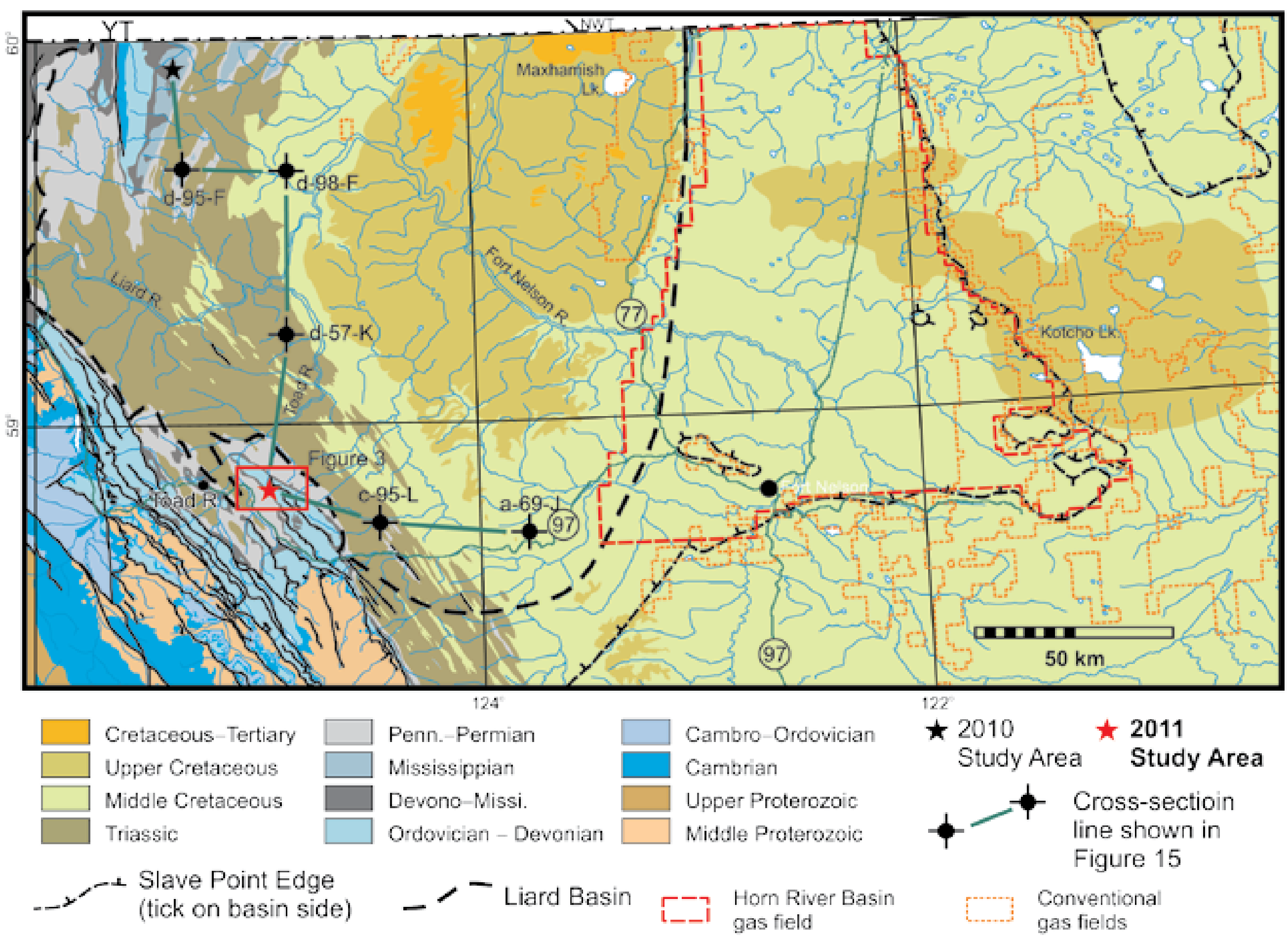

Figure 2. Regional geology of the Rocky Mountains and plains in the vicinity of the 2011 study area (Massey et al., 2005). The outline of the Liard basin is from Mossop et al. (2004). Slave Point edge taken from Petrel Robertson Consulting Ltd. (2003).

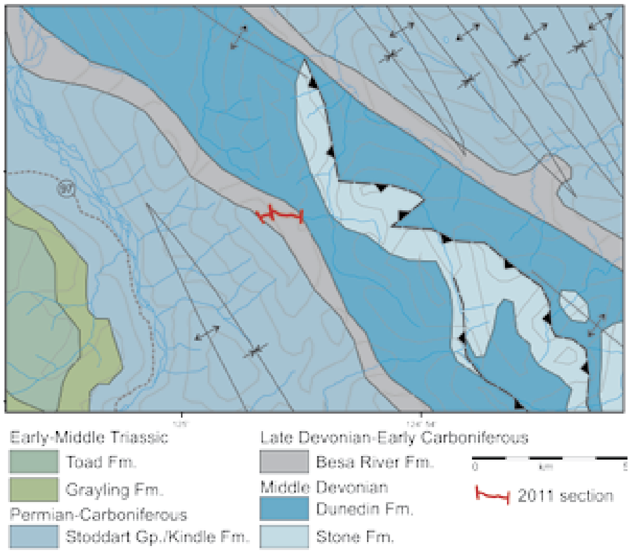

Figure 3. Geology in the immediate vicinity of the 2011 measured section (Massey et al., 2005)

belongs to the Stoddart Group (Halbertsma, 1959; Bamber et al., 1968; Taylor and Stott, 1973), which is equivalent, in part, to the Upper Mississippian Mattson Formation. In the Peace River area, the Stoddart Group is divided, in ascending order, into the Golata, Kiskatinaw and Taylor Flats formations (Halbertsma, 1959). The base of the Golata succession, which sits above the Prophet Formation along the eastern Rocky Mountain Foothills, contains fossils of late Middle to early Late Mississippian age (i.e., early Chesterian; Bamber et al., 1968; Okulitch, 2004). The Prophet Formation disappears further west and northwest such that shale of the Golata Formation is equivalent to the upper Besa River Formation and the top of the latter unit is placed at the first sandstone horizons within the base of the Stoddart Group. These relationships suggest the top of the Besa River Formation is likely Middle to Late Mississippian in age. The Besa River Formation is thus time equivalent to strata between and including Upper Keg River and Golata units found within the eastern Rocky Mountain Foothills and subsurface of the plains in northeastern British Columbia (Fig. 5).

METHODOLOGY AND RESULTS

Field sampling, analysis and reporting generally follows that described in Ferri et al. (2011). Approximately 310 m of rocks belonging to the Besa River Formation were measured and described in two sections along a small, west-facing gully (Fig. 7) located approximately 12 km northwest of Stone Mountain (Fig. 3). Steep terrain prevented the examination of a continuous section resulting in the measurement of two nearly contiguous sections (Fig. 7). The top of the lower section was accessed from a small, parallel tributary to the main creek. The beginning of the upper section is offset approximately 75 m laterally from the lower section, but mapping suggests that little or no overlap or separation occurs between the two sections. Coordinates (UTM, NAD83) for the base and top of the first section, respectively, are 387019E, 6523897N and 386732E, 6523960N and for the base and top of the second section, respectively, are 386742E, 6523899N and 386600E, 6523870N.

Representative chip samples were acquired through 2m intervals along each 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) following a lithium metaborate-tetraborate fusion or aqua regia digestion at Acme Analytical Laboratories (Vancouver, British Columbia) and a second group for rock-eval analysis at the GSC laboratories (Calgary, Alberta). A smaller subset of these samples will also be analyzed for semiquantitative determination of mineral abundances by X-ray diffraction (XRD). Separate samples were collected for thermal maturity determination at the GSC laboratories in Calgary, Alberta through reflected light microscopy. Samples were also acquired from several horizons for Re-Os geochronology at laboratories at the University of Alberta in Edmonton, Alberta. In addition, a handheld gamma-ray spectrometer (RS-230 by Radiation Solutions Inc.) was used to measure natural gamma radiation every 1 m. Gamma-ray spectrometry data was collected over a 2 minute time interval providing concentrations of K (%), U (ppm) and Th (ppm) in addition to total gamma-ray counts. 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 analysis, together with other compositional parameters, were used to assist in the correlation of the outcrop section with equivalent rocks in the subsurface.

In total, 312 m of Besa River Formation shale and siltstone were measured across two sections (Fig. 4). Although the top of the Dunedin Formation was observed, the lowermost 2.5 m of the Besa River Formation was not exposed at the measured section. Several other minor unexposed sections occur in the lower and middle part of the section. Approximately 18 m of the upper section is covered, just below the contact with the Stoddart Group.

The contact with the Dunedin Formation, where exposed, is sharp, but conformable (Nadijwon, 2001). The upper contact with the Stoddart Group appears gradational where more than a 3 m interval of calcareous, coarse siltstone to very fine sandstone beds of the Stoddart Group is intercalated with Besa River shale. This is similar to the upper Besa River Formation contact with the Mattson Formation in the Caribou Range (Ferri et al., 2011).

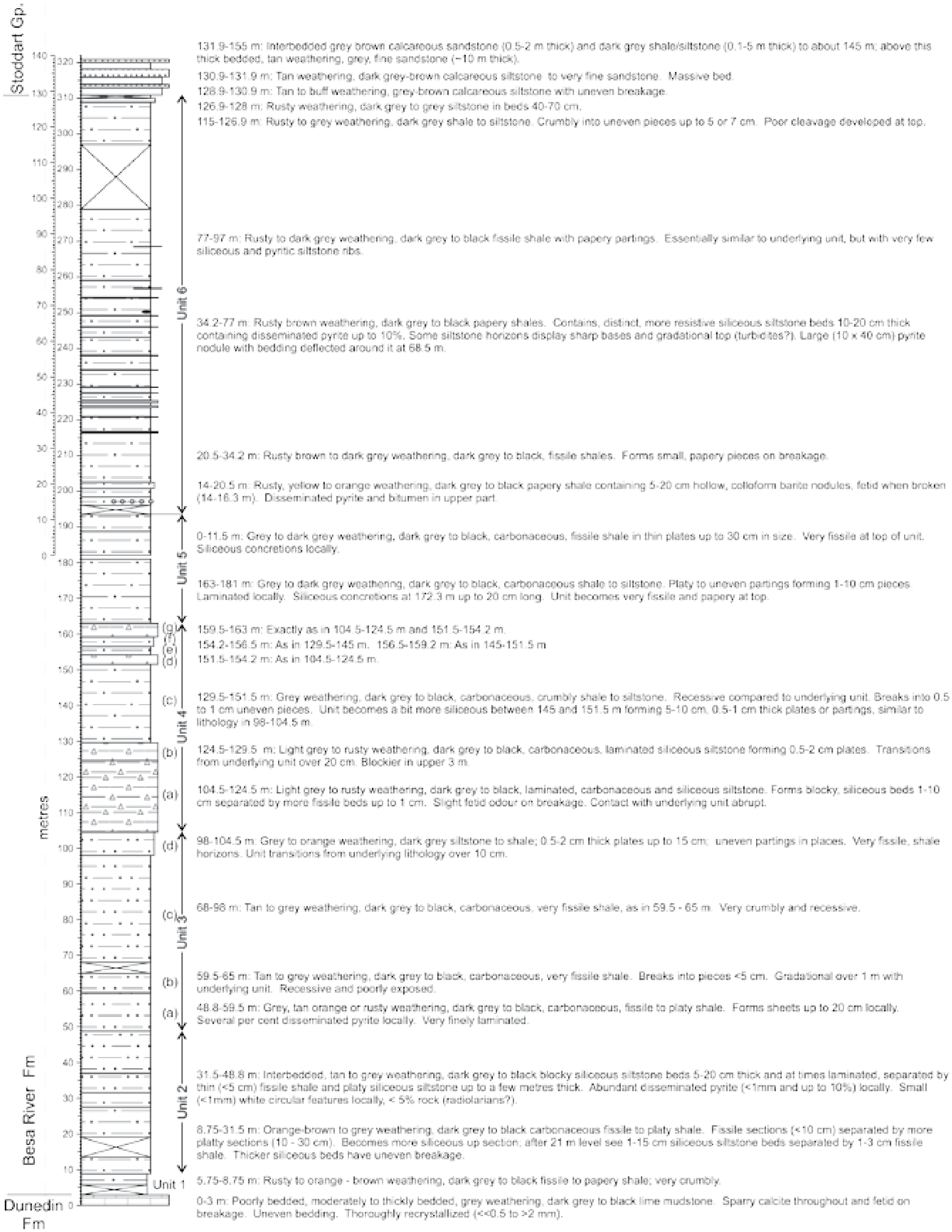

Figure 4. Lithological section of the Besa River Formation measured in the vicinity of Stone Mountain during the 2011 field season; the right-hand scale records cumulative thicknesses for combined sections from the base of section 1; the left-hand scale at the top of the diagram represents height in section with respect to section 2. Thicknesses in descriptive notes are with reference to each section.

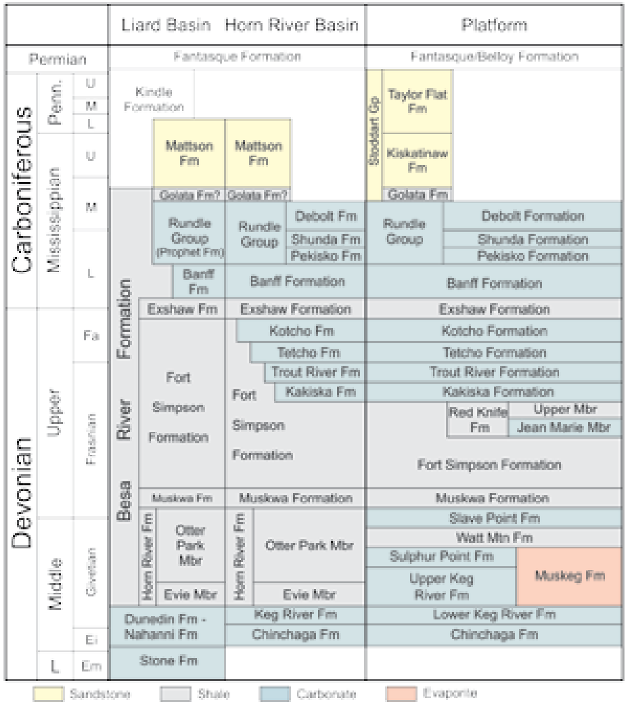

Figure 5. Time stratigraphic chart of the middle to upper Paleozoic showing the main stratigraphic units along the northwest part of the Western Canada Sedimentary Basin (falling within north-eastern British Columbia) and the relationship between shelf and off-shelf sequences.

Thickness and overall rock types of the 2011 section are similar to those measured during the 2010 field season in the Caribou Range. At a distance, both sections contain a lighter weathering zone in the lower part (unit 4; Ferri et al., 2011) that is more siliceous than other units (Fig. 7a, b), although the horizon assumed to be equivalent to this in the Caribou Range is much lighter coloured. Based on field observations, the 2011 section has been subdivided into six units reflecting colour (fresh and weathered), fissility or competence, and overall composition (Fig. 4). The lower half of the section appears generally more carbonaceous and competent than the upper part; i.e., more siliceous, although rock eval data (see below) indicates high organic carbon in the uppermost part. The lowest unit of the section is fissile (Fig. 8a, b) and is overlain by more resistive, platy to blocky shale of units 2 and 3 (Fig. 4, 8c–g). These units locally contain abundant disseminated pyrite and can be rich in organic matter. Unit 4 is characterized by several horizons of blocky, siliceous siltstone/shale beds up to 10 cm thick, separated by thinner, fissile horizons (Fig. 7b, 8h, 9a–g). Unit 4 is overlain by less siliceous, fissile to platy carbonaceous shale of unit 5 (Fig. 9h, 10a). Unit 6 is the thickest package in the section and is represented by a monotonous sequence of fissile shale, which in the lower half contains abundant, more competent, horizons (Fig. 4, 10c, d). Several of these horizons contain disseminated pyrite and are associated with pyrite nodules (Fig. 10e). Small

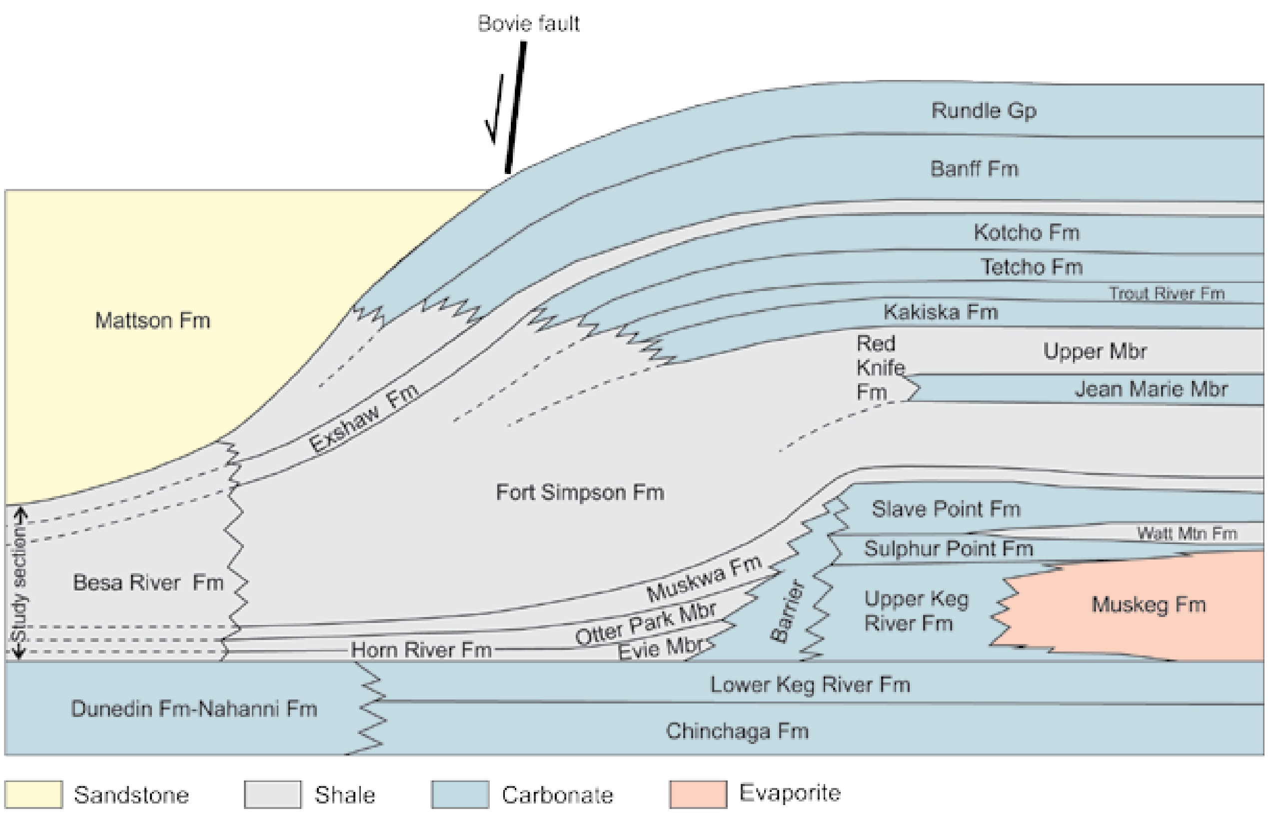

Figure 6. Schematic diagram showing relative thickness variations between middle to upper Paleozoic shelf and off-shelf sequences depicted in Figure 5.

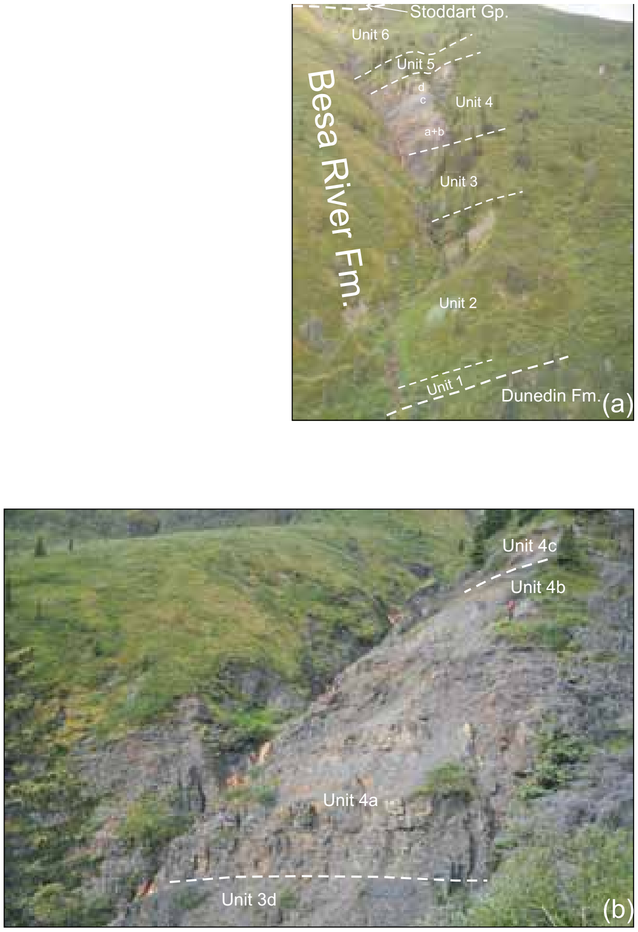

Figure 7. a) Looking west at the 2011 measured section of the Besa River Formation in the vicinity of Stone Mountain; note the light weathering characteristics of unit 4; b) looking west at more resistive, lighter grey weathering lithology of unit 4.

nodules (5–10 cm in diameter), displaying a coliform texture and having a strong fetid odour on breakage, are found along the lower part of unit 6 (Fig. 10b; 15 m level of section 2). Preliminary geochemical analysis of these nodules suggests that they are composed of barite. These nodules are found in roughly the same stratigraphic level as barite nodules observed in the Besa River section of the northern Caribou Range (Ferri et al., 2011).

Rock types spanning units 3 to 4 comprise a repetitive sequence of rock packages suggesting cyclic deposition. The sequences noted in subunits 3c to 4b, 4c to 4d and 4e to 4g define a succession repeated three times in the section (Fig. 8g–9g). The repeated sequence consists of blocky siliceous siltstone and thin shale partings (subunits 4a, b, d, g) overlain by recessive fissile shale (subunits 3c, 4c, e) that transitions upwards into more competent shale (subunits 3d, upper parts of 4c, 4f).

ANALYTICAL RESULTS

Gamma-ray Spectrometry

The trace of total gamma-ray dose (nGy/h) across the section shows several elevated zones spanning unit 1, the lower half of unit 2, across unit 5 and the lowermost part of unit 6 (Fig. 11). Generally baseline total gamma-ray levels and U content (approximately 10 ppm) are similar to the 2010 section. Zones of elevated gamma-ray levels or peaks in the 2011 section only reach intensities of 240 nGy/h, less than half the intensities recorded at the Caribou Range section (Fig. 12; Ferri et al., 2011). Uranium levels in these anomalous zones are also less than half of those seen in the 2010 section (20 versus 50 ppm, respectively) and subsequently the overall gamma-ray trace for the 2011 section is quite different from the 2010 section at the Caribou Range. Thorium levels in the 2011 section, as in the 2010 section, gradually increase towards the top of unit 6 and the relative abundance follows the concentration of K, suggesting its concentration may be tied to clay content. Potassium concentrations are as high as 4% in units 3, 4 and 6 and are at the lowest (1%) within the siliceous zone of unit 4a.

Rock-Eval and Thermal Maturity

Thermal maturity deduced by reflectance microscopy on bitumen and vitrinite range from 2.39 to 3.25% Ro_R, indicating upper dry gas conditions. The scatter of these data, when plotted against depth, does not allow the recognition of a geothermal gradient (Fig. 13).

Due to the high thermal maturity, some rock eval parameters will have questionable significance. Although total organic carbon (TOC) values are generally greater than 1 wt.%, S2 values across the section are generally less than 0.05 mg HC[1] /g rock and S1 values are normally less than 0.02 mg HC/g rock. The T_{max} values from the lowermost part of unit 1, where S2 values are the highest (0.07 mg HC/g rock) and pyrograms show a well-developed S2 peak, are approximately 530°C. The correlation of these T_{max} and average $\%Ro_R$ values are similar to empirical data presented by workers elsewhere (Fig. 14; cf. Dow, 1977; Teichmuller and Durand, 1983; Leckie et al., 1988).

Total organic carbon values range up to 8 wt.% in the upper part of unit 6 (Fig. 11) and concentrations averaging greater than 3 wt.% occur at four levels in the combined sections: unit 1 and the lower part of unit 2, the upper part of unit 3 and the lower part of unit 4, unit 5 and lower unit 6, and the upper-middle part of unit 6 (Fig. 11). Considering the level of thermal maturity displayed by these rocks, TOC levels were likely two to four times higher, depending

[1] Hydrocarbons

Figure 8. a) Fissile, crumbly shale of unit 1 between the 6 and 8.75 m levels of section 1; b) contact between fissile shale of unit 1 and more competent shales of unit 2 (9–10 m level of section 1); c) fissile to blocky shale of unit 2 between the 21 and 23 m levels of section 1; d) fissile to blocky shale of unit 2 between the 46 and 48 m levels of unit 2; e) fissile to platy shale of unit 3 between the 50 and 53 m levels of section 1; f) more fissile shale of unit 3 between the 68 to 73 m level of section 1; g) fissile to platy shale of unit 3 between the 99 and 104 m level of unit 3 section 1 (immediately below the contact with unit 4); h) competent, blocky, siliceous siltstone with fissile shale partings of unit 4 between the 108 and 109 m level of section 1.

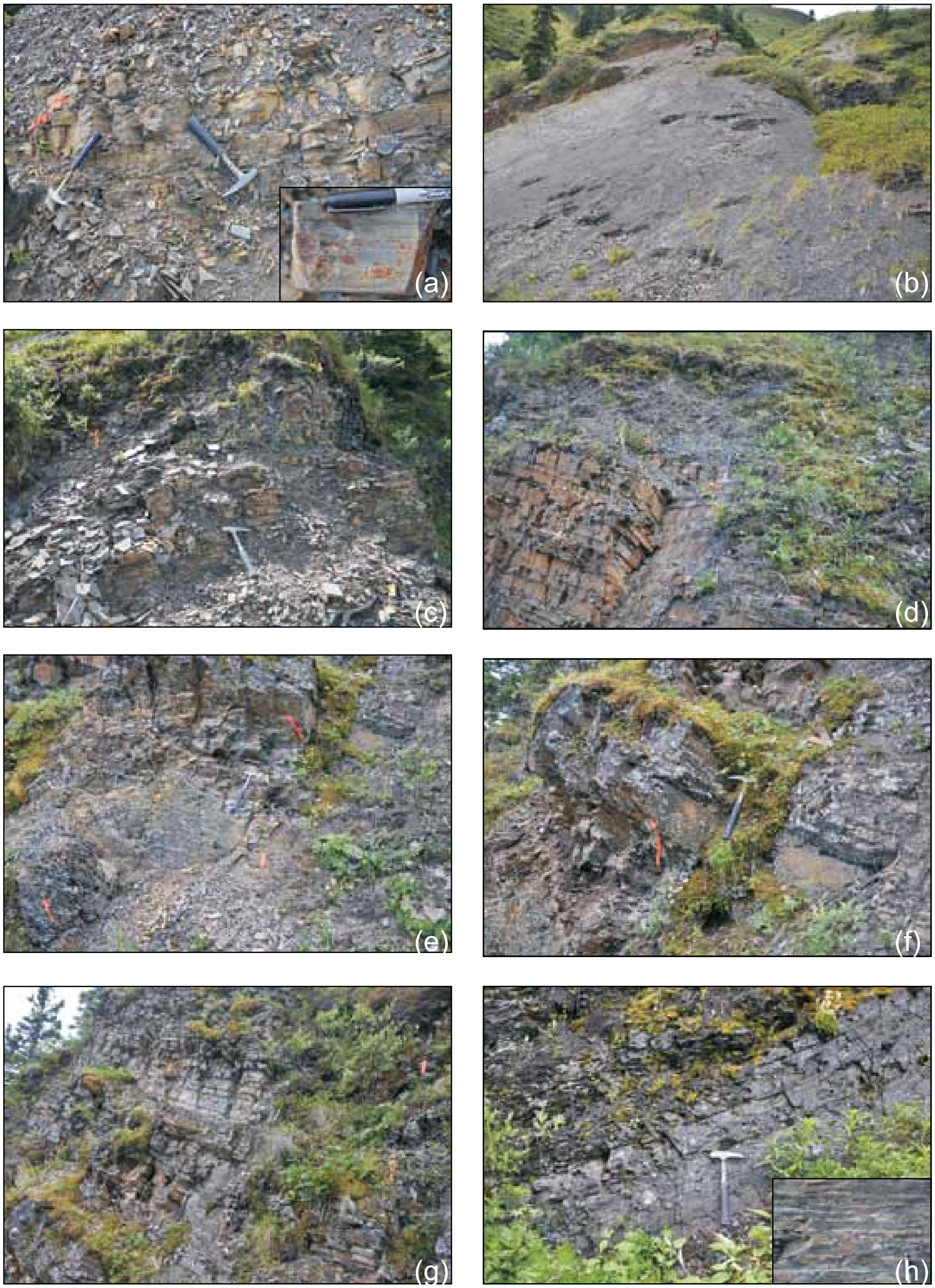

Figure 9. a) Laminated siltstone of unit 4 at the 126 m level of section 1. A close-up of this lithology and the laminations, is shown in the lower right corner inset; b) crumbly, siltstone of unit 4c between the 130 and 150 m levels of section 1; c) more competent and platy shale to siltstone of unit 4c between the 148 and 151 m levels of section 1, just below siliceous siltstone of unit 4d; there is a gradational change from the crumbly shales in the lower part of unit 4c into this lithology; rocks of unit 4d sit sharply on upper unit 4c rocks; d) upper gradational contact between siliceous siltstone and shale of unit 4d and crumbly shale of unit 4e (153 to 157 m level of section 1); e) fissile to platy shale of unit 4f between the 156 and 159 m levels of section 1, just below the contact with overlying siliceous siltstone and shale of unit 4g. This succession (units 4e to 4f to 4g is similar to that of units 4c to 4d); f) contact between units 4f and 4g (159.2 m level of section 1); g) siliceous siltstone of unit 4g between the 159 and 163 m level of section 1; note its similarity to rock types of units 4a and 4d; h) fissile to platy shale of unit 5 at the 172 m level of section 1. Inset in lower-right corner shows siliceous nodules to lenses within parts of this unit.

Figure 10. a) Siliceous nodules to lenses in fissile to platy shales of unit 5 at the 2 m level of section 2; b) close-up of barite nodules along the 15 m level of section 2 within the lower part of unit 6; inset in lower right corner shows internal structure with prismatic crystals; c) fissile to platy shale in the lower part of unit 6 between the 25 to 29 m levels of section 2; d) recessive fissile to platy shale of unit 6 between the 37 and 43 m levels of section 2. Note the more resistant siliceous bed at the 41.5 m level (close-up in inset); these more competent horizons are typically found in the lower part of unit 6; e) a 30 cm long ovoid pyrite nodule within unit 6 at the 68.5 m level of section 2. Inset is a close-up of the nodule showing the coarser pyrite crystals in its core; f) fissile to crumbly shale of the middle part of unit 6 between the 72 to 75 m level of section 2; g) uppermost fissile shale of unit 6 between the 124–128 m level of section 2; the first more resistive calcareous siltstone beds of the Stoddart Group can be seen in the upper left part of the picture; h) grey, calcareous, fine-grained sandstone horizon approximately 1 m thick at the base of the Stoddart Group, 131 m level of section 2.

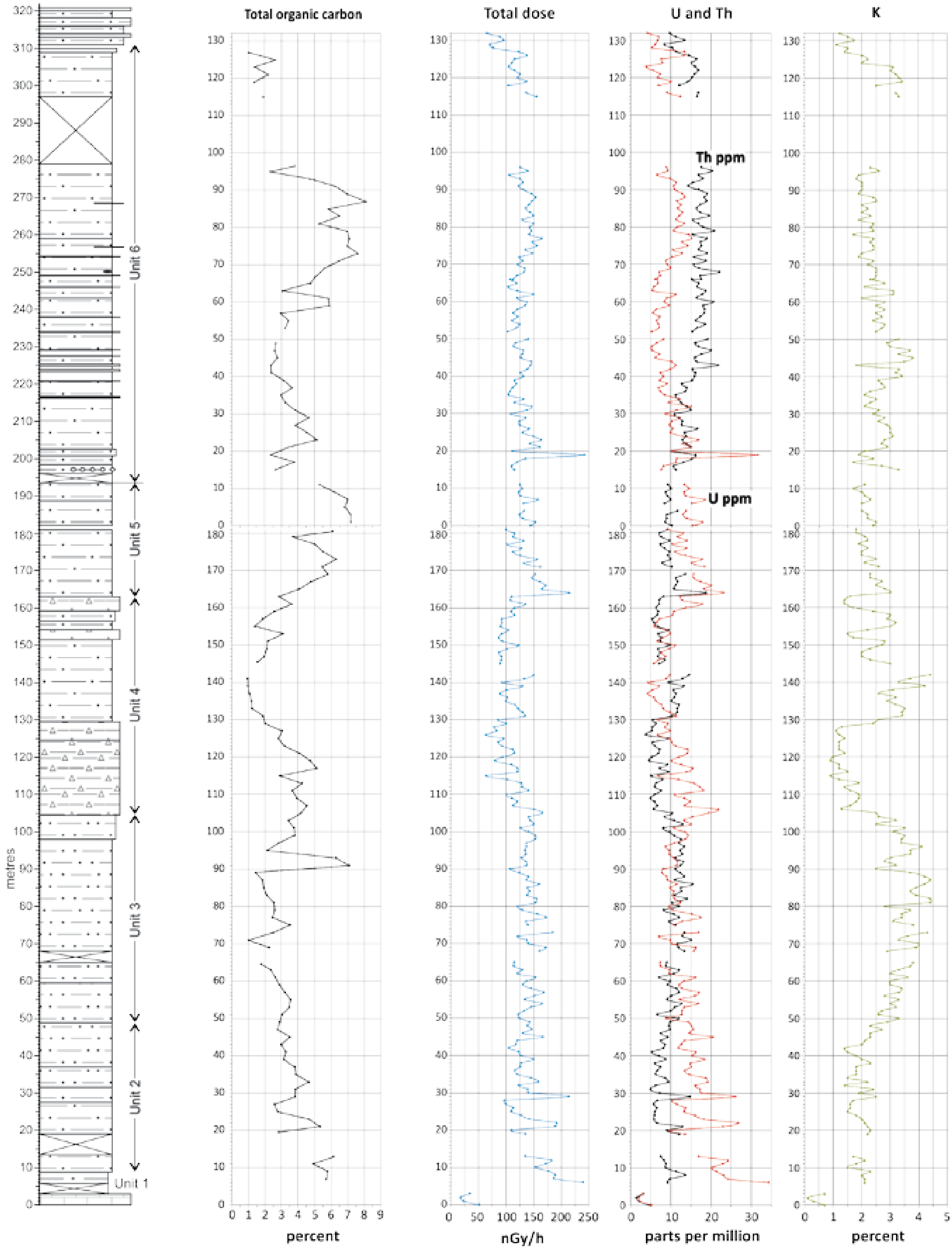

Figure 11. Lithological log of the Besa River section (Stone Mountain area) compared to total organic carbon (TOC) content, total natural radiation (dose) and U, Th and K concentrations. Natural radiation, U, Th and K were determined through a handheld gamma-ray spectrometer.

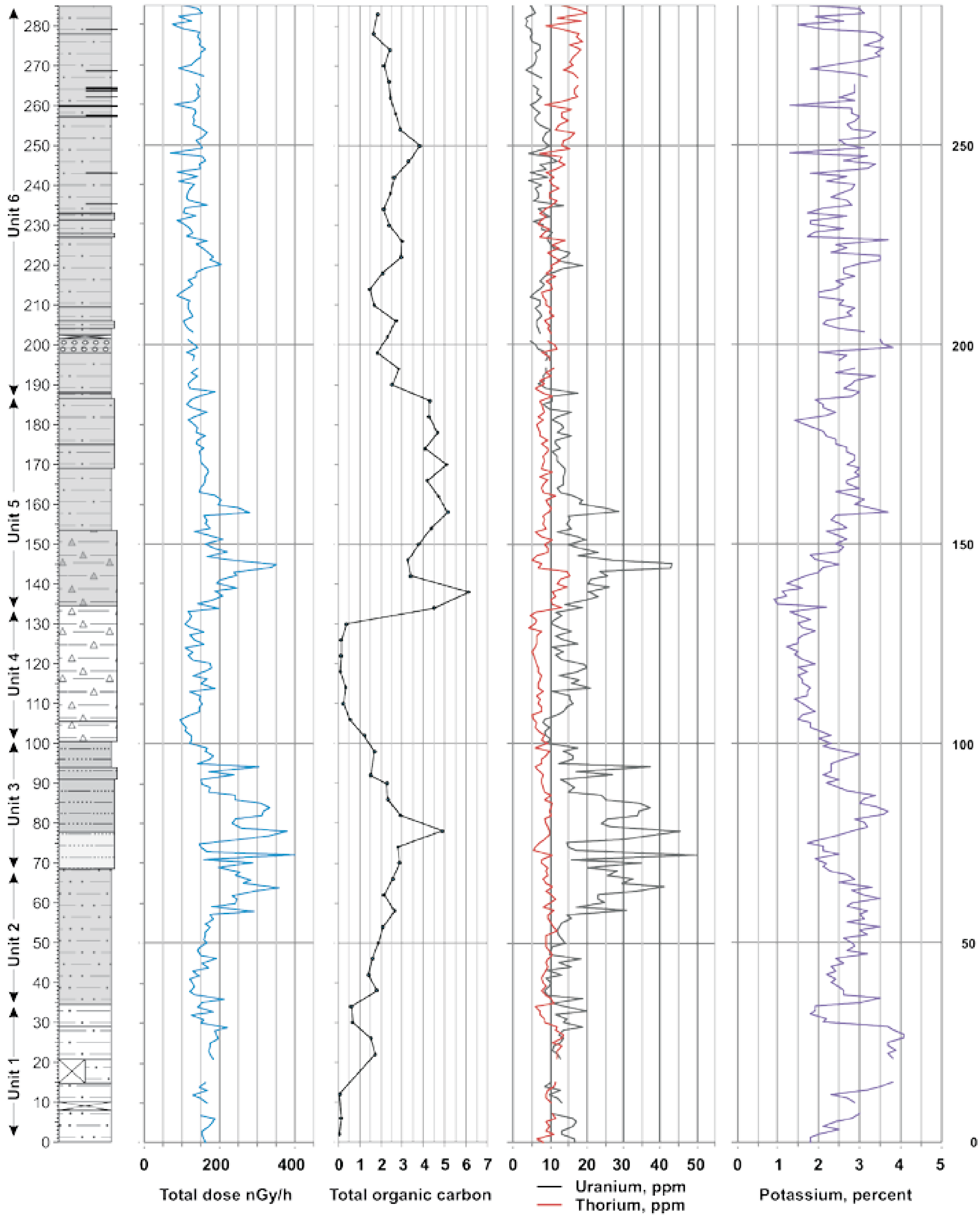

Figure 12. Lithological log of the Besa River section (Caribou Ranges) showing total organic carbon (TOC) content, total natural radiation (dose) and U, Th and K concentrations. Natural radiation, U, Th and K were determined through a handheld gamma-ray spectrometer.

on the original type of organic matter (Jarvie, 1991). The trace of TOC levels with depth generally follows gamma-ray counts and U concentrations, although the magnitude of U concentration excursions from baseline levels does not mimic increases in TOC (i.e., a fivefold increase in TOC content does not equate with a similar increase in U concentrations). In the 2010 section, tripling or quadrupling TOC levels led to roughly similar increases in U content. Empirical evidence from subsurface petrophysical logs has shown that 'hot' gamma-ray zones (i.e., higher than normal

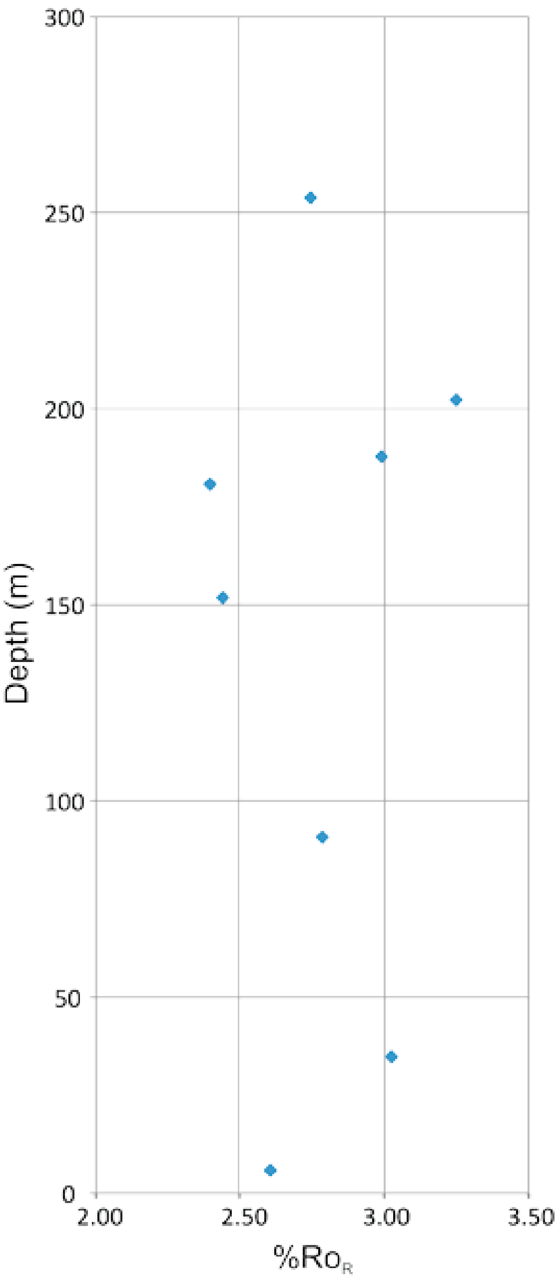

Figure 13. Thermal maturation levels within the measured section based on reflected light microscopy of bitumen and vitrinite macerals. All data has been converted to vitrinite-equivalent values.

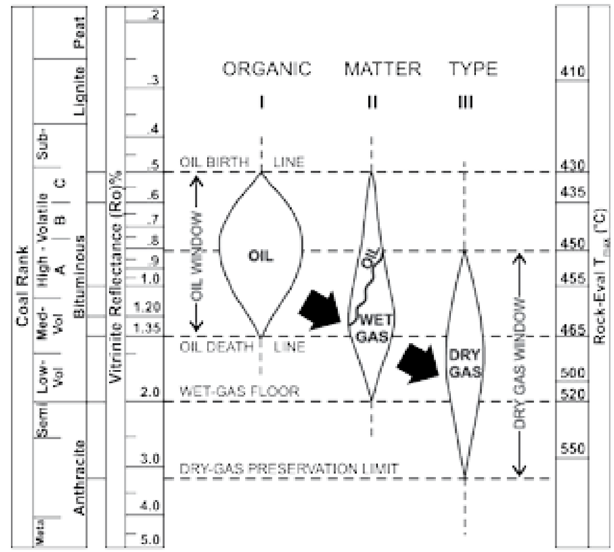

Figure 14. Zones of petroleum generation and destruction for various types of organic matter with reference to coal rank, vitrinite reflectance and Tmax values from Rock Eval analysis (modified from Leckie et al., 1988; cf. Dow, 1977; Teichmuller and Durand, 1983).

U levels) usually correlate with elevated TOC content. This relationship is evident within parts of the current section (i.e., units 1, 2, 5 and the lower part of unit 6), but the correlation fails for the upper-middle part of unit 6, where TOC levels are greater than 4 wt.% over 30 m, with some peaks over 7 wt.%, yet U concentrations increase by only 2.5 times (Fig. 11). The trace of total gamma rays across this zone would not suggest the elevated organic carbon levels within this horizon. This discrepancy may be a surface phenomenon related to oxidation. This shale was deposited under highly reducing conditions, which led to the concentration of U together with other metals. Oxidation of iron sulphides and the subsequent increase in the Eh of surface waters (i.e., acidification) may have led to greater mobility and leaching of U and other metals at the surface.

CORRELATIONS

The 2011 measured section of the Besa River Formation is tentatively correlated with similar sequences in the subsurface, particularly those of the Horn River succession within the Horn River basin. This is based on stratigraphic position, lithology and the outcrop-derived gamma-ray log. The edge of Slave Point carbonate deposition, which defines the southern limit of the Horn River basin, is believed to extend westward into the disturbed belt (Fig. 2). This edge likely swings southward within the disturbed belt, following the trend of the eastern margin of the Kechika Trough connecting with the upper Dunedin carbonate shale-out (upper Keg River to Slave Point) that has been defined in the Williston Lake area (Thompson, 1989; Nadijwon, 2001). A northwest-trending cross section incorporating the measured section and several nearby wells was constructed across the western margin of the Horn River basin and extending into the southern end of the younger Liard basin (Fig. 2).

Due to the rapid southeast increase in the thickness of the Fort Simpson Formation, only five wells that include the Exshaw Formation are incorporated into this cross section (Fig. 15). Reasonably confident correlations of the lower part of the measured section (unit 1 and lower half of unit 2) and subsurface sequences likely associated with the Evie marker of the Horn River succession can be achieved from gamma-ray patterns (Fig. 15). Overlying rocks, up to the base of the lower thick siliceous section of unit 4a, display gamma-ray patterns very similar to those assigned to the Muskwa marker in the subsurface. Gamma-ray spikes displayed within unit 5 and the lower part of unit 6 are correlated with markers assigned to the Exshaw Formation (Fig. 15). This would suggest that the siliceous successions of unit 4 are equivalent to the succession within the Fort Simpson to Kotcho formations. Although blocky siliceous siltstone to shale of unit 4 in the 2011 section has comparable thickness, lithological character and occupies the same stratigraphic position as unit 4 in the 2010 section, the organic carbon content of unit 4 in the 2011 section is considerably higher. The high organic carbon levels of unit 4a are not reflected by the relatively low levels of gamma-ray counts (Fig. 15).

The organic-rich horizon within the upper-middle part of unit 6 was not observed in the 2010 section. Corresponding gamma-ray levels in the 2010 section are subdued across this zone and correlation into the subsurface is difficult. This zone, between the Exshaw and Mattson formations and Stoddart sequences, correlates, in part, with the western shale-out of Rundle Group–equivalent strata (i.e., the Prophet Formation).

CONCLUSIONS

- Approximately 310 m of shale and siltstone belonging to the Middle Devonian to Middle Mississippian Besa River Formation were measured in the vicinity of the Stone Mountain area of northeastern British Columbia.
- The 2011 Besa River Formation section in the Stone Mountain area is broadly similar to that measured in the Caribou Ranges during the 2010 field season. Both are roughly of the same thickness and have a lighter weathering, siliceous siltstone package near the middle part of the succession.
- Peak natural gamma-ray levels (and uranium contents) of the 2011 section are half the levels seen in the 2010 section.
- Correlation of the surface gamma-ray log with the subsurface section to the southeast and northeast indicates the presence of the Evie, Muskwa and Exshaw markers at the surface. This exercise also allows correlation between the 2010 and 2011 sections, confirming subsurface correlations of Besa River rock types in the Caribou Range.
- Rock eval analysis indicates TOC levels of 5–7 wt.% within Evie-, Muskwa- and Exshaw-equivalent strata. In addition, there is another zone of high TOC (up to 8 wt.%) above the Exshaw marker, within the upper part of the Besa River Formation.

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The authors thank Gabriel Altebaumer of the Geological Survey of Canada for enthusiastic and competent assistance in the field. Thanks also to Margot McMechan of the Geological Survey of Canada for the use of the gamma-ray spectrometer. Bailey Helicopters Ltd. provided competent service in the location and demobilization of the field camp.

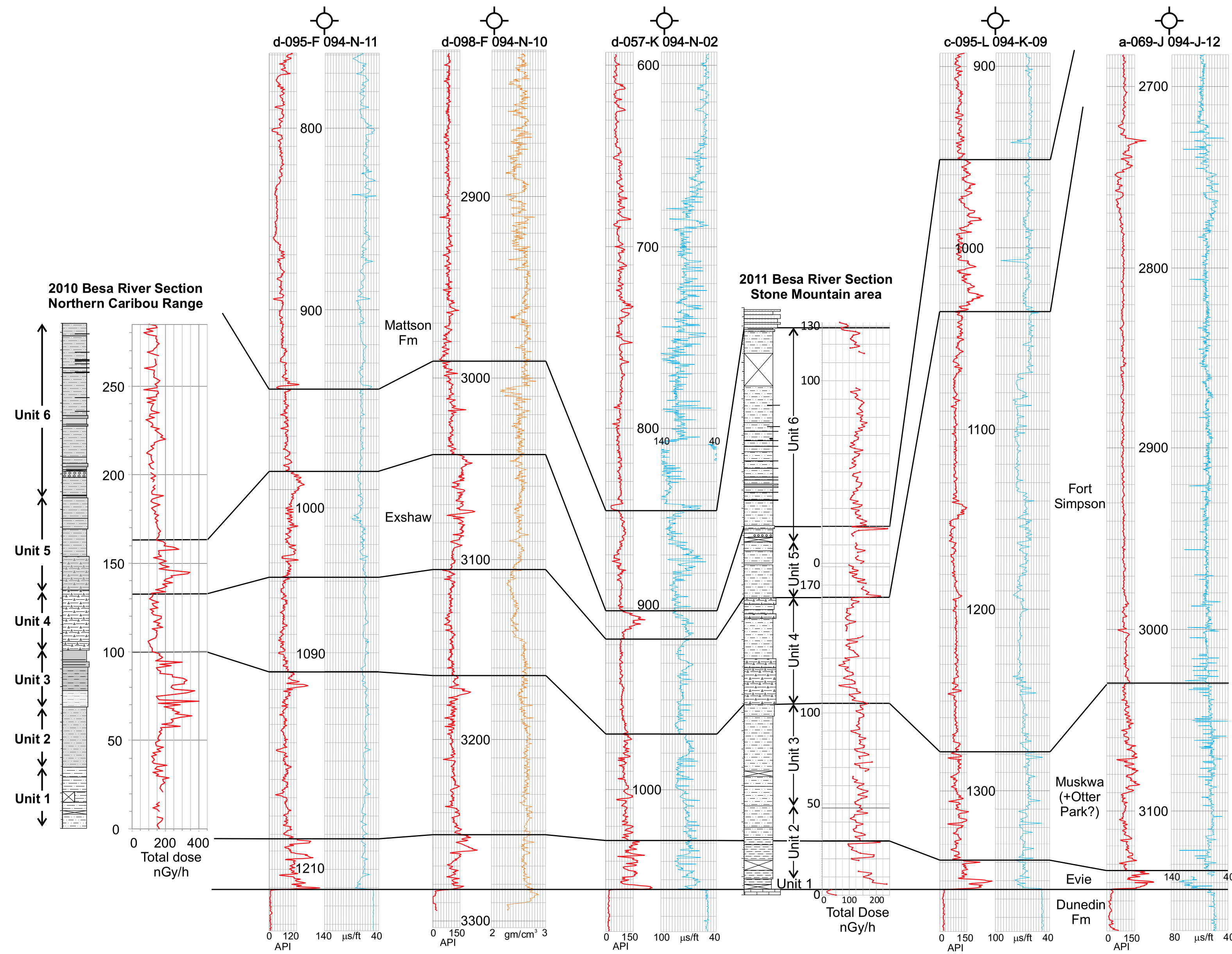

Figure 15. Correlation of the 2011 measured section of the Besa River Formation (Stone Mountain area), several nearby subsurface gamma-ray sections from well-bores, and the 2010 measured section of the Besa River Formation (Caribou Ranges). Location of the section is shown in Figure 2.

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GEOLOGY OF THE TOAD RIVER AREA (NTS 094N), NORTHEAST BRITISH COLUMBIA

Margaret McMechan[1], Filippo Ferri[2] and Larry MacDonald[1]

ABSTRACT

Regional mapping within the Toad River map area (NTS 094N) during the summer of 2011 will be incorporated with published and unpublished geological studies, including the unpublished detailed mapping along the Liard River corridor for BC Hydro, to update the geological database of this map area. More than 8000 m of strata spanning the Mesoproterozoic to Upper Cretaceous occur in the area. Abrupt changes in thickness and facies, and the local absence of specific stratigraphic intervals indicate that block faulting was active during the Middle Cambrian, Ordovician to Silurian, Mississippian to Permian, and Jurassic to Early Cretaceous (pre-Albian). These early faults were commonly reactivated during Cretaceous shortening and controlled the trend and position of younger structures. Thrust faulting is the dominant form of shortening within the competent Mesoproterozoic to Paleozoic successions, whereas detachment folding is the prevailing mechanism within the interlayered competent and incompetent Upper Devonian to Cretaceous successions. Principal detachment horizons include Upper Devonian to Mississippian shale of the Besa River Formation, Triassic shale and siltstone of the Toad/Grayling formations and shale of the Lower Cretaceous Buckinghorse and Garbutt formations. Shortening at the top of the Triassic in the eastern part of the Rocky Mountain Foothills near the Toad River is estimated to be approximately 5–6 km. Shortening at the top of the Triassic across the eastern part of the Liard Fold and Thrust Belt is even less. Hydrocarbon resources occur within large, structural culminations of the Beaver River and Crow River gas fields. In addition, the Paleozoic and Mesozoic successions contain several organic-rich horizons (Besa River Formation, Toad/Grayling formations and Garbutt Formation) that are stratigraphically equivalent to sequences being developed for shale gas resources elsewhere within the Western Canada Sedimentary Basin.

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Key Words: Toad River map area, Liard River, Rocky Mountains, Rocky Mountain Foothills, Mackenzie Mountains, Liard Fold and Thrust Belt, Bedrock geology, GIS-enabled maps, stratigraphy, structure, Tuchodi Formation, Neoproterozoic, Cambrian, Quartzite, Mount Roosevelt Formation, Kechika Group, Nonda Formation, Muncho-McConnell Formation, Wokkpash Formation, Stone Formation, Dunedin Formation, Besa River Formation, Mattson Formation, Kindle Formation, Tika formation, Fantasque Formation, Grayling Formation, Toad Formation, Liard Formation, Luddington Formation, Baldonnel Formation, Pardonet Formation, Chinkeh Formation, Garbutt Formation, Scatter Formation, Lepine Formation, Buckinghorse Formation, Sikanni Formation, Sulley Formation, Dunvegan Formation, Kotaneelee Formation, pre-Cordilleran structure, Detachment folding, Forcier fault, Sulphur Creek fault, Larsen fault

INTRODUCTION

The Toad River map area (NTS 094N) forms the western edge of the Liard Basin (Fig. 1), a sub-basin of the Western Canada Sedimentary Basin, with up to 5000 m of Upper Devonian to Cretaceous sedimentary fill, located west of the Bovie fault and adjacent to the portion of the Horn River Basin undergoing development for shale gas (Wright et al., 1994; Walsh et al., 2005). Three organic-rich horizons with shale gas potential (Besa River, Grayling and Garbutt formations; e.g., Ferri et al., 2011a, b) occur in the Liard Basin and have been deformed and brought near or to the surface in and around this structural depression in the Toad River map area. In addition, significant gas reserves that occur in Middle Devonian carbonate rocks are involved in structures north of the Liard River (Beaver River gas field; 7.1×10^9 m^3 (250×10^9 ft^3). In 2011, the Geological Survey of Canada (GSC) and the British Columbia Ministry of Energy and Mines (MEM) undertook fieldwork in the Toad River area as part of the GSC's ongoing Geomapping for Energy and Minerals (GEM), Yukon Sedimentary Basins project, to update the bedrock geological database, constrain the maturation history and provide a geological synthesis of the area. In 2010, this program focused on the examination of Devonian and Cretaceous shale gas sequences (Ferri et al., 2011a, b) and the mapping of surficial geology deposits that will assist with operational aspects of resource development in the eastern Liard Basin (Huntley and Sidwell, 2010; Huntley et al., 2011).

The Toad River map area contains one of the few regions in the eastern Canadian Cordillera (Foreland Belt) where a pronounced change in the structural trend occurs. Near Liard River, the orientation of regional structures swings from the northwest in the south, to north and northeast in the north (Fig. 1). The area contains the northern end of the Rocky Mountains and the Rocky Mountain Foothills structural subprovinces and the southern end of the Mackenzie Mountains structural subprovince, the Liard Fold and Thrust Belt and the Liard syncline (Fig. 2). Similar to other parts of the Foreland Belt, the topography in the area reflects the underlying geology. Paleozoic and Triassic carbonate strata hold up mountain ranges in the western part of the area. In the eastern Rocky Mountain Foothills and Liard Fold and Thrust Belt, ridges are underlain by anticlines of folded Mississippian and Triassic sandstone units and valleys have formed above synclines. High tree-topped mesas that formed above gently dipping Cretaceous sandstone or conglomerate characterize the Liard syncline.

The Liard Fold and Thrust Belt is known to hold important gas reserves in Middle Devonian structural plays of the Beaver River and Crow River gas fields (Fig. 2). Several gas shows have been found in Mississippian through

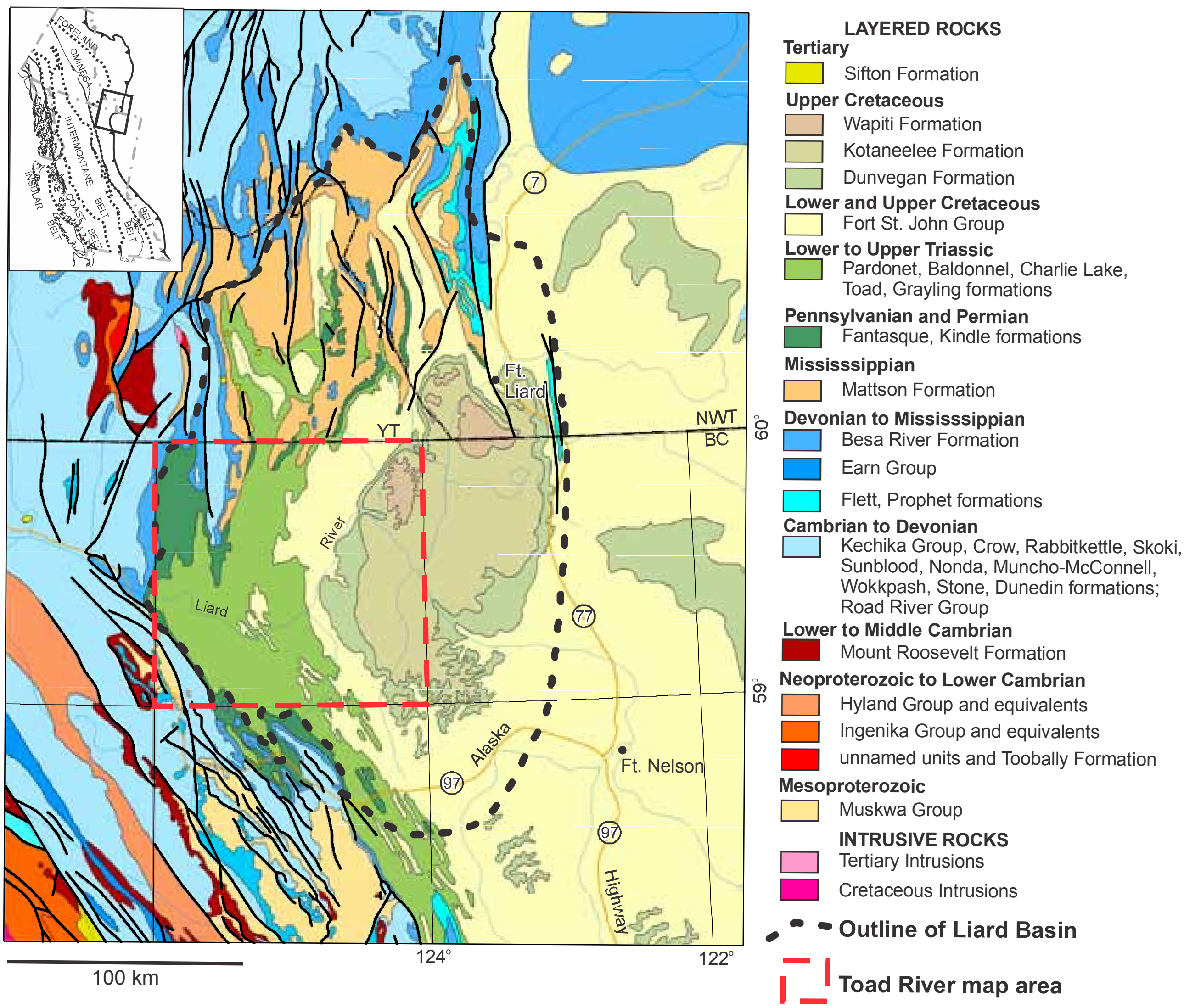


Figure 1. Geology of the Liard Basin and adjacent areas. The red box outlines the Toad River map area. Geology is from Wheeler and McFeely (1991).

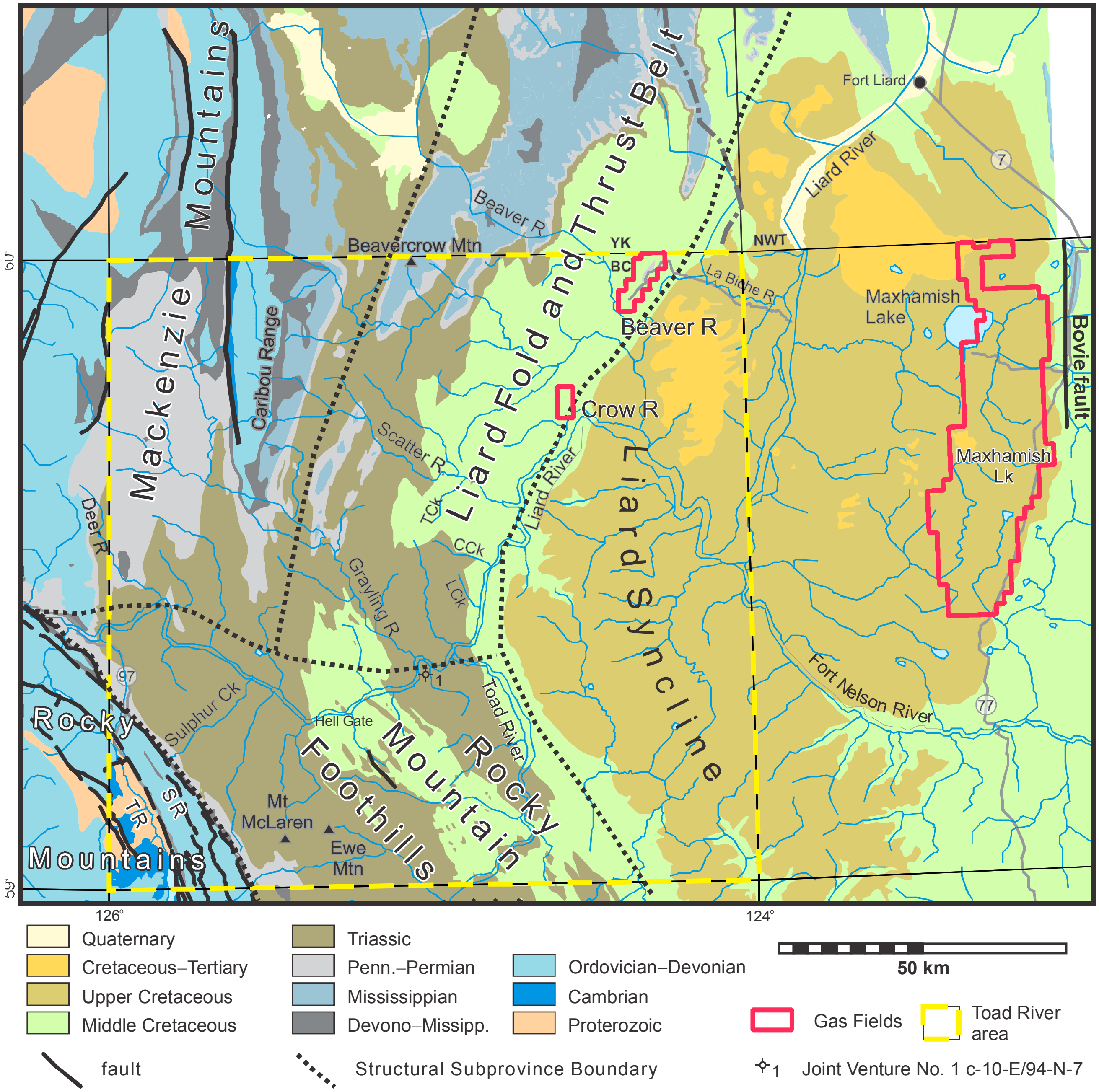


Figure 2. Geological subprovinces in the Toad River area. Abbreviations: CCk, Chimney Creek; LCk, Lepine Creek; SR, Sentinel Range; TCk, Toreva Creek; TR, Terminal Range. Modified from Ferri et al. (2011a). Geology is from MapPlace.ca (BC Geological Survey, 2012) and based on published maps by the Geological Survey of Canada (cf. Taylor and Stott, 1980; Stott and Taylor, 1968; Douglas, 1976; Douglas and Norris, 1976). Structural subprovinces are modified after Gabrielse and Yorath (1991).

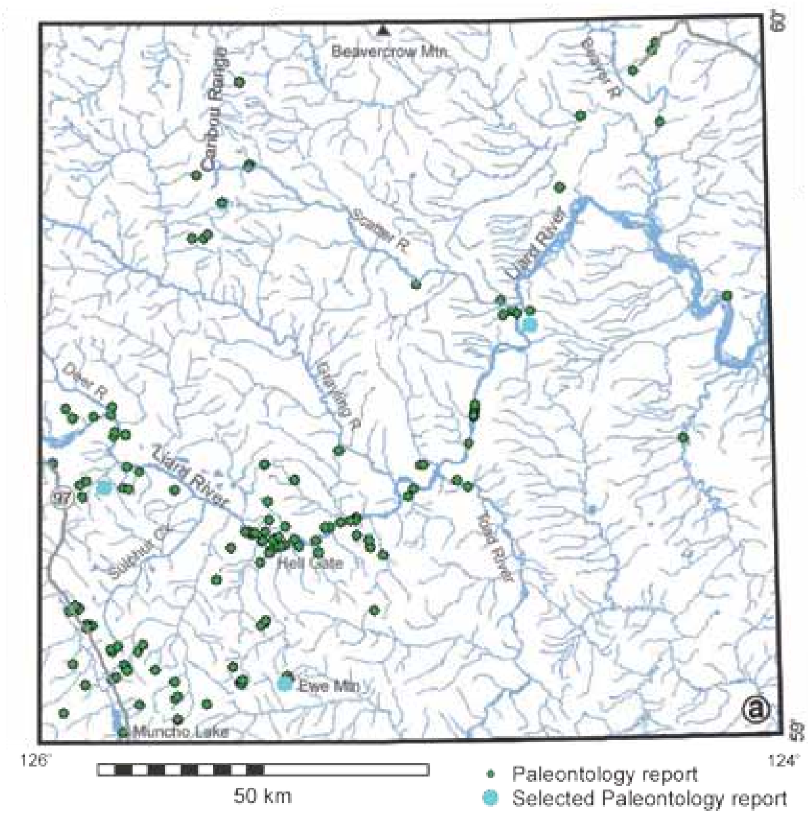
Permian intervals (Walsh et al., 2005) and some shale gas production from Devonian and Mississippian sequences in the Beaver River gas field has occurred (Oil and Gas Journal, 2008). Petroleum exploration in the area began with the Joint Venture No. 1 c-10-E/94-N-7 well drilled on the Toad anticline near Liard River in 1953. In 1958, Amoco Canada Petroleum Company Limited made the first discovery at the Beaver River gas field (Snowdon, 1977). Further drilling delineated that pool and discovered the Crow River gas field. Limited drilling has occurred away from those two fields with only ten exploration wells drilled as of 2011.

Early geological work in the Toad River map area occurred along the Liard and Fort Nelson rivers (McConnell, 1890; Williams, 1923; Kindle, 1944; McLearn, 1945) and then adjacent to the Alaska Highway (Hage, 1944; Laudon and Chronic, 1949). More widespread stratigraphic and mapping studies began with the advent of helicopters in the 1950s. Pelletier (1961), Bamber et al. (1968), Stott (1968, 1982), Taylor and MacKenzie (1970) and Post and Long (2008) have published on Triassic, Cretaceous, Devonian and Cambrian stratigraphy, respectively. The first complete geological map of the Toad River map area was published without an accompanying report in 1980 by Taylor and Stott. The unrevised map was republished in colour in 1999 (Taylor and Stott, 1999). Detailed, unpublished 1:10 000 scale mapping was conducted along most of the Liard River in the 1980s as part of a BC Hydro dam site investigation (Geotex Consultants, 1984).

The current study builds on published and unpublished geological studies, including the detailed mapping along the Liard River prepared for BC Hydro (Geotex Consultants, 1984). New GIS-enabled bedrock geological maps will be produced for the Toad River map area. Each map will include baseline mapping data (location, lithological, structural observations) and baseline data for measured sections (location, observer) together with datasets related to sample acquisition (paleontology reports, Rock Eval™, geochronology and vitrinite reflectance) collected from this project and from historical sources (Fig. 3a, b). This report provides the first summary report on the stratigraphy and structure of the Toad River map area since McLearn and Kindle's summary report (1950) on the geology of northeastern British Columbia.

STRATIGRAPHY

Approximately 8 km of Mesoproterozoic to Upper Cretaceous strata are exposed in the Toad River map area. The oldest strata occur in the southwest part of the Rocky Mountains and the youngest in the northeast part of the Liard syncline (Fig. 2). In general terms, the succession consists of 1) a Mesoproterozoic, clastic-dominated succession deposited in shelf environments after Mesoproterozoic rifting; 2) unconformably overlying clastic-dominated and rift-related uppermost Neoproterozoic–Cambrian strata; 3)



Selected Attributes of LHA09_ED.PaleoReports94N selection

OBJECTID *	REPORT_NO	YEAR	C_NUM	COLLECTOR	LAT	LONG_	MAP_ID	IDENTIFIER	AUTHOR_ID	Shape
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222	Tr1-1982-ETT	1982	C-090882	J.T.Fyles	59.352598	-125.82377	094N/05	ETT	ETT	Point
205	Tr1-1982-ETT	1982	C-090865	P.B.Read	59.078425	-125.334863	094N/03	ETT	ETT	Point

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Figure 3. a) Map showing location of paleontology samples identified in paleontology reports in the Toad River map area; b) ArcMap attribute table summarizing data for the three paleontology samples selected in Figure 3a.

an unconformably overlying carbonate-dominated, shelf-platform succession that persisted through the Middle Devonian; 4) a clastic-dominated upper Paleozoic succession that records local block faulting and extension; 5) easterly derived Triassic clastic and younger carbonate strata that indicate renewed subsidence in the southern part of the area and 6) unconformably overlying Lower and Upper Cretaceous shale-dominated foreland basin strata. Important changes in preservation, thickness and/or facies occur across the area in Cambrian, Devonian, Mississippian, Permian and Triassic units. Some of these changes indicate the presence of older (pre-Cordilleran deformation) faults. Brief descriptions of the 34 stratigraphic units recognized in the study are given below.

Mesoproterozoic

TUCHODI FORMATION, MUSKWA GROUP

Sandstone, siltstone, argillite and dolostone of the Tuchodi Formation (Bell, 1968) are the oldest rocks exposed in the Toad River area. The sandstones are generally grey, very fine to medium-grained, very thin to thick-bedded and vary from grey weathering and siliceous to orange-brown weathering and dolomitic. The sandstones are commonly separated by argillite or siltstone interbeds and partings and are locally mud-cracked and rippled. Resistant sections dominated by siliceous quartzite are up to 50 m thick (Fig. 4a). Intervals of green-grey and grey siltstone with argillite laminae or argillite with siltstone laminae are common. Dolostone is silty or sandy, very thin to medium-bedded, orange-brown weathering and locally has mud-cracked varicoloured argillite interlaminae to very thin interbeds. Several dark, chloritized mafic dikes 10–30 m wide cut Tuchodi strata at a high angle. Both the Tuchodi Formation and the dikes are unconformably overlain by either the unnamed uppermost Neoproterozoic–Cambrian quartzite unit or the Middle Cambrian Mount Roosevelt Formation in the Terminal Range and the Silurian Nonda Formation in the Sentinel Range. More than 500 m of Tuchodi strata are exposed in the Terminal Range.

Proterozoic

UNNAMED SILTSTONE-SANDSTONE UNIT

Locally in the southern Caribou Range, approximately 100 m of dark grey to grey, grey or rusty weathering, very thin to medium-bedded, quartzose siltstone to fine-grained sandstone was recognized beneath the overlying unnamed quartzite unit (Fig. 4b). Finer-grained strata appear slaty and the siltstone-sandstone is locally rippled. The age of this unit is poorly defined. It may correlate with either the Mesoproterozoic Muskwa Group or the Neoproterozoic Windermere Supergroup.

Uppermost Neoproterozoic–Lower Cambrian

UNNAMED QUARTZITE UNIT

Orthoquartzite forms a resistant unnamed unit in the Terminal and Caribou ranges. This rock is pale grey, white or maroon weathering, fine- to coarse-grained, medium- to thick-bedded, massive to laminated and locally burrowed. A reddish cobble conglomerate to breccia several metres thick with a dark grey quartz sandstone matrix and clasts of quartzite occurs at the base of the unit in the Caribou Range. The quartzite unit is unconformably overlain by Silurian dolostone of the Nonda Formation in the Caribou Range and disconformably overlain by brightly coloured, Middle Cambrian sandstone and dolostone of the Mount Roosevelt Formation (Fig. 4c) in the Terminal Range. Estimated thickness ranges from up to approximately 300 m in the Terminal Range to more than 400 m in the Caribou Range. The unit is not preserved beneath the Silurian Nonda Formation in the Sentinel Range.

Middle Cambrian

MOUNT ROOSEVELT FORMATION

The Mount Roosevelt Formation (Post and Long, 2008) is only preserved in the Terminal Range, where it consists of three members. The heterogenic lower member forms a distinctive bright weathering unit consisting of sandstone, siltstone and carbonate. Clastic units include red weathering, planar bedded, pebbly siltstone and muddy sandstone with discontinuous interbeds of white, laminated to thin-bedded, massive carbonate; red-brown weathering, medium-bedded to massive, planar-bedded pebbly sandstone and pebble conglomerate associated with red, hematitic pebbly medium-grained sandstone; and medium grey, dull red weathering, very fine grained, thin- to thick-bedded, locally crossbedded and rippled, variably dolomitic sandstone. Carbonates include pink weathering, fine crystalline locally pebbly and sandy dolostone; buff weathering, grey, medium- to thick-bedded, laminated to massive limestone; and minor pedogenic limestone. The middle and upper members (Post and Long, 2008) consist of red-brown weathering, poorly sorted, cobble to boulder, polymict conglomerate with local discontinuous interbeds of massive pebbly medium-grained sandstone (Fig. 4d). Conglomerates are noncalcareous in the middle member and mainly calcareous in the upper member. Intervals of buff weathering, light grey, massive to crudely bedded, fine to medium crystalline dolostone occur in the upper member. Maximum

Figure 4. a) Quartzite-dominated interval in the Tuchodi Formation, Sentinel Range; b) unnamed Proterozoic fine-grained sandstone to siltstone locally exposed beneath Neoproterozoic–Lower Cambrian quartzite in the Caribou Range; c) bright weathering siltstone, sandstone and carbonate of the lower member of the Mount Roosevelt Formation disconformably overlying the resistant unnamed Neoproterozoic–Lower Cambrian quartzite unit, Terminal Range; d) crudely bedded, matrix-supported conglomerate of the middle member of the Mount Roosevelt Formation, Terminal Range; e) parallel-laminated, cleaved, silty limestone of the Kechika Group, Terminal Range; f) stromatoporoid dolostone in the Nonda Formation, Sentinel Range.

thickness of the lower member is approximately 135 m and estimated thickness of the middle and upper members is 1800 m (Post and Long, 2008).

Upper Cambrian–Ordovician

KECHIKA GROUP

The Kechika Group (Gabrielse, 1963) is only preserved beneath the sub-Nonda Formation unconformity in the Terminal Range. At the base of the Kechika Group, Bell (unpublished GSC field notes, 1963) reported 8 m of medium grey, olive brown weathering, cleaved, very calcareous siltstone with some sandstone interbeds overlain by 64 m of medium grey, grey-brown weathering, thick-bedded, slightly calcareous siltstone with brown weathering more calcareous bands. Most of the Kechika Group exposed in the Toad River map area consists of brown-grey weathering, medium grey, thin- to thick-bedded argillaceous and silty limestone that was locally parallel laminated (Fig. 4e). A few hundred metres of Kechika strata are exposed in the southwestern corner of the map area.

Silurian

NONDA FORMATION

The Nonda Formation (Norford et al., 1966) forms a distinctive, resistant, dark weathering, poorly bedded dolostone unit. Minor white, brown-grey weathering, medium- to thick-bedded, fine- to coarse-grained quartz sandstone that is locally cross-laminated occurs at the base. The main part of the formation consists of dark grey, dark grey weathering, thick-bedded to massive dolostone. Stromatoporoids (Fig. 4f) and corals are common fossils and some beds are biostromal. Vuggy porosity and calcite-filled vugs are common and chert nodules occur locally. Intervals of medium grey, light grey weathering, medium- to thick-bedded, commonly laminated dolostone up to 5 m thick occur mainly in the upper part of the formation. Minor local medium grey, tan weathering, medium- to thick-bedded, silty dolostone is overlain by a few centimetres of dark grey weathering black shale. The Nonda Formation is approximately 290 m thick in the Caribou Range and approximately 300 m in the Sentinel Range (Norford et al., 1966)

Upper Silurian–Lower Devonian

MUNCHO-MCCONNELL FORMATION

The Nonda Formation is disconformably overlain by much lighter grey weathering, resistant, well-bedded dolostone of the Muncho-McConnell Formation (Fig. 5a; Taylor and Mackenzie, 1970). Light to dark grey, light to medium grey weathering, thin- to thick-bedded dolostone with common laminae characterize the Muncho-McConnell Formation. Light grey dolostone is predominant especially in the lower part of the formation, and in most exposures, there is a thin unit of medium grey, tan weathering, argillaceous dolostone at the base. The formation is 246 m thick in the Caribou Range and 349 m in the Sentinel Range (Taylor and Mackenzie, 1970).

Lower Devonian

WOKKPASH FORMATION

The Wokkpash Formation (Taylor and Mackenzie, 1970) forms a distinctive tan to yellow- brown weathering unit in the lower Paleozoic succession. In most of the Sentinel Range, the main part of the formation consists of light grey, bright yellow-orange weathering solution collapse breccia with a few interbeds of red and green argillaceous dolostone and grey medium-bedded dolostone (Fig. 5b). Light grey to white, tan to white weathering, very fine to fine-grained, locally burrowed, dolomitic and nondolomitic quartz arenite overlies the breccia. In the Caribou Range and locally in the southern Sentinel Range, dolostone and dolomitic sandstone form the dominant rock types. The Wokkpash is 113 m thick in the Caribou Range and 109 m in the Sentinel Range (Taylor and Mackenzie, 1970).

Lower–Middle Devonian

STONE FORMATION

The Stone Formation (Taylor and Mackenzie, 1970) forms a thick resistant dolostone unit in the Caribou and Sentinel ranges. The Stone Formation is characterized by light and medium grey, light and medium grey weathering, medium- to very thick-bedded, massive or less commonly laminated dolostone. In the Sentinel Range, the lower part of the formation shows lighter weathering than the upper part (Fig. 5c). Barite cobbles occur locally at the base of the formation in the northern Sentinel Range and indicate the presence of a disconformity (Taylor and Mackenzie, 1970). Zones of brecciated dolostone in a cement of white calcite occur sporadically. The Stone Formation is 473 m thick in the Caribou Range and 586 m in the Sentinel Range (Taylor and Mackenzie, 1970).

Middle Devonian

DUNEDIN FORMATION

The Dunedin Formation (Taylor and Mackenzie, 1970) caps the Paleozoic carbonate succession. In the Toad River area, the exposed Dunedin Formation consists mainly of medium to dark grey, medium and light grey weathering, thin- to very thick bedded limestone (Fig. 5d). The limestone occurs as cycles of thick wackestone beds grading up to thin packstone and grainstone beds separated by thick sequences of wackestone (Morrow, 1978). Crinoids, brachiopods, corals and ostracods are common fossil fragments. Black chert nodules are common near the top of the

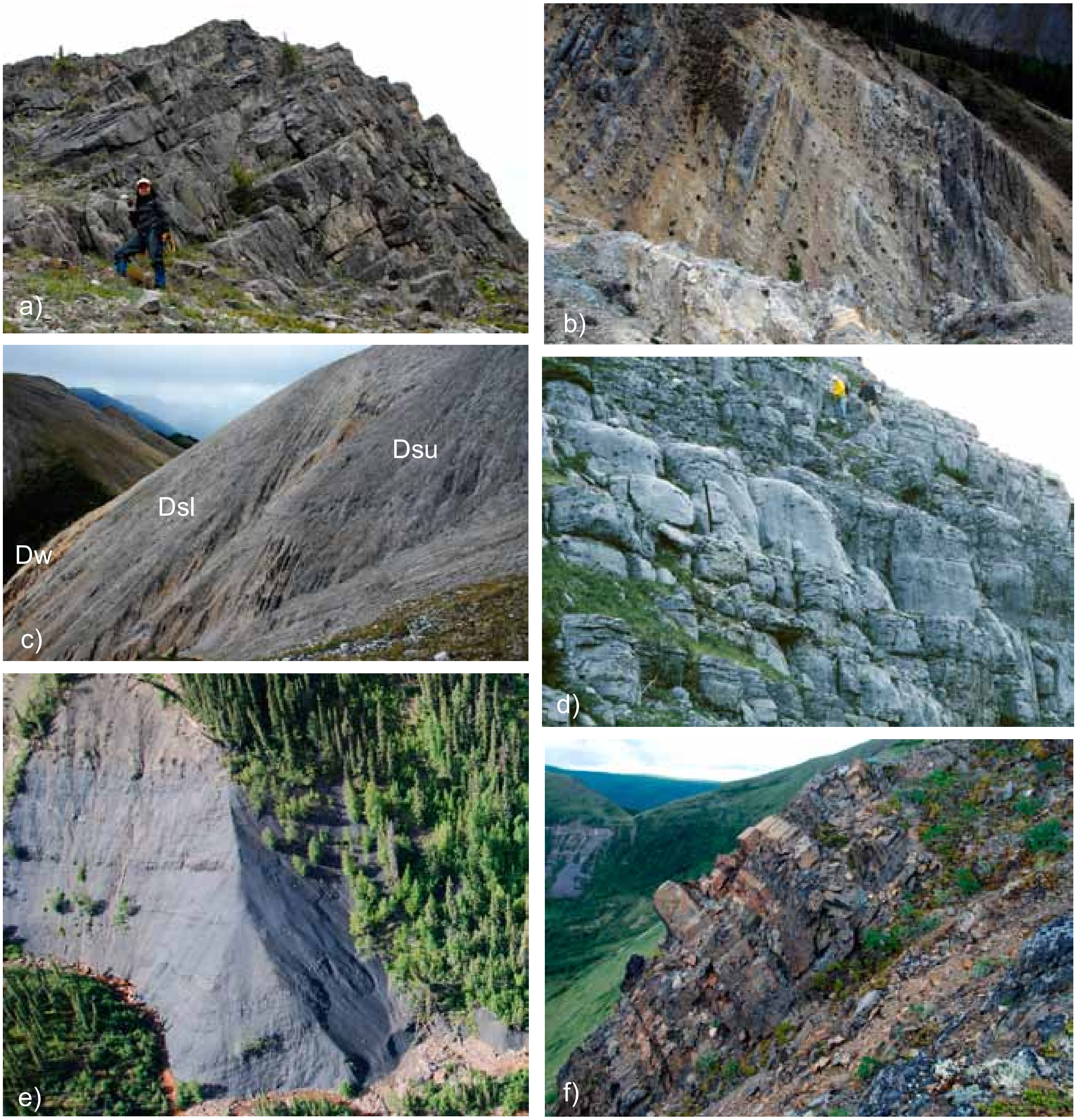

Figure 5. a) Well-bedded dolostone of Muncho-McConnell Formation, Sentinel Range; b) interlayered solution collapse breccia, dolostone and argillaceous dolostone of the bright weathering Wokkpash Formation, Sentinel Range; c) well-bedded dolostone of the Stone Formation stratigraphically overlying the bright weathering Wokkpash Formation (Dw), Sentinel Range. The lower Stone Formation (Dsl) is lighter weathering than the upper Stone Formation (Dsu); d) chert nodule–rich, bedded limestone near the top of the Dunedin Formation, Caribou Range; photography by K.M. Fallas; e) blue-grey weathering shale of the Besa River Formation, east of the Caribou Range; f) graded and interbedded fine-grained sandstone to siltstone from the lower part of the Mattson Formation, southwest of the Caribou Range (north Deer River).

Dunedin in the Caribou Range. Limestone in the basal part of the formation is dolomitic and argillaceous with common shaly partings. Interbeds of grey, yellow-grey weathering, thin-bedded dolostone with common interclasts and algal laminae occur locally. The upper part of the Dunedin changes facies into dark shale of the Besa River Formation near 60°N (Taylor and Stott, 1980). The Dunedin Formation is 288 m thick in the Caribou Range south of the facies change into the Besa River Formation and 340 m in the Sentinel Range immediately south of the Toad River map area (Morrow, 1978).

Middle Devonian–Mississippian

BESA RIVER FORMATION

The Besa River Formation (Kidd, 1962) forms a thick, recessive weathering interval dominated by dark shale and siltstone (Fig. 5e). Shale is dark grey to black, rusty to dark grey to blue-grey weathering, commonly carbonaceous and silty, and locally laminated. Pyrite and orange weathering nodules are common near the top. Siltstone is light to dark grey, tan to orange-brown to rusty weathering, thin-bedded with common shaly partings and local laminations. Light grey to black, rusty to grey weathering, laminated or bedded siliceous shale with laminae of nonsiliceous shale form a 50 m thick subunit in the middle part of the Besa River Formation east of the Caribou Mountains (Ferri et al., 2011a). A few interbeds of quartz arenite occur beneath a gradational contact with the Mattson Formation in the northern half of the area. South of Liard River, the Mattson Formation changed facies into the Kindle Formation and the upper contact of the Besa River is marked by a change from pyritic shale to siltstone interbedded with nonpyritic shale (Bamber et al., 1968; Chung, 1993). The Besa River Formation is approximately 330 m thick east of the Caribou Range and more than 500 m thick in the subsurface east of Liard River. For a detailed description of the Besa River Formation in the east Caribou Mountain area, its geochemistry and correlation with important shale gas formations in the Horn River Basin, see Ferri et al. (2011a).

Mississippian and Pennsylvanian

MATTSON FORMATION

The Mattson Formation (Harker, 1961) comprises three informal members in the north-central part of the map area. The following descriptions are based largely on MacNaughton and Pigage (2003) and Fallas and Evenchick (2006), who examined the Mattson Formation immediately north of the Toad River area. In the Caribou Range and to the east, the lower member consists of light grey or buff, grey to orange weathering, thin- to medium-bedded, well-indurated, fine- to very fine grained quartz arenite with crossbeds, crosslaminations, trace fossils and ripples. Sandstone is interbedded with intervals of dark grey siltstone and shale that typically form coarsening-upward sequences. Minor orange weathering, massive dolostone occurs in eastern exposures. West and south of the Caribou Range, the lower part of the formation dominantly consists of medium to dark grey, dark grey or rusty weathering siltstone and blue-grey and brown-grey weathering, thin- to thick-bedded, graded, laminated, fine-grained sandstone to siltstone (Fig. 5f). Interbeds and lenses of sandy limestone are common in the Deer River area. The middle member consists mainly of white to medium grey to buff, light grey to buff to orange-brown weathering, thin- to very thick bedded, massive to crossbedded to rippled locally calcareous sandstone that is very fine to medium grained (Fig. 6a) with minor interbeds of medium to dark grey, medium grey weathering siltstone and shale. The upper member is characterized by the presence of carbonate or sandy carbonate. It consists of light to medium grey, light grey weathering, thin- to thick-bedded, fine- to coarse-grained, commonly crossbedded, locally calcareous or dolomitic sandstone interbedded with minor grey, medium- to thick-bedded, typically fossiliferous, locally sandy limestone; brown to orange weathering, grey dolostone and dark grey siltstone and shale. The upper member is not recognized in the west and southwest of the Caribou Range. The Mattson Formation is approximately 650 m thick in the Crow River gas field (B.C. Richards, pers comm, 2011) and is not developed south of Liard River.

Mississippian, Pennsylvanian

KINDLE FORMATION

In this report, the name 'Kindle Formation' (Laudon and Chronic, 1949; restricted by Chung, 1993) is used for the siltstone-dominated succession above either the sandstone of the Mattson Formation or the dark shale of the Besa River Formation and below the chert and siliceous strata of the Fantasque Formation. South of the Liard River, the lower part of the (restricted) Kindle Formation consists of dark grey, dark grey weathering shale with a few intervals of dark grey, dark grey weathering, argillaceous, calcareous siltstone overlain by dark grey, dark grey weathering, thick-bedded, argillaceous siltstone interbedded with dark grey, silty shale. These are in turn overlain by medium grey, medium grey weathering, very thin to medium-bedded, slightly dolomitic siltstone showing laminations and burrows. South of the Liard River, the upper part of the (restricted) Kindle Formation forms a parallel-bedded unit with distinctive orange weathering stripes. This upper unit consists of medium to dark grey, light brown-grey weathering, medium-bedded, locally laminated, graded or pyritic siltstone with lesser interbeds of dark grey, dark grey weathering, very silty shale and medium grey, orange weathering, calcareous siltstone that is medium to thick bedded. North of the Liard River, a nearly identical striped weathering unit comprises the entire Kindle Formation. The underlying sandstone, siltstone and limestone succession has been included in the Mattson Formation (Fig. 6b). The (restricted) Kindle Formation at its type section is Mississippian and Pennsylvanian and correlative with the Mattson, Stoddart and Taylor Flat intervals (Chung, 1993). The (restricted) Kindle Formation is 80 m thick at its type section near the hamlet of Toad River on the Alaska Highway (Chung,

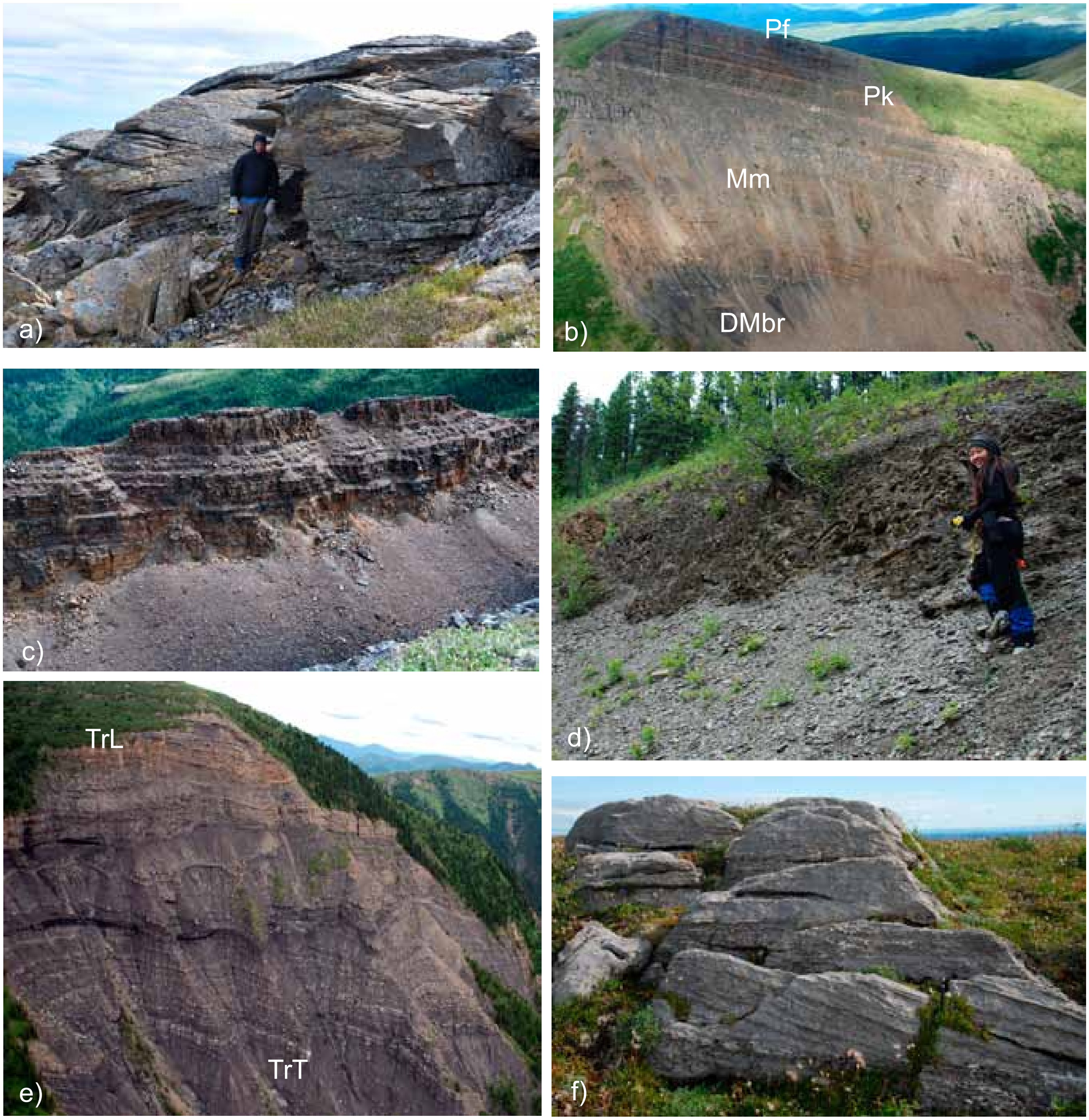

Figure 6. a) Large-scale crossbedding in the middle member of the Mattson Formation, Beavercrow Mountain; b) Besa River to Fantasque section exposed southwest of the Caribou Range (Deer River); black carbonaceous shale of Besa River Formation (DMbr) at base is overlain by the sandstone-dominated Mattson Formation (Mm), which is overlain by parallel-bedded, striped weathering strata assigned to the Kindle Formation (Pk); the section is capped by siliceous mudstone and siltstone assigned to the Fantasque Formation (Pf); c) well-bedded chert of the Fantasque Formation, east side of the Caribou Range; d) light grey weathering, dark grey shale of the Grayling Formation with several more resistant sandstone interbeds, on the south fork of the Scatter River; e) dark siltstone with common sandstone interbeds of the upper Toad Formation (TrT) conformably overlain by the sandstone-dominated Liard Formation (TrL), Rocky Mountain Foothills; f) large-scale crossbedding in calcareous sandstones of the Liard Formation, eastern Rocky Mountain Foothills.

1993), 79 m on the ridge immediately south of the study area and approximately 30 m thick in the Deer River area (Bamber, unpublished GSC field notes, 1965).

Permian

Two disconformity-bounded Permian units, the Tika formation (informal) and Fantasque Formation, occur in the northern part of the area. Elsewhere, only the Fantasque is thought to be present.

TIKA FORMATION

The Tika formation (informal; Currie et al., 2000) is a mixed carbonate and clastic unit. In the northeastern part of the study area, it consists of medium to dark brown, buff weathering, medium-bedded, massive to cross-laminated, silty or sandy limestone and dolostone with rare brachiopod and trace fossils, rhythmically interbedded with lesser dark brown or grey calcareous siltstone and sandstone. Grey weathering, crossbedded, glauconitic sandstone occurs at the base (Fallas and Evenchick, 2006; B.C. Richards, pers comm, 2011). At the Liard River, the Tika formation consists of a lower unit of dark grey, dark grey weathering, calcareous siltstone with worm tracks and pyrite, interbedded with lesser dark grey, medium to dark grey weathering, calcareous, argillaceous siltstone and lenses to beds of medium grey, grey weathering, silty or sandy limestone (Bamber, unpublished GSC field notes, 1965). This is overlain by dark grey, medium grey to rusty weathering, medium-bedded pyritic siltstone commonly grading to dark silty shale with a few interbeds of medium grey, orange weathering, thin- to thick-bedded calcareous siltstone and rare lenses of silty limestone. Interbedded dark pyritic siltstone and dark grey siliceous siltstone occur at the top (Bamber, unpublished field notes, 1965). P.B. Read (unpublished field notes, 1982) reported medium grey weathering, fine-grained sandstone in this same area. Tika strata along the Liard River were previously included in the Kindle Formation by Bamber et al. (1968). The strata are well dated as Lower Permian age by conodonts (Orchard, unpublished paleontology report prepared for Geotex Consultants). The Tika formation is more than 60 m thick on the Liard River (Bamber, unpublished GSC field notes, 1965) and approximately 150 m in the Crow River gas field (B.C. Richards, pers comm, 2011).

FANTASQUE FORMATION

The Fantasque Formation (Harker, 1961) forms a very resistant weathering unit in the northernmost and southernmost parts of the map area. In the north (Fig. 6c), it consists of dark to medium grey, rusty brown weathering, medium- to very thick bedded, spiculitic chert interbedded with minor dark grey to dark brown siliceous siltstone. On the Liard River, the Fantasque consists of 20 m of dark grey to black, dark grey weathering, very thin to medium-bedded chert, overlain by 22 m of dark grey, dark grey weathering siltstone with two brown weathering, medium grey, medium-bedded, fine-grained sandstone beds (Bamber, unpublished field notes, 1965). Immediately south of the map area, the Fantasque consists of 41 m of dark to medium grey, grey to brown weathering, thin- to medium-bedded chert or siliceous mudstone with silty shale partings, overlain by 20 m of dark grey, light to medium grey weathering, medium- to very thick bedded siltstone, argillaceous siltstone and siliceous siltstone (Bamber, unpublished field notes, 1965). The Fantasque is more than 40 m at its type section immediately north of the study area (Bamber et al., 1968), 41 m on the Liard River and 61 m immediately south of the study area (Bamber, unpublished field notes, 1965). Abrupt changes in thickness are mapped across small faults at 60°N (Fallas et al., 2004; Fallas and Evenchick, 2006).

Triassic

In the Toad River map area, the Triassic thins markedly from west to east and northward from the Liard River to 60°N. Thinning is due to increased erosion beneath the sub-Cretaceous unconformity and, to a lesser extent, depositional thinning. Six formations are recognized. The older formations are clastic units that change up-section from shale dominated (Grayling Formation), to interlayered siltstone, shale and sandstone dominated (Toad Formation), to sandstone dominated (Liard Formation). The younger formations are mixed clastic and carbonate (Luddington, Pardonet) and carbonate (Baldonnel) units, and are only preserved in the western Rocky Mountain Foothills. To a large extent, the Grayling and Toad formations are facies equivalents and are mapped together as the Toad/Grayling formations in much of the area. The Liard Formation changes facies westward into the Luddington and Toad formations (Taylor and Stott, 1973).

GRAYLING FORMATION

The Grayling Formation (Kindle, 1944) consists of medium grey, light grey weathering, flaky, laminated, noncalcareous shale with minor interbedded brown-grey weathering, medium grey, very thin to thin-bedded, fine-grained sandstone and medium grey, laminated dolomitic shale (Fig. 6d). A brown-grey weathering, medium grey, irregularly bedded sandstone approximately 10 m thick marks the base of the formation along the Liard River (Bamber, unpublished GSC field notes, 1965). Ripple laminations, ripple marks and sole marks are common in the sandstone. Pelletier (1961) reported that more than 400 m of the Grayling Formation occurred along the Liard River upstream of its confluence with the Grayling River.

TOAD FORMATION

The Toad Formation (Kindle, 1944, 1946) forms a dark weathering siltstone-dominated unit. Dark grey, dark grey to brown weathering, thin- to thick-bedded, commonly laminated calcareous siltstone and grey to brown weathering, dark grey, platy, calcareous siltstone and shale, and minor dark grey or brown weathering, dark grey to black shale comprise most of the Toad Formation. Intervals and interbeds of dark grey, brown-grey weathering, thin- to thick-bedded, very fine to fine-grained calcareous sandstone are more common in the middle and upper part (Fig. 6e). Sandstones are commonly laminated and sharp based. Crossbeds and sole marks occur locally. The Toad Formation is approximately 365 m thick at its type section near the junction of the Toad and Liard rivers and is more than 886 m thick on Ewe Mountain (Pelletier, 1961).

LIARD FORMATION

The Liard Formation (Kindle, 1946) comprises sandstone and subordinate limestone. Limestone is common in the type exposures on the island by Hell Gate on the Liard River but uncommon in more eastern exposures. Sandstone is medium to dark grey, light grey to orange-brown weathering, medium to very thick bedded, very fine to fine grained and calcareous (Fig. 6f). Medium-grained calcareous sandstone occurs locally. Crossbeds, ripples, laminations, scour features, burrows and concretionary or coquinoid layers are locally common. Limestone is buff to light to dark grey, light grey weathering, medium to very thick bedded and varies from massive and hard to sandy or conglomeratic. Kindle (1948) reported limestone intervals of up to 15 m (50 ft.) thick in the type area. Minor interbedded dark grey weathering, dark grey siltstone and shale occurs locally. The Liard Formation is 82 m thick on the Liard River, 14.5 km upstream from the mouth of the Toad River, 183 m thick 6.4 km upstream from the island by Hell Gate on the Liard River and 122 m thick on Ewe Mountain (Pelletier, 1961).

LUDDINGTON FORMATION

The Luddington Formation (Gibson, 1971) consists of calcareous sandstone, calcareous siltstone, siltstone and limestone. Limestone forms a minor component in the Ewe Mountain area (Pelletier, 1961) but is more common further west. Sandstone is calcareous and ranges from medium to dark grey, dark brown to orange-brown weathering, very thick bedded and very fine grained, to light grey weathering, light grey, thick bedded, crossbedded and medium to coarse grained. Calcareous siltstone is dark grey to buff weathering, medium grey to black, laminated, and commonly interlaminated to thinly interbedded with calcareous, laminated, very fine grained sandstone (Fig. 7a). Noncalcareous siltstone is dark grey, medium grey weathering, thick bedded, laminated and blockier weathering than calcareous siltstone. Limestone is mainly grey-brown weathering, medium grey, very thin to thin-bedded, platy and variably silty. Parallel lamination is common; ripple cross lamination, cut and fill structures occur locally. Minor medium grey weathering, black, thin- to medium-bedded, locally bioclastic, silty limestone also occurs. The Luddington is more than 290 m thick at Ewe Mountain and more than 450 m thick in the Mount McLearn area (Pelletier, 1961; adjusted to exclude limestone of the Baldonnel and Pardonet formations at top).

BALDONNEL FORMATION

The Baldonnel Formation (Hunt and Ratcliffe, 1959) is a resistant, light weathering limestone recognized in the western Rocky Mountain Foothills. The formation consists of light to medium grey, light grey weathering, medium- to very thick bedded, crinoidal lime grainstone to packstone (Fig. 7b). Crossbeds and irregular light grey cherty nodules are common. The Baldonnel Formation is estimated to be approximately 150 m thick north of Sulphur Creek and at Mount McLaren in the western Rocky Mountain Foothills.

PARDONET FORMATION

The dark limestone and siltstone of the Pardonet Formation (McLearn, 1960) is preserved locally at the tops of ridges in the western Rocky Mountain Foothills. Limestone is dark grey, medium to dark grey to dark brown-grey weathering, thin- to thick-bedded with common wavy crenulated laminations (Fig. 7c) and fossils. Limestone varies from lime wackestone to grainstone and is commonly carbonaceous, argillaceous and silty (Gibson, 1971). Dense coquina beds consisting of whole and fragmented pelecypod and brachiopod beds are relatively common. Siltstone is dark grey, dark grey to dark brown-grey weathering, thin- to thick-bedded and commonly laminated. To the south, siltstone occurs mainly in the upper part of the formation (Gibson, 1971). Less than 100 m of the Pardonet Formation is preserved in the western Rocky Mountain Foothills.

Cretaceous

The base of the Cretaceous is marked by a regional erosional unconformity that, in the Toad River area, downcuts underlying Triassic strata in the northward and eastward directions. An abrupt change in the thickness of Triassic strata preserved beneath this unconformity occurs in the Rocky Mountain Foothills and suggests local pre-Cretaceous (pre-Albian) downfaulting (Fig. 8). The overlying thick shale-dominated section is divided into several recessive weathering, marine shale formations (Garbutt, Lepine, Sully, Kotaneelee) separated by more resistant sandy or conglomeratic formations (Scatter, Sikanni, Dunvegan, Wapiti; Stott, 1968). Sandstone and conglomerate of the Chinkeh Formation locally occur at the base. In the southern part

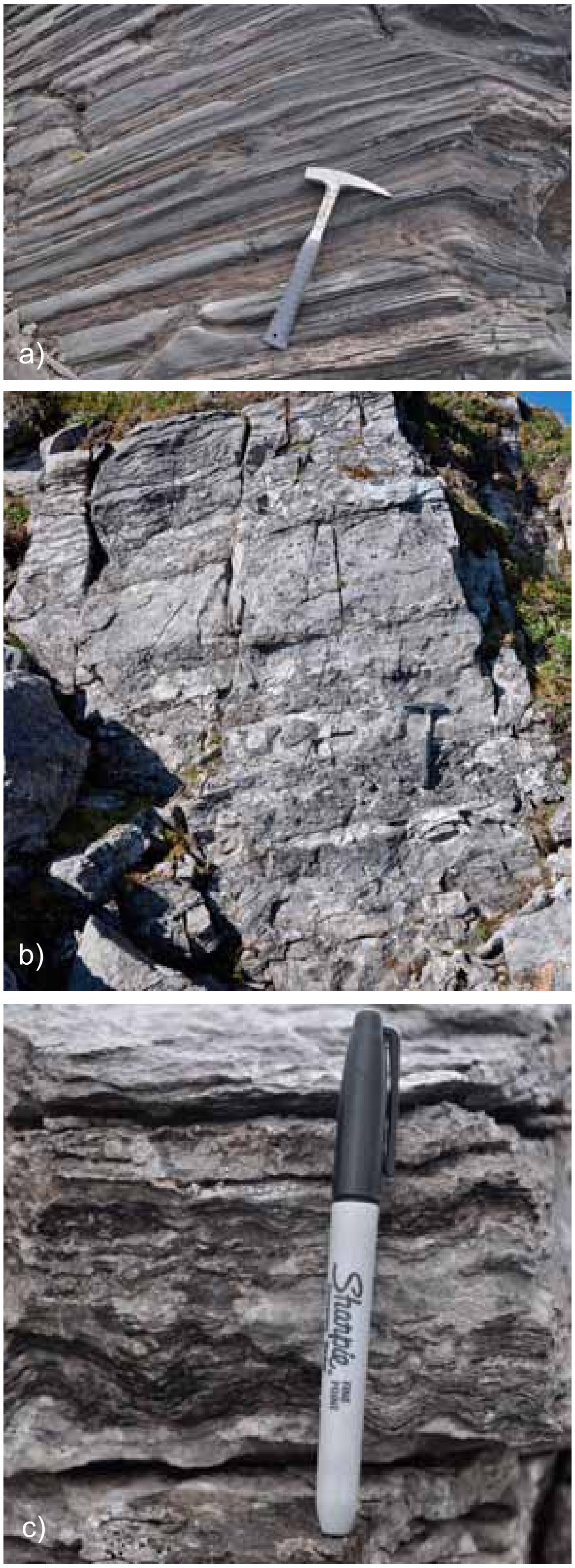

Figure 7. a) Very thinly interbedded, parallel-laminated, variably calcareous siltstone and very fine grained sandstone of the Ludington Formation, western Rocky Mountain Foothills; b) resistant, light grey weathering limestone of the Baldonnel Formation with irregular cherty nodules and layers, western Rocky Mountain Foothills; c) crinkly laminated Pardonet Formation, western Rocky Mountain Foothills.

of the area, the Scatter Formation is not developed and the Buckinghorse Formation forms a thick shale succession at the base of the Cretaceous. Only the Garbutt, Buckinghorse and Scatter formations were examined in this study and the following descriptions are based mainly on Stott (1968, 1982).

CHINKEH FORMATION

The Chinkeh Formation (Leckie et al., 1991) locally forms a thin sandstone and conglomerate unit north of the confluence of the Toad and Liard rivers. Leckie et al. (1991) reported a coarsening-upward sequence of very fine to medium-grained glauconitic sandstone with hummocky crossbedding capped by a thin unit of log-bearing conglomerate on Lepine Creek. Stott (1968) reported up to 1.5 m (4–5 ft.) of fine-grained, glauconitic, argillaceous sandstone with a few chert pebbles and wood fragments that occur locally beneath the Garbutt Formation in the Scatter River area. The Chinkeh Formation is 9 m thick on Lepine Creek (Leckie et al., 1991).

GARBUTT FORMATION

Shale of the Garbutt Formation (Kindle, 1944) forms the basal unit of the Cretaceous where the Chinkeh Formation is not developed and the Scatter Formation is developed. In these areas, glauconitic mudstone or a few chert nodules occur at the base of the formation (Stott, 1968; Ferri et al., 2011b). In the Scatter River area, the Garbutt consists of two main parts (Stott, 1968). The lower part consists of striped dark grey weathering, silty shale with numerous thin, commonly parallel laminated or cross-laminated, silty or sandy lenses and beds, capped by a unit of thin-bedded, fine-grained, silty sandstone. The upper part (Fig. 9a) consists of dark grey, commonly rusty weathering, rubbly mudstone and shale with rows of reddish-brown weathering concretions and common interbeds of grey, planar or cross-laminated, very fine grained sandstone to siltstone near the top. Slump structures occur locally. The Garbutt Formation is 290 m thick in the Chimney Creek–Scatter River area (Stott, 1968, 1982).

SCATTER FORMATION

The Scatter Formation (Kindle, 1944) is best developed in the Scatter River area where three members (Bulwell, Wildhorn and Tussock; Stott, 1982) are present. The Bulwell member (Fig. 9a, b) consists of grey and greenish-grey, thin- to thick-bedded, fine- to very fine grained, commonly glauconitic sandstone and interbedded argillaceous silty sandstone and silty mudstone. The sandstone is commonly laminated and contains abundant ripple marks, worm burrows, trails and castings and crossbedding (Stott, 1982). South of 50°25’N, the sandstone becomes more shaly and eventually grades into shale. The Wildhorn member (Fig. 8b) consists of dark grey to black, dark grey to rusty

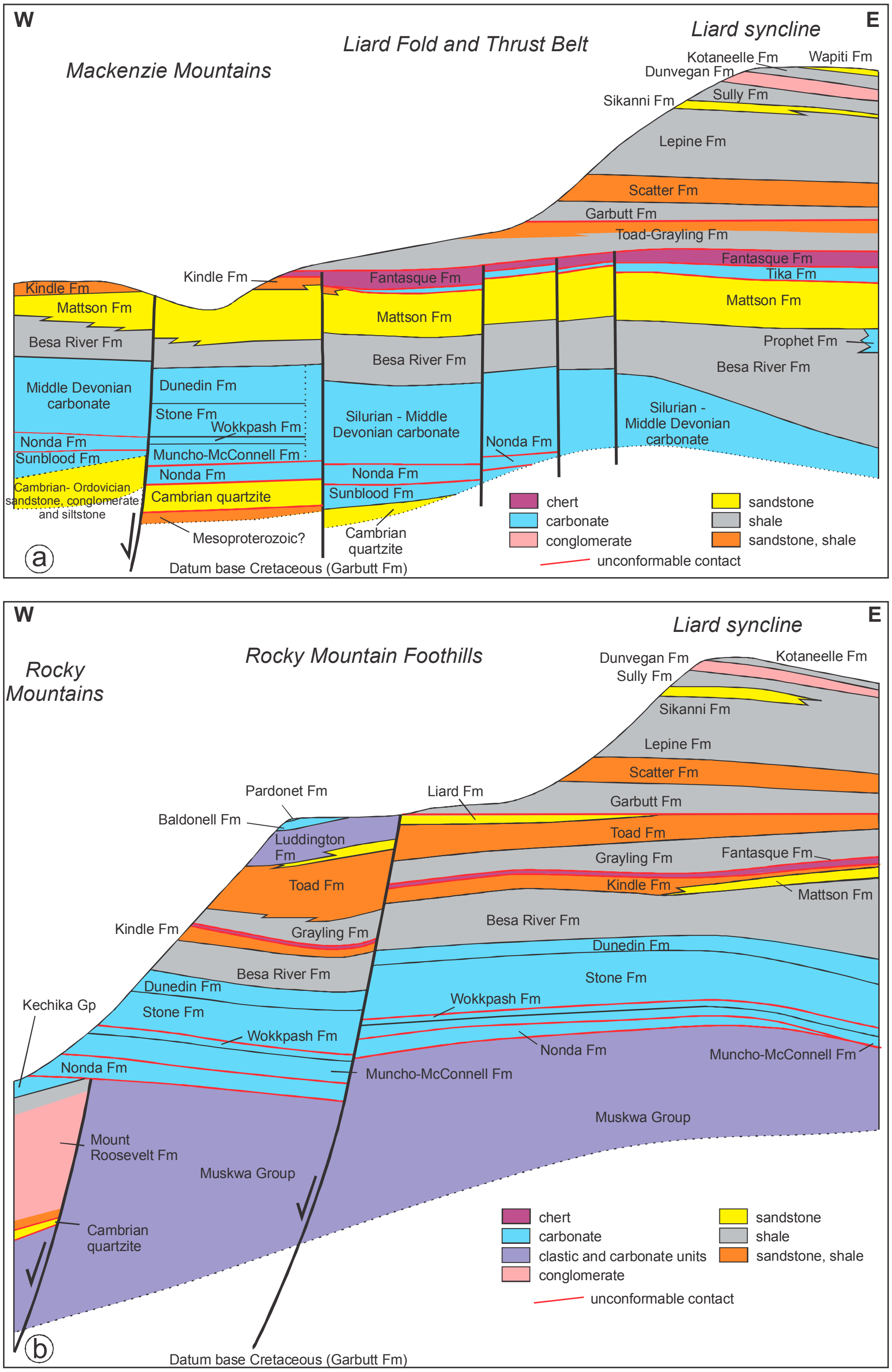

Figure 8. a) Schematic stratigraphic cross-section across the northern Toad River map area; b) schematic stratigraphic cross-section across the southern Toad River map area. Pre-Triassic (Toad/Grayling) small displacement faults similar to those in the northern cross-section may occur in the subsurface east of the unnamed pre-Garbutt Formation fault. None are shown due to the absence of seismic control.

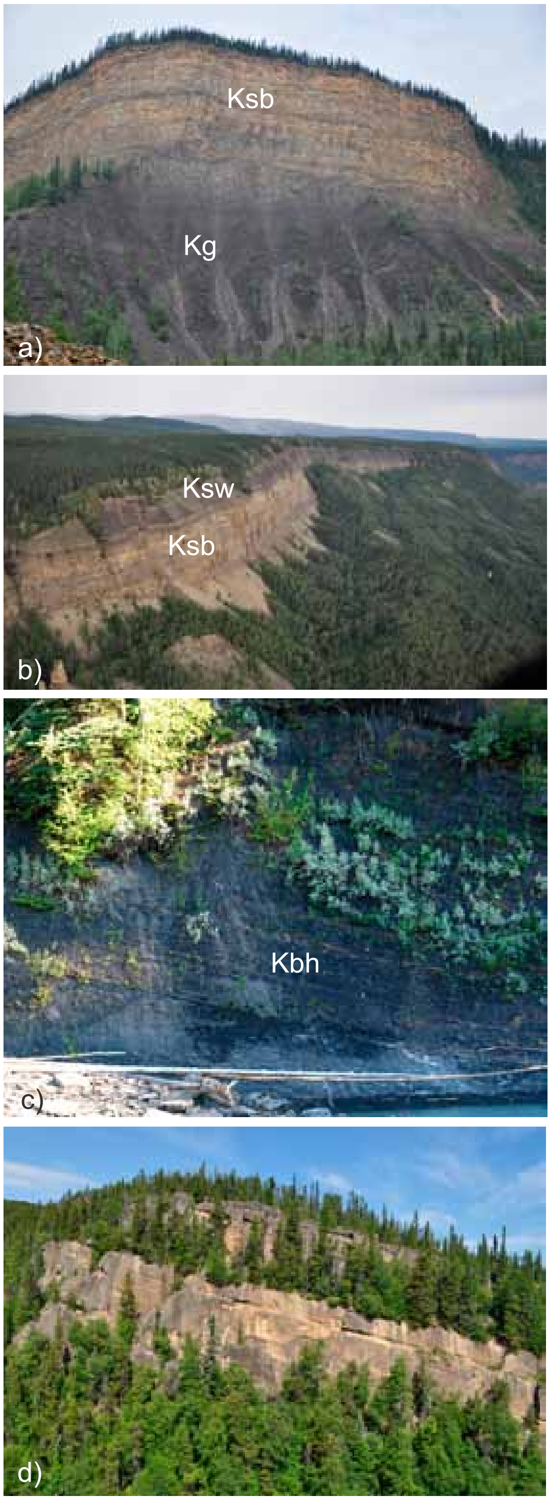

Figure 9. a) Dark weathering shale of the Garbutt Formation (Kg) gradationally overlain by Bulwell member sandstone of the Scatter Formation (Ksb) along the type section of the Garbutt Formation, lower Toreva Creek; b) Bulwell member sandstone of the Scatter Formation (Ksb) is overlain by dark silty shale of the Wildhorn member of the Scatter Formation (Ksw), Liard Fold and Thrust Belt, north of Scatter River; c) dark weathering silty shale with sideritic concretionary bands exposed along Toad River near the base of the Buckinghorse Formation (Kbh); d) resistant conglomerate of the Dunvegan Formation along Dunedin River.

weathering silty mudstone with reddish-brown weathering sideritic concretions becoming more common in the upper part. Thin beds of argillaceous siltstone and sandstone occur near the top. The Tussock member comprises alternating units of sandstone, siltstone and silty mudstone. Sandstone is generally greenish-grey, argillaceous, silty and glauconitic, thin- to thick-bedded with common burrow mottling, worm trails and laminae. Beds of cleaner, grey, crossbedded sandstone occur locally near 50°30'N (Chimney Creek area; Stott, 1982). Siltstone is dark grey, grey or rusty weathering, argillaceous and finely laminated. Silty mudstone is black and weathers blocky and rusty (Stott, 1982). South of 50°30', sandstone of the Tussock Member grades laterally into argillaceous siltstone and mudstone strata that are included in the Lepine Formation. The Scatter Formation, at its type section on the Scatter River, is 347 m thick and an estimated 378 m thick on Chimney Creek (Stott, 1982).

LEPINE FORMATION

The Lepine Formation (Kindle, 1944) comprises the thick shale succession between sandstones of the Scatter and Sikanni formations. Between approximately 50°20' and 50°29'N, the Lepine Formation includes the equivalents of the middle and upper members of the Scatter Formation. In this area, the basal part of the Lepine Formation comprises black, silty, concretionary mudstone with a few units of argillaceous siltstone. Ammonites are common in concretions. Elsewhere, the Lepine Formation comprises a basal unit of black, flaky to fissile shale overlain by dark grey, commonly rusty weathering, silty mudstone with reddish-brown weathering concretions. Minor interbedded platy siltstone occurs in the middle and in the uppermost part of the formation (Stott, 1968, 1982). The Lepine Formation is approximately 910 m (3000 ft.) thick on the Liard River opposite Chimney Creek and approximately 1100 m thick where only the Bulwell Member is left in the Scatter Formation (Stott, 1968, 1982). The Lepine Formation is 893 m thick in the subsurface east of the Liard River (Stott, 1968, 1982).

BUCKINGHORSE FORMATION

The Buckinghorse Formation (Hage, 1944) forms the basal unit of the Cretaceous where the Scatter Formation is not recognized. It includes the correlatives of the Chinkeh, Garbutt, Scatter and Lepine formations. The lower part of the Buckinghorse Formation consists of dark grey to black, locally rusty weathering, silty shale with orangish weathering sideritic concretions (Fig. 9c) and a few thin bentonite seams. The middle part of the succession consists of very thin to thin-bedded siltstone with dark grey silty shale interbeds. The upper part of the succession is assumed to be dark grey concretionary mudstone (Taylor and Stott, 1973;

Stott, 1982). The thickness of the Buckinghorse Formation should be approximately 1200 m along Toad River.

SIKANNI FORMATION

The Sikanni Formation (Hage, 1944) consists of sandstone units separated by mudstone units. In the southern half of the area, it consists of three or four resistant sandstone units up to 30 m thick, comprising mainly grey, light brown-grey weathering, finely laminated, locally cross laminated, siliceous fine-grained sandstone. Coarse-grained sandstone and conglomeratic sandstone occur locally (Stott, 1982). Sandstone units are separated by intervals of dark grey to black mudstone with a few concretions. In the northern part of the area, the Sikanni Formation loses its resistant character and the upper sandstone grades into mudstone included in the Sully Formation, and the lower sandstone grades into argillaceous sandstone and mudstone (Stott, 1982). The Sikanni Formation is 132 m thick opposite Scatter River and more than 140 m thick northeast of Lepine Creek (Stott, 1968, 1982). On the La Biche River, immediately north of the Toad River map area, sandstone appears to have disappeared completely and the Sikanni Formation is not present (Fallas, 2006).

SULLY FORMATION

In the northern part of the Toad River map area, the Sully Formation (Stott, 1960) consists of lower and upper members comprising dark grey to black, rusty weathering, silty mudstone with reddish-brown weathering sideritic concretions separated by a middle member comprising medium grey to black, light grey weathering, flaky to fissile shale containing some interbeds of light grey weathering platy siltstone. Thin beds of grey, fine-grained, laminated and cross-laminated sandstone occur in the upper member. The upper member becomes extremely silty as it grades into the sandstone at the base of the overlying Dunedin Formation (Stott, 1982). The lower member is replaced by sandstone of the Sikanni Formation in the southern part of the area. The Sully Formation is 305 m thick opposite Scatter River (Stott, 1982).

DUNVEGAN FORMATION

The cliff-forming Dunvegan Formation (Fig. 9d; Dawson, 1881) comprises a basal sandstone overlain by conglomerate-dominated cycles of carbonaceous mudstone, massive conglomerate and coarse-grained sandstone. The basal sandstone is brown weathering, fine to coarse grained and laminated or crossbedded. It is commonly capped by a thin unit of coal or carbonaceous mudstone. Pebble to cobble conglomerate forms thick resistant units that commonly show crude horizontal stratification or large-scale crossbeds. Clasts are quartz, quartzite and chert, and are set in a coarse-grained cherty sandstone matrix. Sandstones vary from fine grained to conglomeratic, are commonly laminated and may grade upward into siltstone and silty mudstone (Stott, 1968, 1982). The Dunvegan Formation is 183 m thick opposite Scatter River and 160 m thick at the big bend of the Liard River (Stott, 1982).

KOTANEELEE FORMATION

The Kotaneelee Formation (Hage, 1945) consists mainly of dark grey to black, rusty weathering shale with sideritic concretions. An interval of thin-bedded, fine-grained sandstone occurs in the upper part of the formation in the Beaver River area (Stott, 1968). Immediately east of the map area at La Jolie Butte on Liard River, the sandstone is 14 m thick and occurs 38 m below the top of the formation (Stott, 1968). The Kotaneelee Formation is estimated to be approximately 180 m thick in the northeastern corner of the map area.

WAPITI FORMATION

A thin veneer of the Wapiti Formation (Dawson, 1881) caps some of the ridges in the map area. No outcrops have been examined by Stott (1968, 1982) or in this study. Taylor and Stott (1980) described the formation as sandstone, mudstone and coal in the legend accompanying their map.

STRUCTURE

The Toad River area encompasses a dramatic swing in the orientation of structures in the Foreland Belt, from northwest south of the Liard River, to north and northeast north of the Liard River (Fig. 2). Cecile et al. (1997) attributed this change to the Liard Line (Cecile and Norford, 1991), a northeast-trending fault zone interpreted to have formed during Neoproterozoic rifting as a transfer fault. The structural style of the Toad River area was largely controlled by the lithological character of the deformed stratigraphic sequences and to a lesser extent by the amount of shortening. Thick competent Proterozoic and latest Neoproterozoic to Middle Devonian carbonate and sandstone successions favoured the development of thrust faults. Interlayered incompetent and competent Upper Devonian to Cretaceous shale and sandstone successions favoured the formation of detachment folds. Interlayered successions are exposed over most of the map area and folds dominate the structural style. Most structures in the Toad River area formed during Cretaceous Cordilleran compressive deformation. In some places, older structures are observed or inferred from abrupt changes in the stratigraphic record. These older structures appear to have controlled the trend and location of subsequent Cordilleran-aged structures, particularly in the northern part of the area.

Older pre-Cordilleran deformation structures

Muskwa Group strata were folded, faulted and weakly metamorphosed prior to the deposition of the unconformably overlying latest Neoproterozoic to early Paleozoic strata. Immediately south of the Toad River area, Mesoproterozoic Muskwa Group strata were folded and cut by reverse and normal faults prior to the intrusion of Neoproterozoic mafic dikes (Taylor and Stott, 1973). Immediately north of the Toad River area, Mesoproterozoic or Neoproterozoic strata were folded and faulted prior to deposition of lower Paleozoic sandstone, conglomerate and siltstone (Fallas et al., 2004).

Changes in thickness and/or facies outline several older structures formed prior to Cretaceous compressive deformation. South of the Liard River, two northwest-trending structures have been recognized on the basis of surface geology (Fig. 10). The Forcier fault zone (Taylor and Stott, 1973), in the west, is the most obvious older structure in the map area. It separates up to 1.8 km of predominantly conglomeratic Middle Cambrian Mount Roosevelt strata on the west from an uplifted block on the east where Silurian rocks rest unconformably on Middle Proterozoic rocks, and is one of the faults defining the eastern edge of the lower Paleozoic Kechika graben (Post and Long, 2008). South of the map area, the Forcier fault becomes north-trending and has west-side-down normal stratigraphic separation (Taylor and Stott, 1973). The eastern fault exposed south of the Liard River is indicated by an abrupt change in the thickness of Triassic strata preserved beneath the sub-Cretaceous unconformity (see Fig. 8b). To the south, at the latitude of the Alaska Highway, a large change in facies and preservation of Mississippian and Pennsylvanian strata beneath the sub-Permian (Fantasque) unconformity (Bamber et al., 1968; Chung, 1993) indicates episodic motion on this structure. The thickness of the Mount Roosevelt Formation decreases markedly across a transverse east-northeast–trending fault exposed in the Terminal Range. This suggests the transverse fault may be following a Middle Cambrian antecedent structure.

North of the Liard River, several pre-Cordilleran compressive deformation structures have been recognized on the basis of surface geology and well control (Fig. 10). These structures trend north to northeast. Older motion on the north-trending Larsen fault is inferred from relationships exposed along strike to the north, where conglomeratic Cambrian and Ordovician strata occur west of the fault and latest Neoproterozoic to Cambrian orthoquartzite and no Ordovician strata occur east of the fault in the Caribou Range (Fallas et al., 2004). Motion on the curvilinear northeast- to north-trending Bovie structure greatly affected the thickness of Mississippian, Pennsylvanian, Permian, Triassic and Lower Cretaceous strata on either side of it (e.g., Leckie et al., 1991; Wright et al., 1994; MacLean and Morrow, 2004). Main periods of precompressive deformation motion along the structure occurred in the Pennsylvanian to Permian and in the Early Cretaceous (MacLean and Morrow, 2004). The northeast-trending segment of the structure had minor early Paleozoic motion (Fig. 17 in MacLean and Morrow, 2004). The other older faults shown in Figure 10 are indicated by changes in the thickness of Permian units across each fault. The absence of Ordovician strata in the Caribou Range suggests that the westernmost of these may have undergone pre-Silurian movement (Fig. 8a). Smaller faults with Mississippian- to Permian-aged displacement (and limited or no reactivation) occur in the subsurface near the big bend in the Liard River (Hodder, 2002). Access to proprietary seismic data will be needed to map these and similar structures in the subsurface of the Toad River area.

Structural style of the Foreland Belt

Thrust faults and faulted folds dominate the surface structural geometry of the competent Mesoproterozoic to Middle Devonian succession. These strata are only exposed in the Caribou Range and Rocky Mountains (Fig. 2). In the Caribou Range, the west-directed Larsen fault dies out southward into the core of a west-facing anticline and most of the range is a gently east-dipping (20–30°) homoclinal panel. Two longer strike-length thrust faults occur in the Rocky Mountains: the Forcier and Sulphur Creek faults (see Fig. 2, 10 for locations). These underlie the Terminal and Sentinel ranges, respectively. Other less continuous northeast-directed thrust faults (discussed below) are common. In the Terminal Range, a north-trending cleavage has developed in Middle Cambrian and Ordovician argillaceous sediments associated with open folding. Structural relationships in the Forcier fault change markedly across a transverse east-northeast–trending fault exposed near the western boundary of the map area. North of this transverse fault, a prominent fold pair has developed in the immediate hangingwall of the Forcier fault that is absent south of the transverse fault. The fault acted as a primary tear fault during compressive deformation. This tear fault, the Larsen fault and the Forcier fault all appear to have followed older structures.

Thrust faults are readily observed in the well-defined Paleozoic carbonate section exposed in the Sentinel Range and west-directed back thrusts occur locally. Map-scale hangingwall anticlines have developed along the Sulphur Creek fault (Fig. 11a) and in the southern part of the map-area, two structurally higher faults. The structurally higher of these truncates an anticline and back thrust in its footwall and clearly formed later (Fig. 11b). The Sulphur Creek fault forms the boundary between the Rocky Mountains and Rocky Mountain Foothills structural subprovinces. At the north end of the Sentinel Range, the Sulphur Creek fault

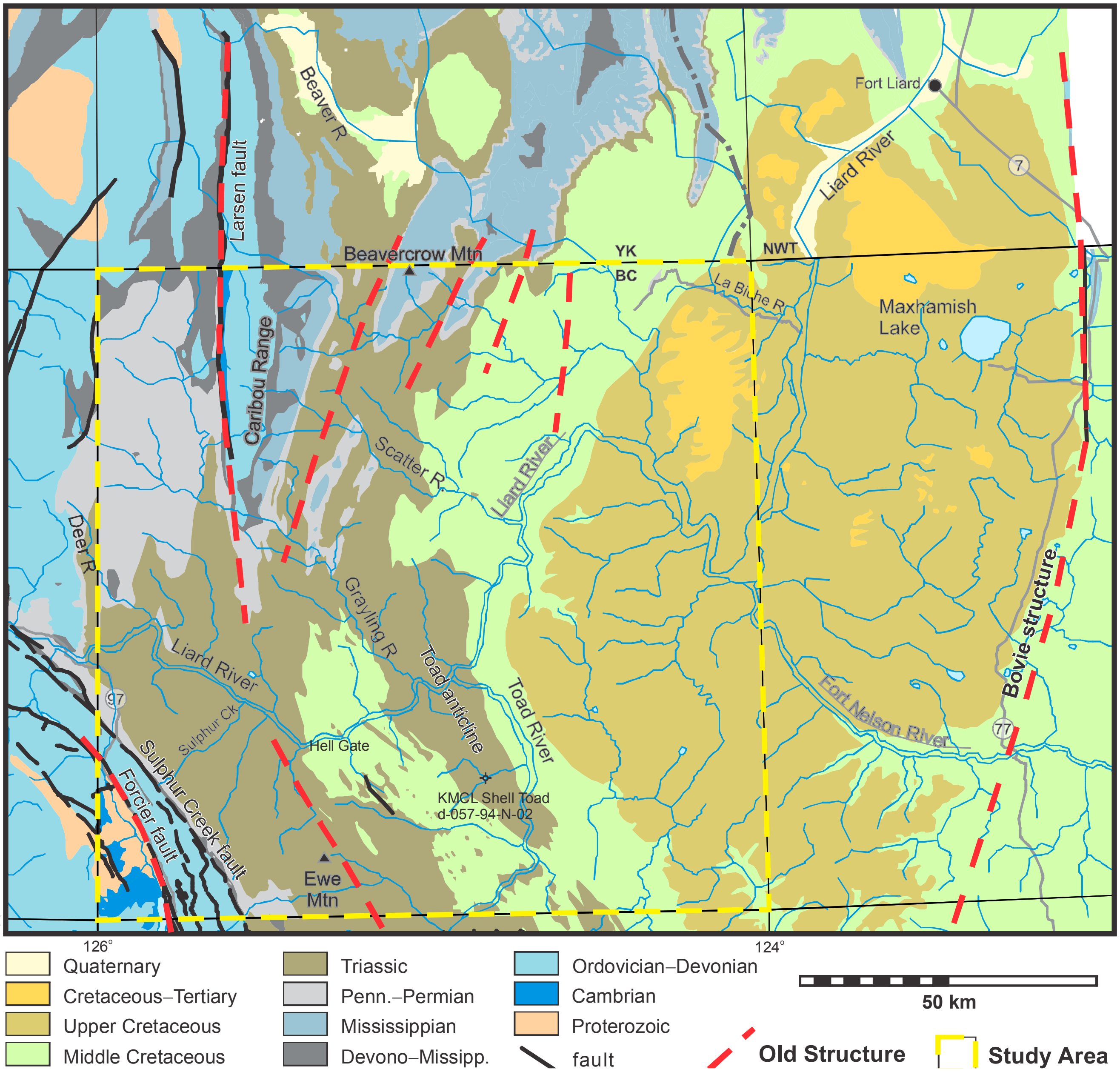

Figure 10. Map showing location of older pre-Cordilleran deformation structures. Several of these appear to have been reactivated during Cordilleran compressive deformation.

cuts across the anticline in its hangingwall and a syncline occurs in the hangingwall. At the southern edge of the map area, conical, close to tight-folded, faulted, chevron folds have formed in the Dunedin Formation along the leading edge of the Sulphur Creek fault (Fig. 11c).

Upper Devonian to Lower Cretaceous strata exposed in the Rocky Mountain Foothills, the Mackenzie Mountains and the Liard Fold and Thrust Belt have been deformed primarily by folding (Fig. 2). Fold wavelength is largely controlled by the thickness of the dominant (more competent) member (Currie et al., 1962). Mappable faults are uncommon. Even good exposure and detailed 1:10 000 scale mapping along the Liard River revealed only a few laterally discontinuous thrust faults with small stratigraphic separation (Geotex Consultants, 1984). Small-scale faults and detachment folds are locally common in the Besa River and Toad/Grayling (Fig. 12a) formations and in the cores of folds.

In the Rocky Mountain Foothills, changes in fold wavelength, amplitude and geometry from one stratigraphic level to another indicate three main detachment horizons: Besa River, Toad/Grayling and Garbutt/Buckinghorse were used (Fig. 8b). The Besa River Formation separates fault and fold structures in the Paleozoic carbonate succession from much smaller amplitude and wavelength folds in the Kindle and Fantasque formations (Fig. 12b). Most folds in

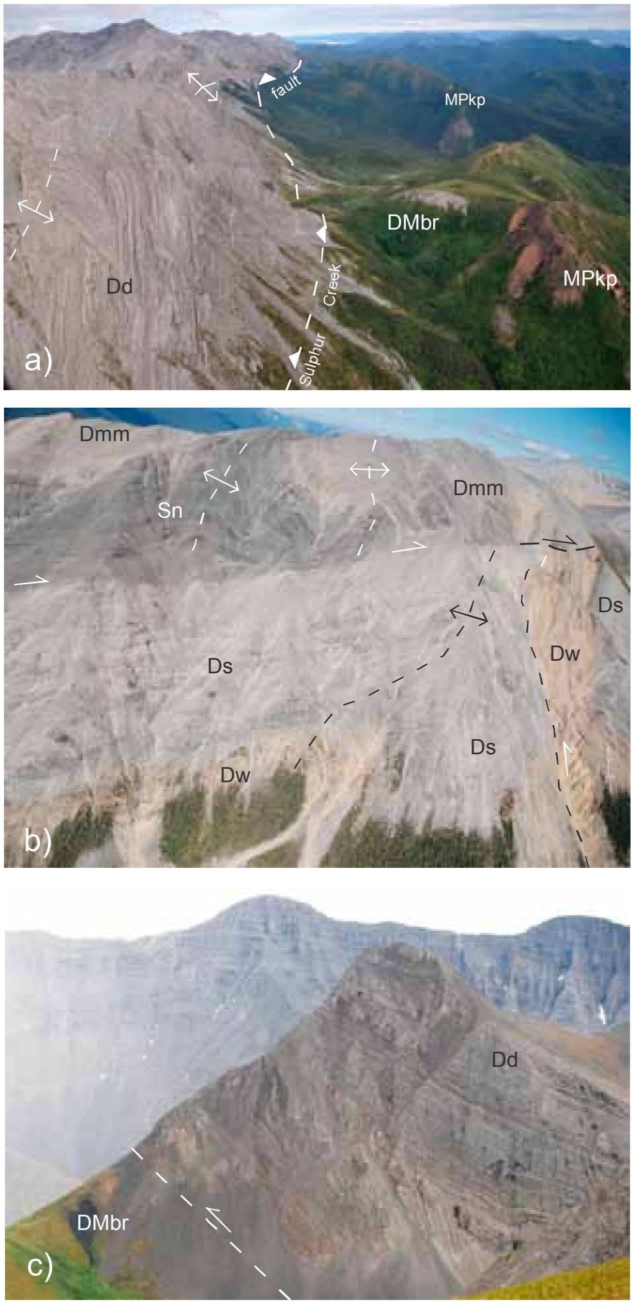

Figure 11. a) Hangingwall anticline along the Sulphur Creek fault outlined by well-bedded Dunedin limestone (Dd), eastern edge of the Sentinel Range, view to the northwest. The low ridge to east is held up by siltstone and siliceous sediments of the Kindle and Fantasque formations (MPkf). The treed valley in between is underlain by recessive shale of the Besa River Formation (DMbr); b) a knife-sharp thrust fault with hangingwall folds truncates the east limb of a hangingwall anticline and a west-directed back thrust in the underlying thrust sheet; southern Sentinel Range, view to the northwest. Abbreviations: Dmm, Muncho-McConnell Formation; Ds, Stone Formation; Dw, Wokpash Formation; Sn, Nonda Formation; c) tight, faulted chevron folds in the immediate hangingwall of the Sulphur Creek fault, eastern edge of the Sentinel Range near the southern end of map area, view to the southeast. Well-bedded Dunedin Formation limestone (Dd) is faulted over black Besa River shale (DMbr).

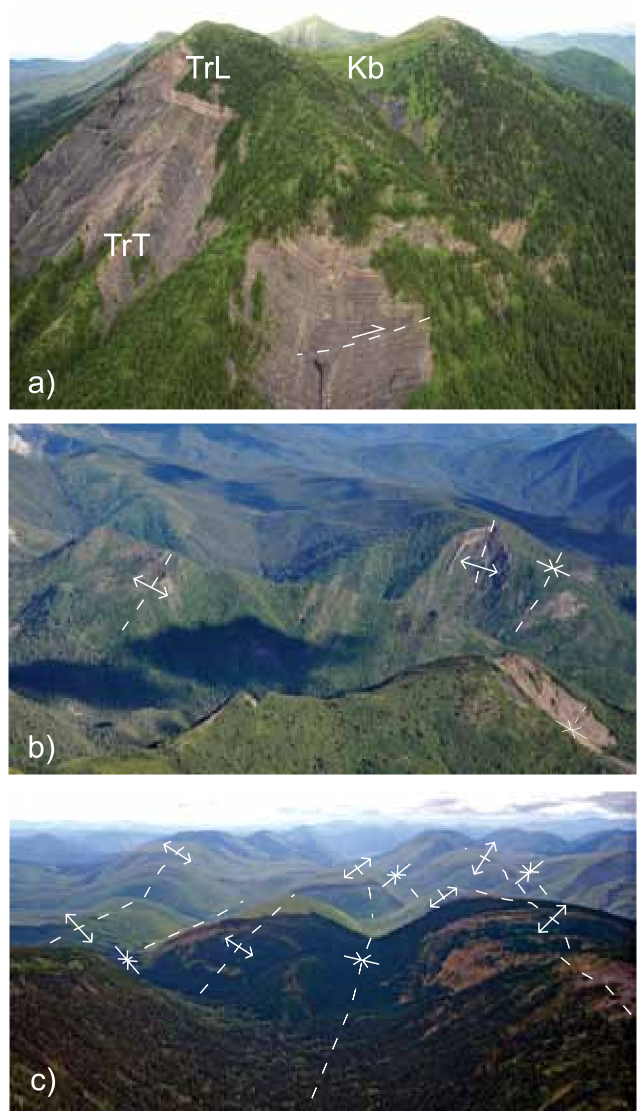

Figure 12. a) Minor fault and detachment folds within interlayered siltstone, sandstone and shale of the upper Toad Formation (TrT), in the central part of the Rocky Mountain Foothills. Resistant sandstone of the Liard Formation (TrL) forms a large asymmetric syncline cored by dark marine shale of the Buckinghorse Formation (Kb); view to the northwest; b) folded Kindle Formation, western edge of the Rocky Mountain Foothills; view to the northeast; c) rounded concentric and box-folded anticlines in the Liard Formation, southeastern Rocky Mountain Foothills. In this area, resistant sandstone of the Liard Formation is directly overlain by recessive shale of the Buckinghorse Formation and the geometry of anticlines in the Liard has controlled the topography of the underlying ridge.

the Kindle-Fantasque interval are chevron folds with planar limbs and narrow hinge zones (Fig. 12b). In contrast, folds in the Liard Formation range from rounded concentric to planar-limbed chevron folds (Fig. 12c). These have broad cores and relatively steep limbs. Where the Liard Formation is overlain by Cretaceous shale, fold geometry is beautifully portrayed by the topography (Fig. 12c). Unlike straight-limbed chevron folds, rounded concentric folds require upper and lower detachments (Dahlstrom, 1969). In this area, they indicate the presence of detachments in the overlying Cretaceous shale and the underlying Toad/Grayling intervals. Mapping in the easternmost Rocky Mountain Foothills, where the Liard Formation has been removed by pre-Cretaceous erosion, suggests much of this detachment occurs within the Toad Formation. In the westernmost Rocky Mountain Foothills, changes in fold geometry from the Kindle-Fantasque to Luddington intervals require the use of detachments in the Toad/Grayling interval. Folds in the Luddington Formation are mainly chevron folds. Flat-bottomed synclines (Fig. 13a) are relatively common. Most folds in the eastern Rocky Mountain Foothills are upright and fairly symmetric. In the western Rocky Mountain Foothills, asymmetric, northeast-facing folds with an associated axial-planar cleavage are common and overturned folds occur locally. Typical fold wavelengths are 2–4 km in the Luddington-Baldonell intervals in the western Rocky Mountain Foothills, 1–2 km in the Liard Formation and 1 km in the upper Toad Formation near Toad River in the easternmost Rocky Mountain Foothills. Smaller-wavelength (200–300 m) fold trains are developed locally in the Grayling Formation near the Liard River (Geotex Consultants, 1984). Estimated shortening of folded strata exposed at the top of the Triassic in the southeastern Rocky Mountain Foothills near Toad River is 5–6 km (20–25%).

In the Mackenzie Mountains, the Besa River Formation forms a prominent detachment horizon separating folds in the Mattson, Tika, Kindle and Fanstasque intervals from the underlying Paleozoic carbonate. Fold wavelength is highly dependent on the thickness of the more competent Mattson sandstone in the succession. Where this sandstone is thick in the northern Caribou Range, the fold wavelength is approximately 5 km. Where the sandstone interval is thinner and the Tika-Kindle interval is more silty, the fold wavelength is commonly 1–2 km.

In the Liard Fold and Thrust Belt, well data indicates the Besa River Formation continues to form a detachment horizon even though surface features such as the Beaver River anticline (Fig. 13b) coincide with the subsurface anticline of fractured Middle Devonian carbonate that forms the Beaver River gas field (Snowdon, 1977). Although poor exposure and limited shortening make it more difficult to discern, changes in fold geometry from the Mattson-Fantasque interval to the Liard Formation in the southwest or the Scatter Formation in the east indicate the Toad/Grayling formations formed a detachment zone, at least locally. The surface geology near 60°N is dominated by four large, south-plunging anticlines (Fig. 2). Each anticline faces northwest with a steeper western limb. Small west-directed thrust faults die out southward along the west limb of the two anticlines east of Beavercrow Mountain (e.g., Fig. 14). The anticlines are long wavelength structures (approximately 10 km) and show that relatively little shortening occurred in the Mattson Formation and younger strata across the Liard Fold and Thrust Belt at this latitude. To the south in the Scatter River area, the eastern part of the Liard Fold and Thrust Belt is composed of gentle- to open-folded Scatter Formation with less than 1 km of shortening.

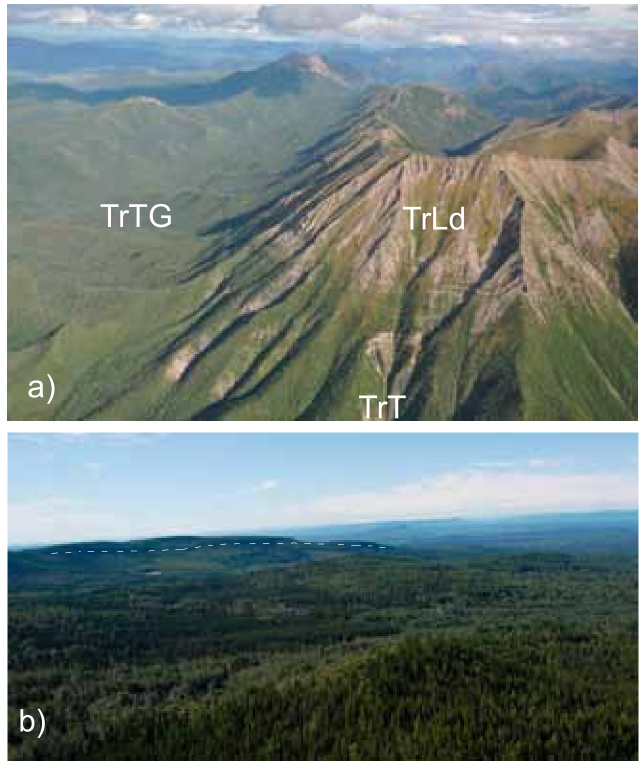

Figure 13. a) Flat-bottomed syncline in the western Rocky Mountain Foothills near Liard River. The adjacent valley is underlain by siltstone, sandstone and shale of the Toad/Grayling formations. Abbreviations: TrLu, Luddington Formation; TrT, Toad Formation; TrTG, Toad/Grayling formations; b) looking south along the Beaver River anticline at the south end of Beaver River gas field. The dotted line outlines the base of the sandstone in the Scatter Formation.

In the Toad River map area, interference fold structures between northeast and northwest trends are developed locally in the northern part of the map area (for example, north of the Crow River gas field). The only example observed in the Rocky Mountain Foothills occurs immediately east of the Sentinel Range, where a northwest-facing, overturned syncline has developed in the northwest-trending folded panel of the Kindle and Fantasque formations.

Subsurface structural style of the Foreland Belt

Deep drilling shows that Proterozoic and Paleozoic carbonate strata are involved in Cretaceous compressive structures under the Rocky Mountain Foothills and the Liard Fold and Thrust Belt. Without seismic control, the interpretation of subsurface structural geometry is extremely difficult due to the presence of detachment horizons separating different fold geometries, together with precompressive deformation faults. For example, the KMCL Shell

Toad d-057-94-N-02 well was drilled into uplifted Mesoproterozoic rocks in the Toad anticline (Fig. 10). Immediately east of the well, the west limb of the Toad anticline forms an east-dipping homocline and the west limb of the Liard syncline. The geometry of the fault carrying the Mesoproterozoic to Middle Devonian section is unknown. It could be a small displacement east-directed blind thrust, a larger displacement west-directed blind thrust or a pop-up structure. In the future, it is hoped that access to proprietary seismic information will help guide the construction of a series of structural cross-sections across this geologically interesting part of the Foreland Belt.

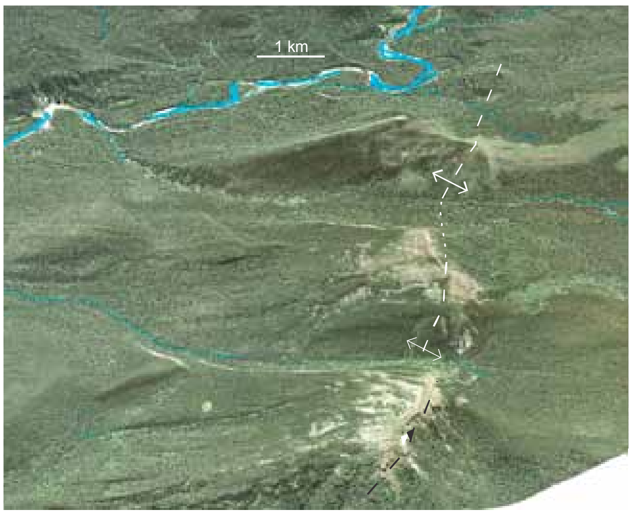

Figure 14. Draped orthophoto–digital elevation model image giving a three-dimensional perspective view of large Mattson cored anticline east of Beavercrow Mountain; view to the south-southwest from near 60°N latitude.

SUMMARY

- Results from mapping during the summer of 2011 will be combined with unpublished and published historical information to produce new GIS-enabled bedrock geological maps of the Toad River area.
- More than 8000 m of Mesoproterozoic; Neoproterozoic-Cambrian; Lower, Middle and Upper Paleozoic; Triassic; and Cretaceous strata are exposed in the Toad River, including three organic-rich units with shale gas potential.
- Local abrupt changes in thickness and/or facies indicate that block faulting occurred in the area during the Middle Cambrian, Ordovician–Silurian, Mississippian–Permian and Jurassic–Early Cretaceous (pre-Albian). Most older faults recognized at the surface were reactivated during Cretaceous compressive deformation.
- Shortening in the more competent Mesoproterozoic and Paleozoic successions was primarily by thrust faulting.
- Shortening in the interlayered competent and incompetent Upper Devonian to Cretaceous successions was primarily by folding. Locally important detachment horizons occur in upper Devonian–Mississippian (Besa River) shale, Triassic (Toad/Grayling) shale and siltstone and Lower Cretaceous (Buckinghorse/Garbutt) shale.
- Estimated shortening at the top of the Triassic across the eastern part of the Rocky Mountain Foothills near the Toad River is 5–6 km. Even less shortening occurs at top of the Triassic across the eastern part of the Liard Fold and Thrust Belt.
- Future plans include the construction of regional balanced structural cross-sections. Access to proprietary seismic information would greatly assist this process.

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HYDRAULIC FRACTURE WATER USAGE IN NORTHEAST BRITISH COLUMBIA: LOCATIONS, VOLUMES AND TRENDS

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ABSTRACT

Water demand for gas development in northeast British Columbia is dictated by certain aspects of multistage hydraulic fracturing. Approximately 500 wells, dating from 2005 to 2010, each with more than three fracture stages, were analyzed in terms of water use and gas production. Special focus was placed on fracture type, stimulation volume, well location and number of fractures per well. The water volume per fracture stage can vary by an order of magnitude depending on the completion method used. Water use is amplified by the number of completions per well. Slickwater completions are a preferred method because of their low cost and their ability to generate high stimulated reservoir volumes. The completion method and (to a lesser extent) the number of completions per well, is dictated by the geology of the basin. Gas production in the Montney Trend is very economical is terms of water use compared to the Horn River Basin. Water demand is expected to be high in the Cordova Embayment and the Montney North Trend. As water use is increasing rapidly, ongoing monitoring and improved database access are recommended for the Horn River Basin, the Montney North Trend, the Cordova Embayment and the Liard Basin.

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INTRODUCTION

Predicting potential water demand for gas development in northeast British Columbia is necessary for water management. One of the British Columbia Ministry of Energy and Mines' goals is to facilitate industry's needs for water and to share information on water use with other ministries and stakeholder groups, including the Ministry of Environment; the Ministry of Forests, Lands and Natural Resource Operations; the British Columbia Oil and Gas Commission (OGC); the Canadian Association Petroleum Producers and communities. Access to water is a requirement for sustaining industry growth. Accordingly, anticipation of potential water demand is critical to the Ministry of Energy and Mines' mandate.

Predictions for water use are based on trends in well development and the specific multistage hydraulic fracturing approach being used. To date, most of the assumptions made on industry-required water volumes and the rate of usage in British Columbia has been based on reports from industry operations in two areas of the province: the Montney Trend and the Horn River Basin (HRB). The volume of water used by the oil and gas industry in northeast British Columbia varies widely from less than 1000 m^3 to more than 70 000 m^3 per well (Kennedy, 2011). It is important to establish the extent to which estimates for water use in one play are a meaningful proxy for industry-related water use in other areas.

The purpose of this report is to gain an understanding on the aspects of multistage hydraulic fracturing that most affect water consumption and the location and extent to which they are being employed. Specifically, information is sought on the choice of completion method, the number of fracture stages per well, the horizontal length of the wells that is fractured and anticipated water returns for multistage fracture wells in the province. This information is important because it may provide insight into whether or not significant differences in water-use volumes exist between the province's major gas plays, and guidance on future efforts to predict industry-related water demand. The scope of the project is limited to wells with multiple hydraulic fracturing stages.

BACKGROUND

Multistage hydraulic fracturing

Hydraulic fracturing (known as 'fraccing', 'frac'ing' or 'fracking') is the process of creating a fracture in rock using pressurized fluid. It is primarily used in petroleum development to increase well production. Fractures create free space in a rock mass for oil or gas to move easily from the rock matrix to the wellbore and up to surface. Because the high-pressure environment of the rock formation naturally causes a fracture to close, the fracture is propped open with sand or ceramic grains (proppant). The open fracture allows gas and fluid to flow through to the wellbore. Wellbores may have a vertical, horizontal or directional orientation and the process can occur at any specific location along the wellbore, but is more commonly implemented at multiple locations along a horizontal wellbore section. Water use per well is determined by the type of stimulation treatment employed and is amplified by the number of completions per well.

Two methods of generating multiple fractures along a wellbore are commonly used in northeast British Columbia: plug and perf (PnP) and open hole multistage systems (OHMS; Kimmitt, 2011). The PnP method cements the production casing (or liner) in the horizontal wellbore and then punctures the casing at select locations to create fractures. Fracturing is initiated from the wellbore in stages (hence the term 'multistage') and after each stage is fractured (known as a 'completion'), a plug is set to seal off that zone. All of the plugs are drilled out afterwards. The OHMS method (also called the ball-drop system) leaves the production zone open (without casing) and uses a tool to mechanically create access points for fracturing between packers. The packers are automated and do not have to be drilled out. The method of stimulation, in part, determines the number of completions in a well and their spacing (King, 2010). The PnP system takes more time to complete than OHMS but allows for more freedom in locating fractures. The OHMS completions are more constrained with respect to the upper limit of fracture stages per well, although this limit has been improving with time (Themig, 2011). Additionally, OHMS reduces the time that fracture fluid is in contact with the rock; therefore, it reduces the risk of formation damage.

Fracture completions are used to increase well production by increasing the volume of rock that can connect with the wellbore or the 'stimulated reservoir volume'. Because hydraulic fracturing is expensive but necessary for increased production, the number of completions per well is generally optimized in long horizontal wells with many fracture stages (Cipolla et al., 2009; McDaniel and Rispler, 2009; Schweitzer and Bilgesu, 2009). If there are too few fracture stages per well, production may not be maximized. Conversely, stages that are too tightly spaced can increase the risk of 'screen out' or longitudinal fractures, which also impair production (Roussel and Sharma, 2010). Taylor et al. (2010) hypothesizes that 75 m is an ideal spacing for most shale gas reservoirs.

In northeast British Columbia, three types of completions (or treatments) are generally used: slickwater, energized and energized slickwater. The treatment style used is a function of economics and geology (King, 2010). Slickwater treatments use high volumes of water with low concentrations of sand and trace amounts of friction-reducing chemicals. This treatment type tends to propagate large fractures and as such is generally the most economical treatment choice (Kazakov and Miskimins, 2011). Slickwater fractures propagate best in brittle heterogeneous rock with higher silica content and lower clay content, as is the case in the Barnett shale (Mayerhofer et al., 2008; Buller et al., 2010; East et al., 2010; Wang and Miskimins, 2010). Long complex fracture networks created by this technique enhance the well's stimulated reservoir volume (Taylor et al., 2010); however, slickwater fractures have low sand concentration with rapid proppant settling. As a result, fracture flow capacity can be limited (King, 2010). An additional challenge is that these completions often have return water rates of less than 30% (Burke et al., 2011). Slickwater fracture treatments are not practical for all geological environments.

Energized treatments are the method of choice for softer, more ductile rocks such as siltstone or shale with clay or carbonate rocks and underpressured horizons. Energized treatments use comparatively small amounts of water, relying instead on the use of foams and polymers to support the suspension of large concentrations of sand. Softer rock formations have the capacity to absorb the stress of a stimulation treatment without necessarily generating a fracture network (Buller, 2010). The higher proppant concentrations that characterize energized treatments help to keep fractures open because softer rocks tend to heal quickly (East et al., 2010).

Energizing components also provide quick and efficient fluid return to surface (flowback; Bene et al., 2007; Warpinski et al., 2008). The percentage of return water from energized treatments can be up to 70% (Arthur et al., 2008). Because low permeability can cause a capillary effect that draws water into the formation and low reservoir pressures do not create enough flow for the gas to displace the liquid from the formation (Wylie et al., 2007), compressed gases such as carbon dioxide (CO_2) or nitrogen gas (N_2) are used to help 'energize' the return of water to the surface. Formation damage can occur if water-sensitive clays are present that might swell and block gas migration pathways (Bene et al., 2007; Taylor et al., 2009). Depth is also a factor in the effectiveness of energized fluids. Energized fluids lose their ability to transport proppant at greater depths because the fluids are less able to generate bubbles; therefore, slickwater treatments may be more appropriate in these environments.

If an environment is equally conducive to both slickwater and energized fractures, slickwater fractures generate a higher stimulated reservoir volume and better production at a lower cost than energized fractures (Romanson et al., 2010). Energized treatments perform better in softer rocks, although the fracture halflength is less and the cost of treatment is greater (East et al., 2010; Burke et al., 2011). Table 1 shows how treatment types vary with brittleness and geology.

Energized slickwater treatments are a hybrid of both types and are not clearly defined in the literature. In general, the large amounts of water associated with slickwater completions are used in combination with the compressed gases used to create foams in energized treatments. The rationale for using energized slickwater treatments is to create a large stimulated reservoir volume while mitigating problems associated with water in the formation, such as formation damage and reduced flowback (Zelenev et al., 2010; Burke et al., 2011). Compressed gases, such as N_2, are often used.

In terms of the fluids used for completions, either energized or nonenergized fluids, polymer gels can be used in varying degrees and configurations to increase the viscosity of the fluid to support proppant in solution (Kargbo et al., 2010; LaFollette, 2010). Initially, treatments were freshwater based, although saline water can now be used in both energized and slickwater treatments by employing specialized friction-reducing agents. The reuse of fracture fluid can improve well economics (Paktinat et al., 2011).

Current Assumptions about hydraulic Fracture–Related Water Use in British Columbia

The National Energy Board (2009) indicates that hydraulically fracturing wells can be water-intensive procedures; however, data are limited. Water is not necessarily required for all hydraulic fracturing in gas-bearing shale; yet, high volumes are required for developing the HRB shale. It is important to understand the differences in order to understand regional water demand.

To date, most of the assumptions made on industry-required volumes and the rate of usage in British Columbia has been based on general knowledge of the province's two major plays: the Montney Basin and the HRB. This range represents a significant difference in the amount of water required by industry for multistage hydraulic fracturing. In the Montney Trend, water demand can be from 200 m^3 to 4600 m^3 water per fracture stage with wells needing 800 to 13 000 m^3 water per well (Dunk, 2010; Burke et al., 2011). In the Horn River Basin, water demand ranges from 2500 to 5000 m^3 per fracture stage with values ranging from 10 000 to 70 000m^3 per well (Horn River Producers Group, 2011).

A more thorough assessment of water demand in northeast British Columbia is required. Meaningful analysis will establish whether specific conditions exist for the rates of water usage, and whether a combined analysis of water use in the Montney Basin and the HRB is a meaningful proxy for industry-related water-use requirements in other areas.

TABLE 1. FRACTURE TREATMENT VARIATION WITH BRITTLENESS (ADAPTED FROM BULLER, 2010).

Brittleness	Fluid Viscosity	Energized	Fluid Volume	Proppant Volume	Proppant	Example
70%	Slickwater	No	High	Low	Low	Muskwa, Barnett
60%	Slickwater	↑	↑	↑	↑	
50%	Hybrid	|	|	|	|	Marcellus
40%	Linear gel	|	|	|	|	
30%	Crosslnked gel	|	|	|	|	
20%	Crosslinked gel	↓	↓	↓	↓	Haynesville
10%	Crosslinked gel	Yes	Low	High	high	

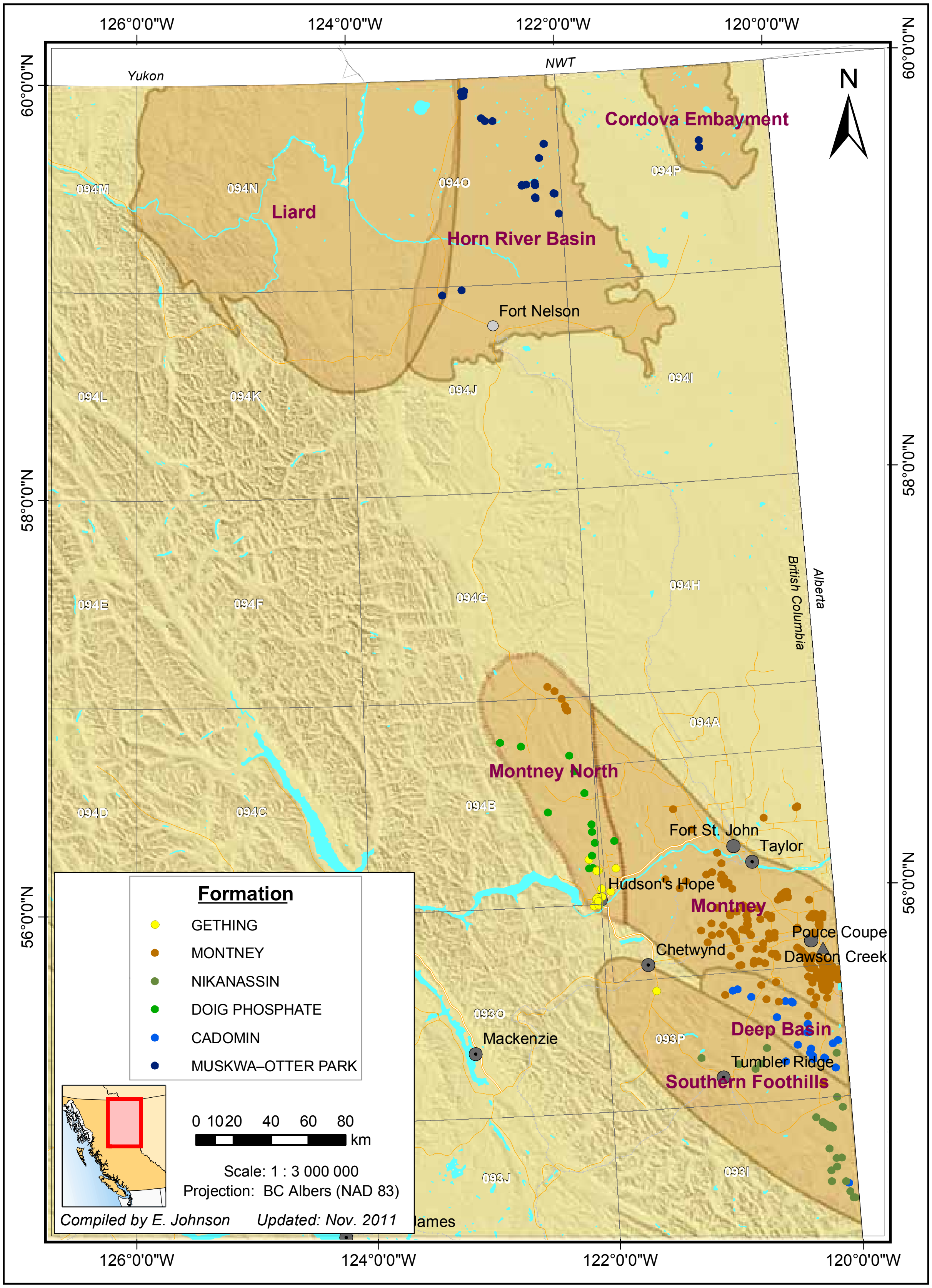

Figure 1. Major basins with multistage fracturing in northeast British Columbia. Wells are indicated as solid dots and formations are grouped by colour.

TABLE 2. GEOLOGICAL ASPECTS OF HORIZONS WITH MULTISTAGE FRACTURING.

Formation	Target	Depth Average (m)	Pressure Average (kPa)	Gradient Average (kPa/m)	Temperature Average (°C)
MONTNEY	Siltstone and shale	2300	31500	2.3	86
MUSKWA–OTTER PARK	Shale	2600	39300	2.1	115
EVIE	Shale	2800	41200	2.2	142
DOIG PHOSPHATE	Shale	2200	31200	2.1	71
CADOMIN	Sandstone and conglomerate	2500	16700	0.9	80
NIKANASSIN	Sandstone with shale & siltstone	2900	26100	1.6	103
GETHING	Coal	700	8200	0.4	39

Geology of the major basins

Geological aspects such as the lithology, geochemistry and petrophysics of a formation are partially determined by the depositional environment. The following section provides a brief geological summary of the target formations in the basins of northeast British Columbia. Figure 1 shows the geographic distribution of the basins. Table 2 provides a brief summary of the lithology, depth, pressure and gradients for the formations.

MONTNEY TREND AND MONTNEY NORTH TREND (MONTNEY, DOIG PHOSPHATE AND GETHING SHALES)

The sandstone, siltstone and shale of the Triassic Doig and Montney formations in northeast British Columbia were deposited on a westward-prograding shelf on the paleocontinental margin (Edwards et al., 1994). Sediments grade westerly from near-shore fine-grained sandstone and siltstone deposits to deep-water shale (Walsh et al., 2006). The lithology in the Montney Trend changes to the northeast and sediments have increased silica and shale content leading to different completion practices. In this report, the Montney North Trend is defined as a separate region.

Shale gas potential exists in two zones: 1) the Lower Montney, in sandy, silty shale of the offshore parts of the basin and 2) the Upper Montney, below the shoreface, where silt has buried tight sand (National Energy Board, 2009). The Montney is locally more than 300 m thick and is developed in portions using stacked horizontal wells. The Montney play is a world-class natural gas play and it is estimated to contain an original-gas-in-place of 35–250 trillion cubic feet (Tcf) of natural gas (Adams, 2010). In some areas, the Montney is a dry-gas reservoir, transitioning to an oil reservoir in other areas with retrograde condensate production in transition areas (Taylor et al., 2009).

The contact between the Montney Formation and the overlying Doig Formation is marked by a distinctive shale unit with abundant phosphatic grains (the Doig Phosphate). The Doig shale above the phosphate grades upwards into a clean shoreface sandstone that in many areas is indistinguishable from the overlying Halfway Formation (Walsh et al., 2006). In the Montney North region, the Doig Phosphate is predominantly shale.

The Gething Formation is a coal-bearing formation that consists of two coal measures separated by a sandstone-siltstone layer (Legun, 1991). The formation contains cumulative coal thicknesses that range up to 17 m. As the coal is mostly high-volatile A bituminous, the Gething is being developed for coalbed methane (CBM; Ryan et al., 2005). North and south of Hudson's Hope, the formation dips moderately to the east and it is generally too deep for development.

HORN RIVER BASIN AND CORDOVA EMBAYMENT (EVIE, OTTER PARK AND MUSKWA FORMATIONS)

The Horn River Basin (HRB) and the Cordova Embayment formed during the Middle Devonian when the Presqu'ile barrier reef extended northward along the eastern edge of the Horn River Basin (Fig. 2). Clay, siliceous mud and organic debris deposited on either side of the reef formed the Evie, Otter Park and Muskwa shale members of the Horn River Group (British Columbia Ministry of Energy and Mines and National Energy Board, 2011); hence, the shales targeted for development in the HRB are the same as those in the Cordova Embayment.

The Evie member is the lowermost shale. It consists of organic-rich, variably calcareous and siliceous shale. The uppermost part of the unit includes more silt. In the Horn River Basin, the Evie thins westward from more than 75 m to less than 40 m thick in the vicinity of the Bovie Lake structure on the western margin (British Columbia Ministry of Energy and Mines and National Energy Board, 2011).

The Otter Park member consists of calcareous shale. This shale reaches a maximum thickness of more than 270

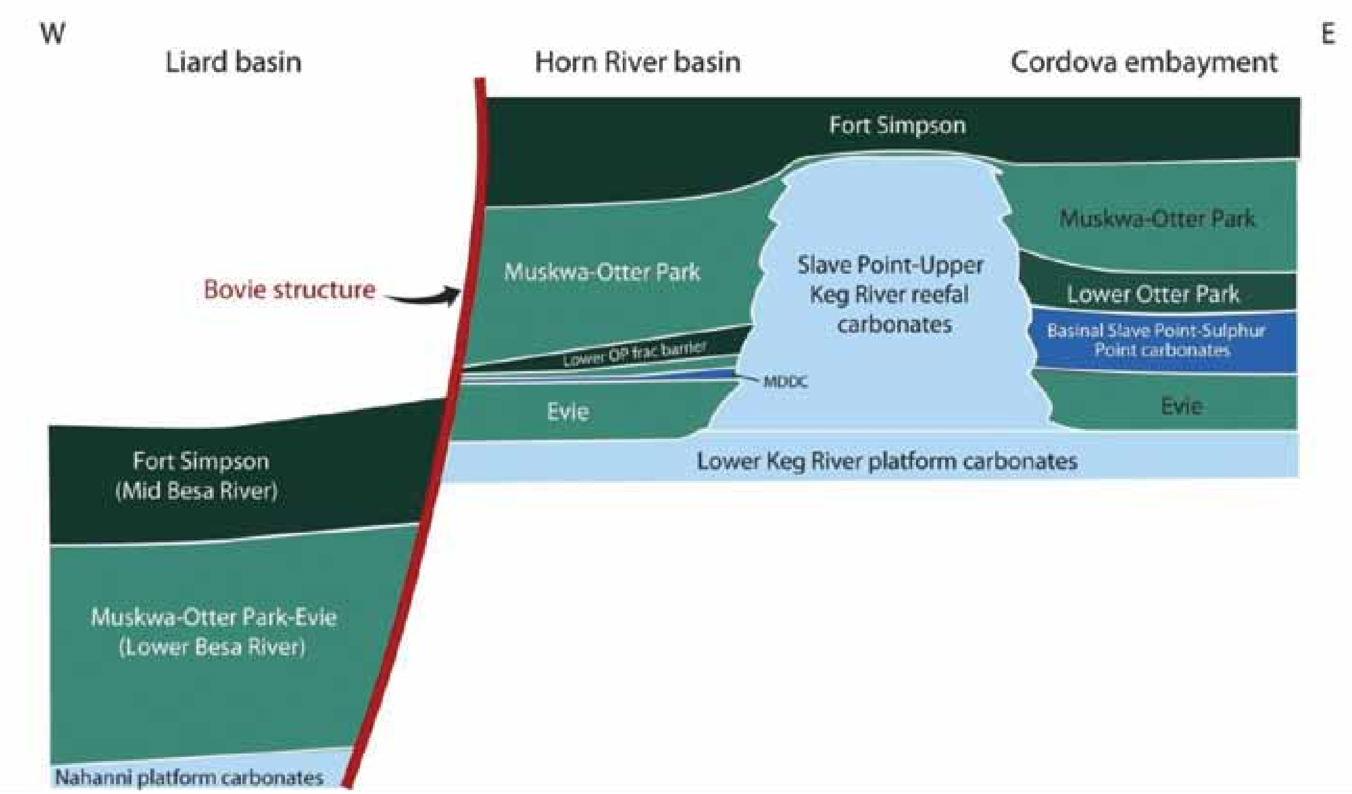

Figure 2. Illustrated cross section depicting shale of the Horn River Basin and the Cordova Embayment separated by the Presqu'ile barrier reef (Ministry of Energy and Mines and National Energy Board, 2011).

m in the southeast corner of the Horn River Basin. The shale thins to the north and west, where it includes siliceous black interbeds (British Columbia Ministry of Energy and Mines and National Energy Board, 2011).

The Muskwa member consists of organic-rich, siliceous shale. In the Horn River Basin, the Muskwa is 30 m thick adjacent to the Presqu'ile barrier reef and thickens westward to more than 60 m. The exception to this pattern is in the southeast corner of the Horn River Basin, where the Muskwa thins considerably and the Otter Park thickness reaches its maximum. The Muskwa is not restricted to the Horn River Basin but thins and extends over the top of the barrier reef and is present through the rest of northeast British Columbia strata (British Columbia Ministry of Energy and Mines and National Energy Board, 2011). The Muskwa and Otter Park shales are coupled together for this research.

DEEP BASIN (CADOMIN FORMATION)

The Cadomin Formation is the oldest unit in the Deep Basin and unconformably overlies the Nikanassin Group. The Cadomin is derived from sediments from the west that were transported northwards. It contains widespread sandstone and conglomerate that range from 5 to 25 m thick. A maximum thickness of approximately 170 m is reached in the area southwest of Monias (Tuffs et al., 2005).

Industry has recognized the Cadomin as a potential gas target for more than two decades but early forecast reserves have not yet been realized. Deep Basin Cadomin fields are underpressured. Prior to 2001, there was no commercial gas production from the Cadomin in northeast British Columbia. Industry had drilled 250 vertical wells that penetrated the Cadomin Formation (Cutbank Ridge area) but only 20 had flowed gas. In 2001, hydraulically fractured vertical and horizontal wells in lower-permeability reservoirs in the thicker Cadomin sections of British Columbia yielded economic gas returns.

LIARD BASIN (BESA RIVER FORMATION)

The Liard Basin formed through continuous subsidence and deposition from the Cambrian to the Late Silurian. Late Devonian uplift caused a thickened succession in the northern and eastern parts of the basin (CBM Solutions, 2005).

The Besa River shale has been identified as a source rock zone and a potential fractured reservoir. It is just beginning to be economically developed. The Besa River represents the deep-basin equivalent formations to the package, including the succession from the Horn River Formation to the Debolt Formation (Fig. 3). The Besa River Formation contains carbonaceous siltstone to shale units and is more than 2000 m thick (CBM Solutions, 2005). There is

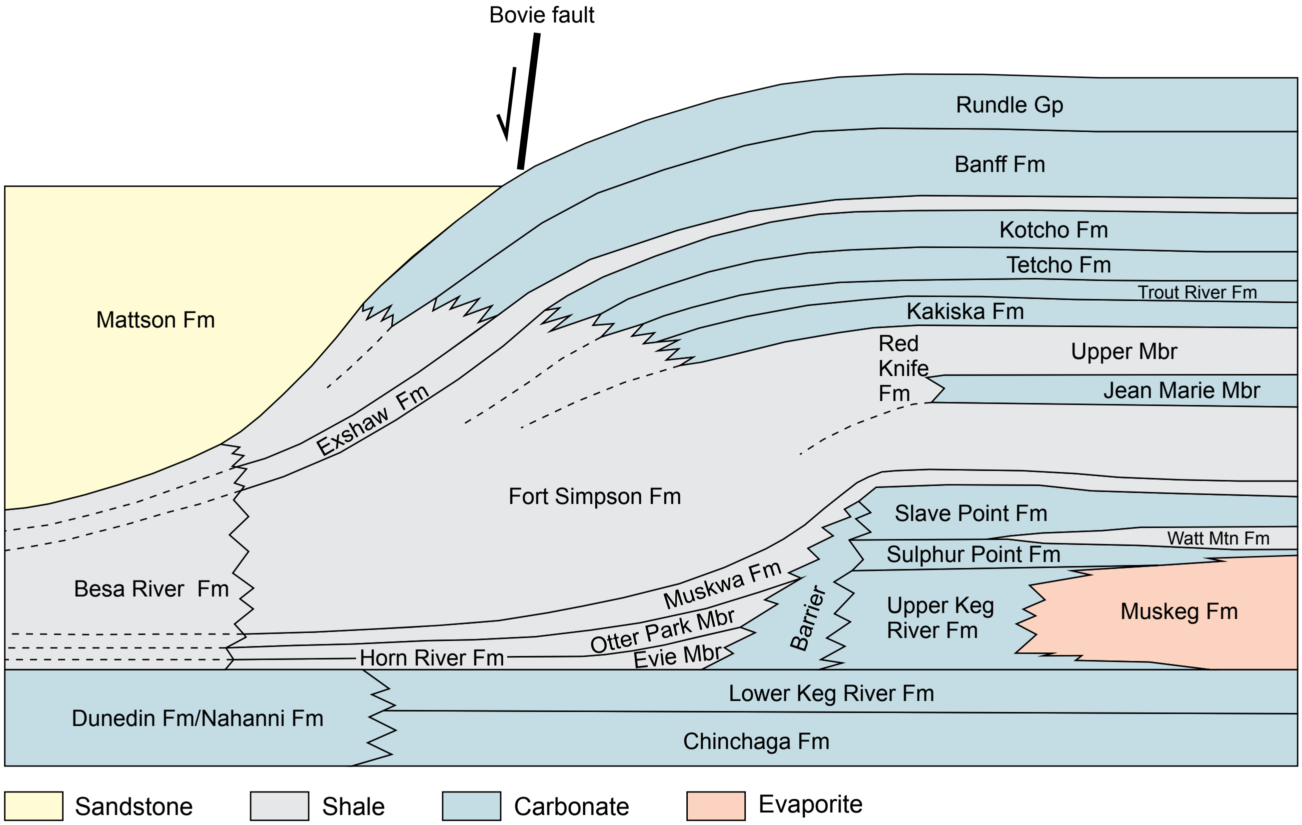

Figure 3. Schematic diagram shows the transition (in grey) between the Besa River Formation in the Liard Basin (left) to the package in the Horn River Basin (right), which ranges from the Evie, Muskwa–Otter Park members through the Debolt Formation (Ferri et al., 2011).

a central unit in the Besa River Formation of siliceous siltstone, which is correlated with the Fort Simpson Formation (Ferri et al., 2011).

SOUTHERN FOOTHILLS (NIKANASSIN GROUP)

The Nikanassin Group represents a thick clastic wedge of sediments that thins to the east. It is composed of various very fine to medium-grained sandstone beds with interbedded shale and siltstone (carbonaceous in part), and various coal beds. Sandstone intervals have intergranular and fracture porosity that is generally less than 6% with permeabilities less than 0.1 mD, so there is tight gas potential. In northeast British Columbia, the Nikanassin consists of the Minnes Group, including the Monteith, Beattie Peaks, Monach and Bickford formations, from oldest to youngest (Stott, 1998; Miles et al., 2009). Gas development includes directional wells parallel to bedding planes within fold limbs.

METHODS

A database of well information was compiled with data from the OGC Integrated Resource Information System (IRIS) database and augmented with data from IHS AccuMap® and geoLOGIC Systems geoSCOUT program. The new database was constructed to focus on metrics related to multistage hydraulic fracturing; therefore, it does not include data from all wells, only those with fracture completion information (7117 wells out of the 30 997 wells in British Columbia as of September 2011 where a ‘well’ consists of a unique well identifier and completion event, UWI-CE). Most of the data is complete through to the end of 2010. Much of the fracture completion information is manually verified by OGC staff, so the records in the IRIS database lag behind the current date by approximately six months.

Only wells with more than three stages per well event were included in the multistage hydraulic fracturing research. Patterns emerged from the initial database of more than 7000 wells when the threshold for ‘multistage’ was set. There were 509 wells with multiple completions. Thirteen of these wells were eliminated because they were outside the time and space guidelines for this project (completed after 2003 and in northeast British Columbia). The remaining 496 wells were used for analysis. Some of the well data are confidential and are included with group data for trend analysis, but excluded in regions where drilling is too sparse to ensure the confidentiality of the operators, specifically in the Cordova Embayment and the Liard Basin.

Not all basins were analyzed at all stages of this study. Many of the analyses focused specifically on horizontal multistage wells (399 wells) in the Montney Trend, the Montney North Trend, the Deep Basin and the Horn River Basin. Some exclusions are noted below:

- Gething wells were excluded from most analyses. Hydraulic fracturing associated with the Gething Formation is substantively different than for other shale and tight gas targets because Gething wells are focused on coalbed methane extraction. Well depths are comparatively shallow, wells are vertical and water usage in hydraulic fracturing is minimal.
- Nikanassin Group wells were excluded from some analyses. Nikanassin wells target tight gas with typically four to six fracture stages along directional wells with nominal water usage. Because these wells are directional, not horizontal, they were not directly comparable for all comparisons with horizontal wells.
- The Cadomin Formation was included in the analyses, but it should be noted that it is not classified as unconventional. Wells target conglomerate and sandstone in a low-pressure environment; however, the approach taken to development uses high-volume horizontal multistage (HVHMS) completions, so this formation was included.
- Wells from the Cordova Embayment are too few to be representative.

Compiled data fields for analysis include both well data (e.g., location, operator, dates, field, orientation, confidential status and formation) and fracture-specific information (e.g., fracture depth, stimulation volume, dates, comments and stimulation pressure). Production data were included, where available. These data included date, volume of gas per producing day, water per producing day and cumulative totals.

Much of the fracture data was in the 'comments' field of the IRIS database. This field was analyzed to determine proppant mass per fracture, fracture treatment type (energized with CO_2 or N_2, slickwater or nitrified slickwater) and fracture type (refracture, failed fracture, data fracture injection fracture or mini fracture). The style of treatment was not determined for 12% of wells in the database. Well data were categorized by location into basins and enhanced with analyzed fracture data for the lateral length, average fracture spacing, average stimulation volume per fracture, stimulation volume per well, average proppant mass per fracture, proppant mass per well, average stimulation pressure, dominant treatment type, water to sand ratio and pressure-depth gradient.

There was some ambiguity in the database where mini fractures were used test the character of the rock in advance of a full hydraulic fracture. The water usage for injection tests, data fractures, mini fractures is small and these fractures were excluded from the analyses. There was also some duplication where failed fracture attempts and refracturing efforts were recorded. Although it would be desirable to separate out these events from the overall fracture database, it was not feasible given the nature of the data entries. Efforts were made, however, to exclude these events when calculating fracture spacing and averages of water and sand for the well so that the data would not be unduly biased.

The average spacing between fracture stages was calculated by two methods. The first method involved taking the distance from the top of the shallowest stage to the bottom of the deepest stage and dividing by the number of stages. The second method involved calculating the offset distance between each stage and calculating the average for the well. Differences between the two methods were found to be negligible. As such, the offset method was used to generate spacing distance for the analyses.

Well and fracture data were analyzed for relationships and trends by crossreferencing. Microsoft® Excel® software was used for common statistical analysis including histograms and linear regression. Variables assessed included date, stimulation volume (by fracture or by well), mass of proppant, ratio of water to proppant, gas production from the first four months and gas production after 24 months. Common groupings included formation, basin, treatment type and stimulation volume (low, moderate, high).

The spatial distribution and grouping by basin for the formation fractured, well orientation, treatment type and the stimulation volume of water was evaluated using ESRI® ArcGIS®.

Production rate, cumulative production and returned water curves were created as averages for formation, basin and treatment type. Approximately half of the wells in the database have two years or more of public gas production information (243 wells). The majority of wells are in the Montney Formation (190 wells). There were not enough producing wells in the Doig Phosphate (three wells) or the Evie member (four wells) to be representative. Production data were isolated for production after 24 months and crossreferenced with stimulation volume and lateral length. A metric for water usage was developed by normalizing the water used for fracturing a well against cumulative gas production after two years for that well. Note that this metric is not directly comparable with published metrics for the volume of water used relative to the estimated ultimate recovery of gas.

Comparisons were made between production rates (gas units per producing day) and i) well stimulation volumes, ii) sand placed in formation and iii) the number of fracturing stages. Correlation analysis was performed between water consumption indicators and initial gas production (an average of the production for the first four months), and production after two years. This analysis was performed for gas production both as a volume per producing day and as a cumulative volume. Basins were compared by the amount of water required to develop a unit of gas after two years of production.

RESULTS

Research results are grouped into two main sets of findings pertaining to 1) the location, history of development and trends in multistage horizontal wells in northeast British Columbia and 2) the interrelationship between the number and style of completion with water usage and production.

Development trends

Almost all the multistage hydraulic wells are located in a small number of formations and are restricted to a few basins. More than 96% of multistage wells are located in seven formations and five basins (Fig. 1). These formations include the Montney Formation along the Montney Trend; the Doig Phosphate horizon in the Montney North region; the Muskwa, Otter Park and Evie members in the Horn River Basin; the Cadomin Formation in the Deep Basin; and the Nikanassin Group in the Montney Trend and Southern Foothills (Table 3).

Multistage wells across northeast British Columbia are predominantly horizontally oriented in keeping with the stratigraphic orientation for the Western Canadian Sedimentary Basin in northeast British Columbia. The average depth for multistage horizontal wells is more than 2 km (Table 2). Vertical wells are common near Hudson's Hope, where they are used to develop the Gething coalbed methane at a depth of approximately 1 km. Directional wells were closer to the deformed belt in the Southern Foothills, where Nikanassin sandstone and conglomerate sediment dip. Table 4 shows the relative number of wells and their orientation.

Overall, the Montney Trend has been the most active of the five major basins with the most wells drilled. Of the total number of multistage horizontal wells (496), 310 are located in the Montney Formation within the Montney Trend. Development with horizontal multistage hydraulic wells began in 2005 and has been the most quickly developed of the basins. Multistage drilling began in the HRB in 2007, but at a much slower pace. By 2010, there was more than five times the number of multistage horizontal wells in the Montney Trend than in the HRB (Fig. 4). Drilling in the Deep Basin has been ongoing for more than a decade with ever-increasing technological complexity. Multistage horizontal drilling began in 2007, but the number of new wells has tapered off since 2008. Multistage drilling began more recently in the Montney North (in 2008) and has since increased steadily. Development of the Nikanassin Group began in the Montney Trend in 2005 and continued in the Southern Foothills in 2007, although the number of wells drilled (26) is insignificant compared to the number drilled in the Montney Formation.

TABLE 3. MULTISTAGE WELLS BY BASIN AND FORMATION IN NORTHEAST BRITISH COLUMBIA.

Formation	Montney Trend	Horn River Basin	Montney North Trend	Deep Basin	Southern Foothills Trend	Grand Total
MONTNEY	310		7			317
DOIG PHOSPHATE			13			13
GETHING	2		16		1	19
MUSKWA-OTTER PARK		46				46
EVIE		20				20
CADOMIN				31		31
NIKANASSIN	15				11	26
Grand Total	327	66	36	31	12	472

TABLE 4. WELLBORE ORIENTATION FOR FORMATIONS IN NORTHEAST BRITISH COLUMBIA.

Formation	Vertical	Horizontal	Directional
MONTNEY	5%	87%	8%
DOIG PHOSPHATE	15%	54%	31%
GETHING	95%		5%
MUSKWA–OTTER PARK	8%	92%	
EVIE		100%	
CADOMIN		90%	10%
NIKANASSIN			100%

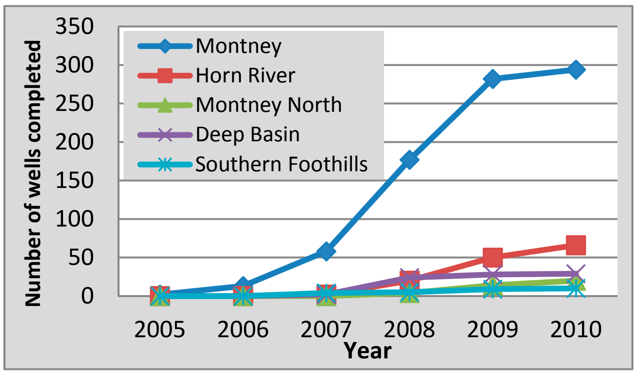

Figure 4. Development activity showing the well count for multistage wells in northeast British Columbia by basin.

Completions, water use and production

A strong uniformity in the stimulation treatment is employed for any given basin (Fig. 5). This uniformity exists irrespective of operator. Multistage hydraulic wells in the HRB were almost exclusively slickwater completions. Slickwater treatments were also the primary system employed in the development of the Deep Basin Cadomin sandstone and conglomerate. Wells in the Montney were predominantly energized. The only exceptions to uniformity in treatment type within regions were the Montney North and Southern Foothills. A diversity of treatment methods were used here (Table 5). The majority of energized treatments were CO_2 based, although energized slickwater treatments are predominantly N_2 based.

The number of fracture stages per well has increased across northeast British Columbia, except in the Southern Foothills, where four to six fractures per well are consistently used. In regions where slickwater fracturing has become the preferred treatment method (e.g., the HRB, the Deep Basin), the number of fracture stages per well has increased dramatically (Fig. 6). From 2009 to 2010, operators almost doubled the number of fracture stages per well from 10 to 19 in the Horn River Basin. Fracture stages increased dramatically for the same period in the Deep Basin, from 9 to 15. Increases were modest in the Montney and Montney North trends. Increased production was associated with increased numbers of fracture stages in the HRB and the Deep Basin (Fig. 7). Conversely, production did not improve for energized wells in the Montney.

There has also been a general trend towards reduced spacing between fractures over time in northeast British Columbia. For instance, the spacing between completions decreased steadily in both the HRB shale and the Montney Formation (Fig. 8). At present, completions are commonly less than 150 m apart, having tightened up from more than 300 m apart in 2005.

The lateral length of wellbores for multistage wells in northeast British Columbia has also increased annually. Lateral length was 1800 m for both the HRB and the Montney Trend (Fig. 9). The increase in lateral lengths for wells in the HRB was far faster than for the Montney Trend, which showed a stepwise increase with increments of 300 m over 5 years, whereas the horizontal lengths in HRB increase annually by 200 m or more. Further analysis revealed a relationship between the fractured horizontal length and well productivity in the HRB (Fig. 10). A positive exponential relationship was found between the lateral length of a well and gas production for the Muskwa–Otter Park shales. Increasing the total horizontal fracture distance from 0.5 to 1.5 km translated to an increase in gas output from 600 to 3600 e^3m^3 per well after two years of production. No similar relationship was found between lateral length and productivity for energized wells in the Montney.

In terms of water usage, slickwater treatments were the most water-intensive technique, using 13 times more water per fracture than an energized fracture (Table 5). On average, slickwater treatments used 2100 m^3 per stage. By comparison, the average energized treatments (CO_2) used approximately 155 m^3 per fracture stage. Hybrid energized slickwater treatments require approximately 800 m^3 per fracture stage. Significant variability exists in the amount of water used for any given slickwater treatment. In both the HRB and the Deep Basin, slickwater water volumes vary over an order of magnitude, from 400 m^3 to almost 5000 m^3; however, the nature of the distribution of volumes in the HRB is different from the distribution in the Deep Basin. The mean fracture volume for the Deep Basin is half that of the HRB.

Differences in consumed water volumes were also found between the various basins. Water consumption in the HRB was climbing at a far faster rate than in other basins (Fig. 11). The cumulative volume of water used in the HRB was almost four times greater than that used in the Montney Trend despite the substantial difference in well numbers. The difference in consumption between the HRB and Montney changed from 1.5:1 in 2008, to 2.1:1 in 2009 to 3.5:1 in 2010. Note that development activity and water consumption in the Deep Basin did not keep pace with

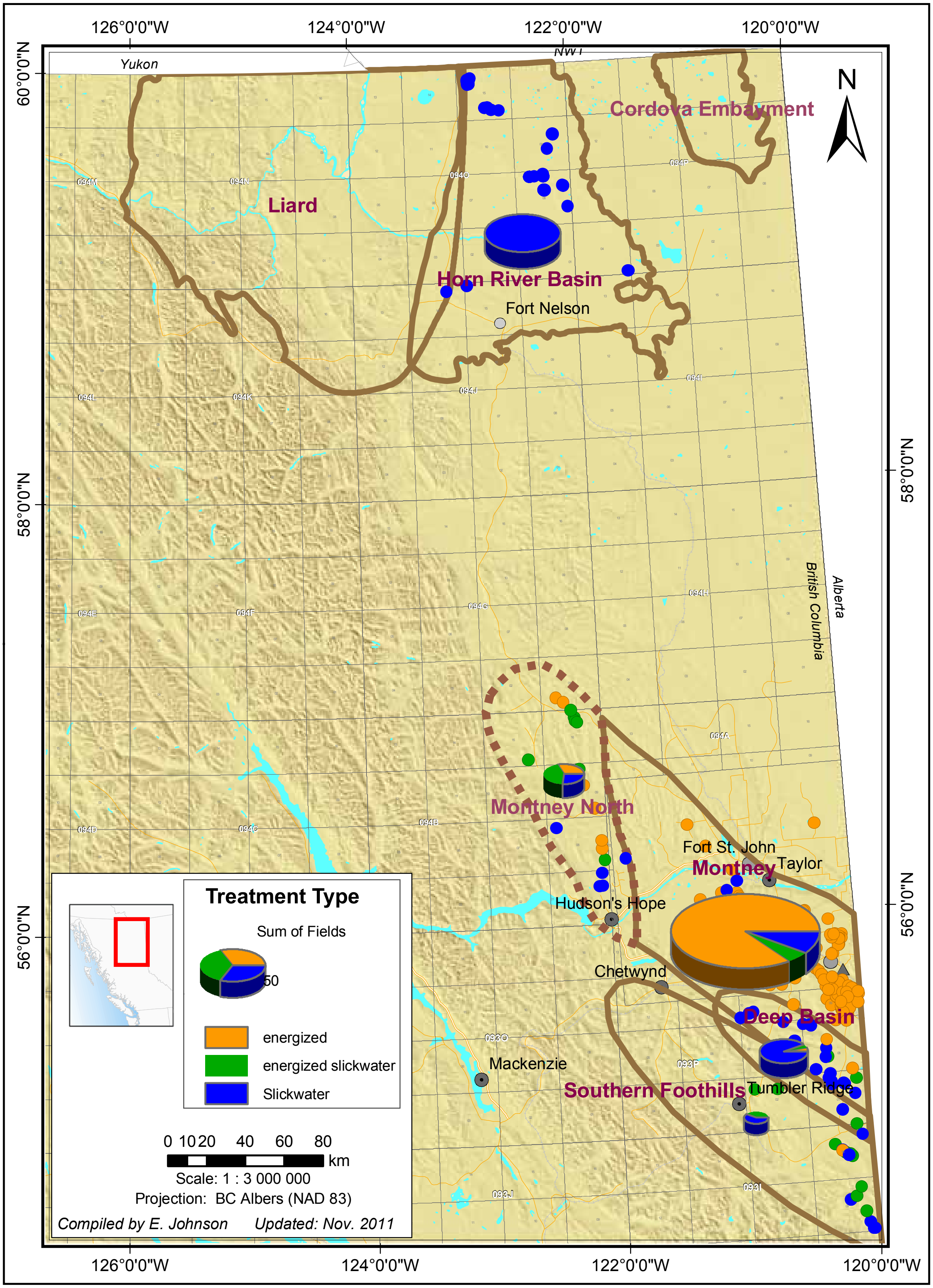

Figure 5. Types of fracture treatments and their distribution across northeast British Columbia. Wells are colour-coded by treatment type and pie charts represent the relative proportion of treatment types for wells a given basin.

TABLE 5. ATTRIBUTES OF FRACTURE TREATMENT METHODS USED IN NORTHEAST BRITISH COLUMBIA.

Frac Treatment	Sub-type	Water per Stage (m^3)	Sand per Stage (T)	Stimulation Pressure (kPa)	Water/sand (m^3/T)	Count of Fractures
Energized	CO_2	155	95	56134	2	5585
	CO_2/N_2	134	113	48347	1	601
	N_2	227	101	53092	2	1691
		168	**98**	**54880**	**2**	**7877**
Energized slickwater	CO_2 slickwater	443	64	54436	9	44
	Nitrified Slickwater	822	136	52374	10	550
		791	**130**	**52541**	**10**	**594**
Slickwater		2101	178	59827	14	8126
		2101	**178**	**59827**	**14**	**8126**

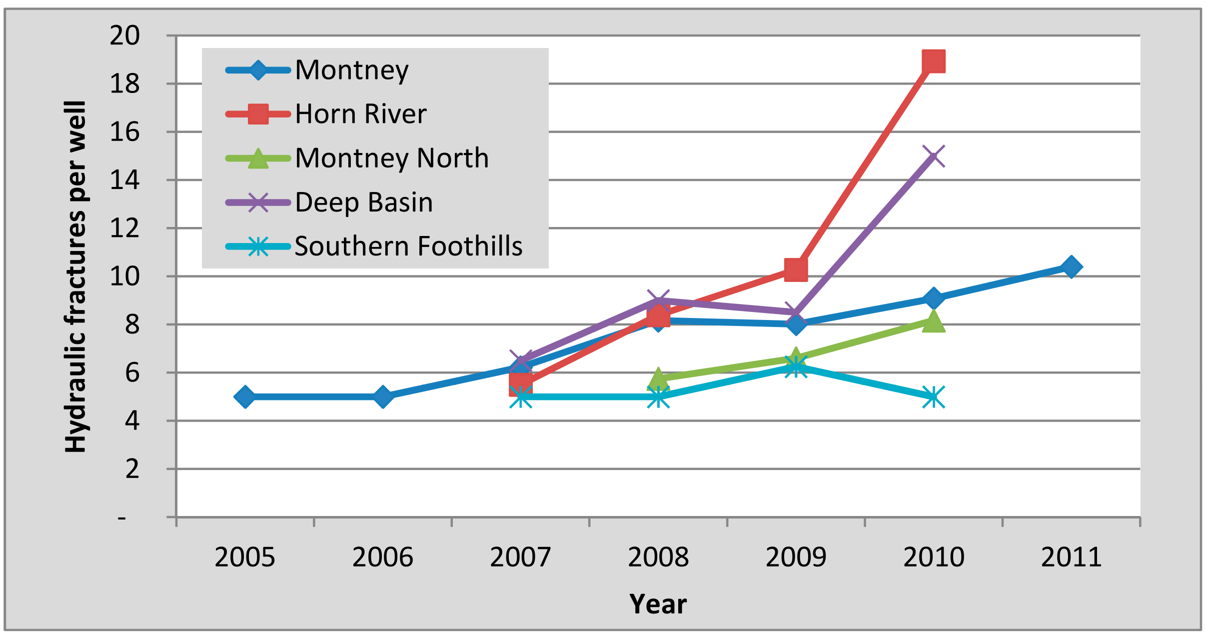

Figure 6. Average number of fracture stages for wells by basin between 2005 and 2010.

HRB (Fig. 4, 11).

The ratios of the volume of water required to develop a unit of gas varied significantly by basin (Fig. 12). In the Montney Trend, very little water was required to produce gas, averaging 0.06 m^3 per unit gas (where a unit of gas is 1000 m^3 measured after 24 months of production). The amount of water necessary to produce gas is higher for the Montney North, the Deep Basin and the HRB (0.2, 0.3 and 0.5 m^3 water per unit gas, respectively).

A strong relationship was found to exist between the initial daily production rate and fracture features (stimulation volume and proppant placed in formation) for slickwater fractures in the Muskwa–Otter Park shales (Table 6). The relationship between stimulation volume and production strengthened with time (Table 7). This indicates that stimulation volume injected in a slickwater fracture reflects the stimulated reservoir volume with gas production coming from deep fractures beyond the immediate vicinity of the wellbore. The relationship was not as strong between proppant and production because sand

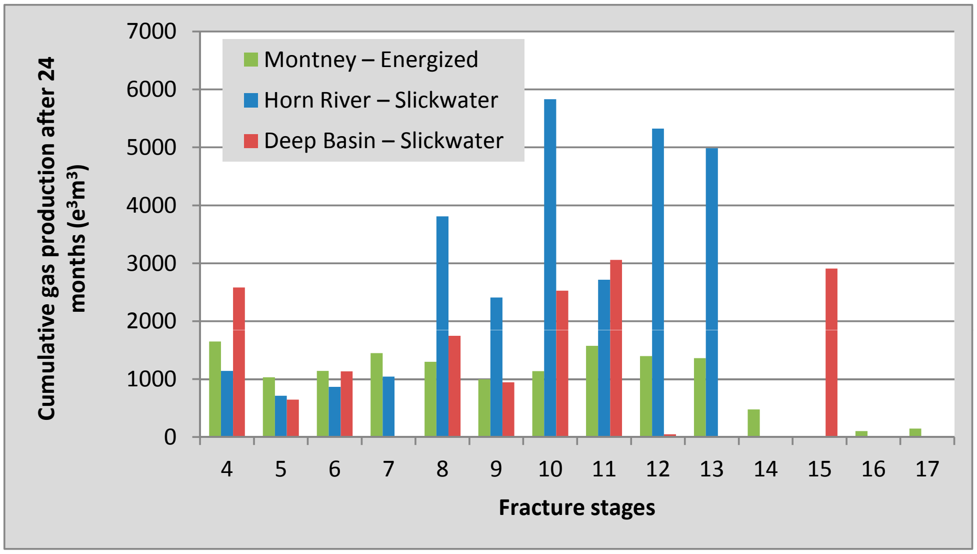

Figure 7. Produced gas as a function of the number of fracture stages per well.

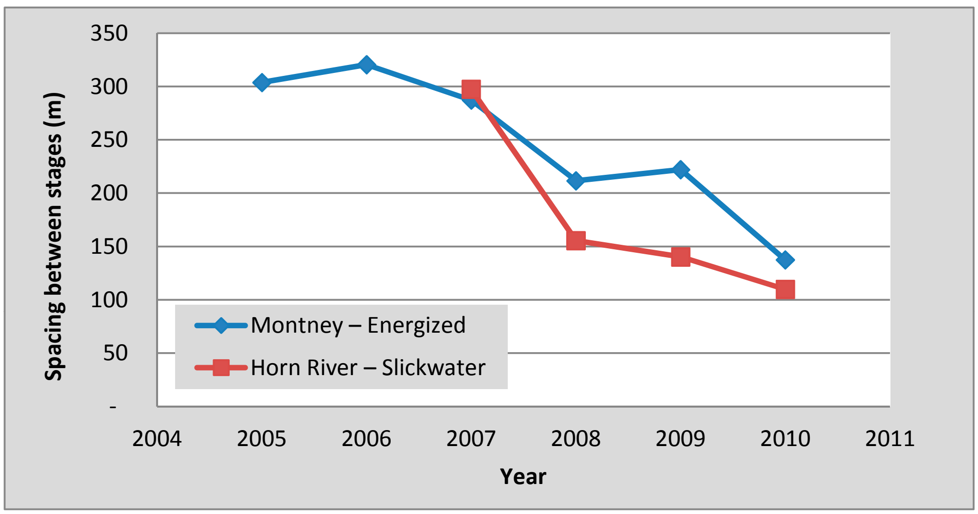

Figure 8. Changes in the average spacing between fracture stages from 2005 to 2010.

falls out of suspension during injection and therefore does not represent the stimulated reservoir volume as precisely as water volume. There was only a weak relationship between daily production and the number of fracture stages per well. There was no relationship between production rate and fracture features or number of fractures for the Montney. Weak relationships exist in the Nikanassin Group for fracture features and production rate but not number of fractures and production rate.

The strong linear relationship between production rate and stimulation volume is displayed graphically in Figure 13. Although there are not many wells with a long production history in the HRB, the relationship is sufficiently statistically significant to be predictive. For the Muskwa–Otter Park members, the rate of gas production after two years will be roughly 0.0018 the original stimulation volume used.

The production curves for the Muskwa–Otter Park shales show that increased stimulation yields increased production at all points in the production history (Fig. 14). This has implications for the estimated ultimate recovery from a well. The curves generally maintain their separation for more than 36 months of production, although small improvements in production from slightly higher stimulation volumes wane over time. Large production improvements from large volumes persist. The higher the stimulation volume, the greater the production rate and estimated ultimate recovery. Raising the stimulation volume by 23 000 m^3 (from 11 600 m^3 to 34 600 m^3) yielded 45 500 e^3m^3 more gas over 24 months.

In general, the return volumes reported were low compared to the literature (Fig. 15). The volume of return water from slickwater treatments was very small. In the HRB, slickwater return in the 20 months following well completion was only 17%. The use of nitrogen (N_2) with slickwater

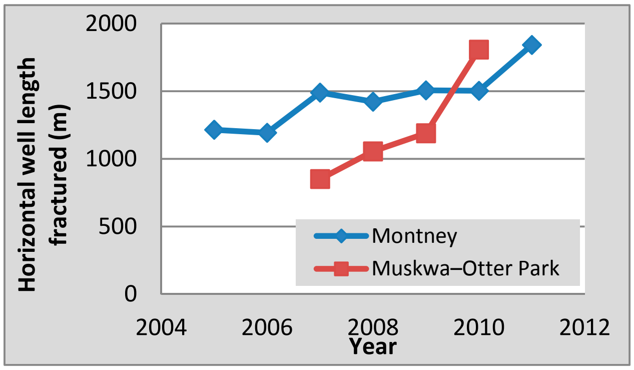

Figure 9. Average horizontal wellbore lengths for two formations between 2005 and 2010.

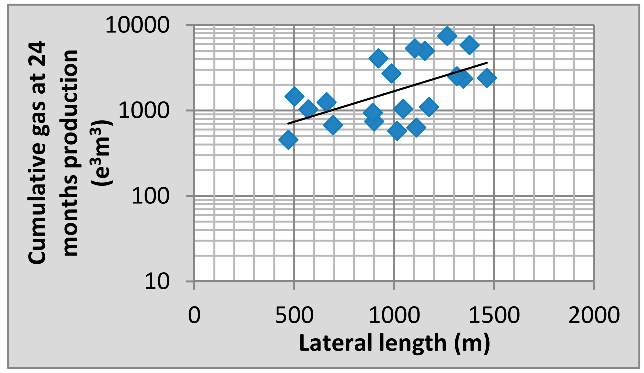

Figure 10. Cumulative gas production after 24 months for wells in the Muskwa–Otter Park shales in the Horn River Basin.

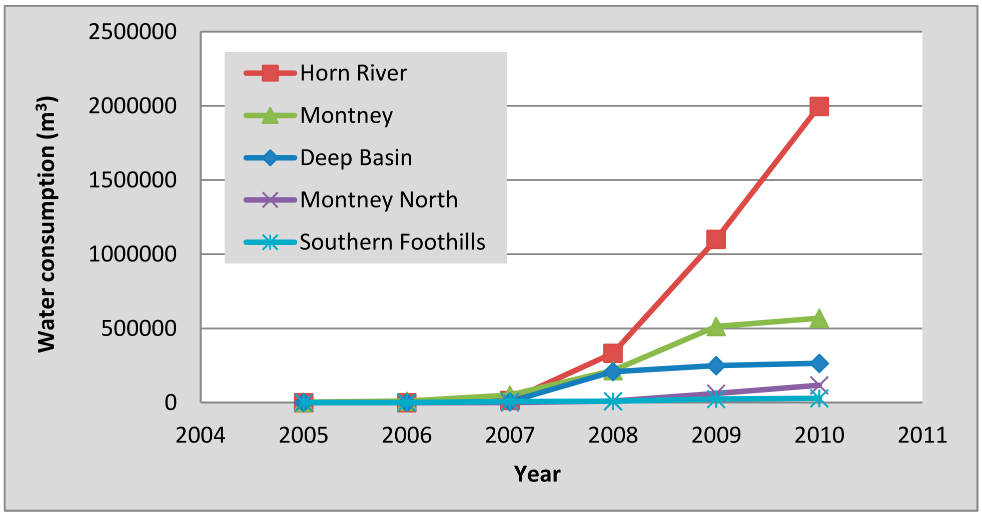

Figure 11. Cumulative water consumption by basin between 2005 and 2010.

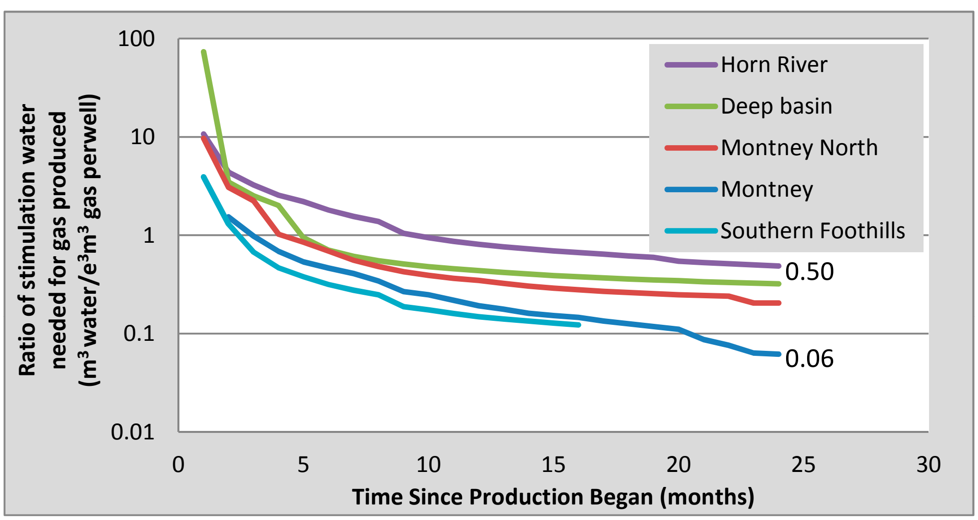

Figure 12. Average ratio by basin of the water initially required for hydraulic fracturing to develop every 1000 m^3 gas.

TABLE 6. CORRELATION COEFFICIENT (R2) BETWEEN GAS PRODUCTION RATES AND HYDRAULIC FRACTURING OVER THE FIRST FOUR MONTHS OF PRODUCTION. SIGNIFICANT CORRELATIONS, THOSE WITH AN R^2 VALUE MORE THAN 0.75 ARE HIGHLIGHTED IN BOLD TEXT.

Gas production for the first 4 months (e^3m^3/day)	Formation	Stimulation water per well (m^3)	Sand per well (T)	Number of frac stages
Energized	**Montney**	0.06	0.01	0
Energized Slickwater	**Nikanassin**	0.37	0.53	0.11
Slickwater	**Muskwa–Otter Park**	**0.83**	**0.82**	0.47
	Cadomin	0.51	0.68	0.34

TABLE 7. CORRELATION COEFFICIENT (R2) BETWEEN GAS PRODUCTION RATES AND HYDRAULIC FRACTURING AFTER TWO YEARS OF PRODUCTION. SIGNIFICANT CORRELATIONS, THOSE WITH AN R^2 VALUE OVER 0.75, ARE HIGHLIGHTED IN BOLD TEXT.

Gas production at 2 years (e^3m^3/day)	Formation	Stimulation water per well (m^3)	Sand per well (T)	Number of frac stages
Energized	**Montney**	0.01	0.06	0.02
Energized Slickwater	**Nikanassin**	**0.79**	0.4	0
Slickwater	**Muskwa–Otter Park**	**0.9**	**0.71**	0.31
	Cadomin	0.2	NA	0.06

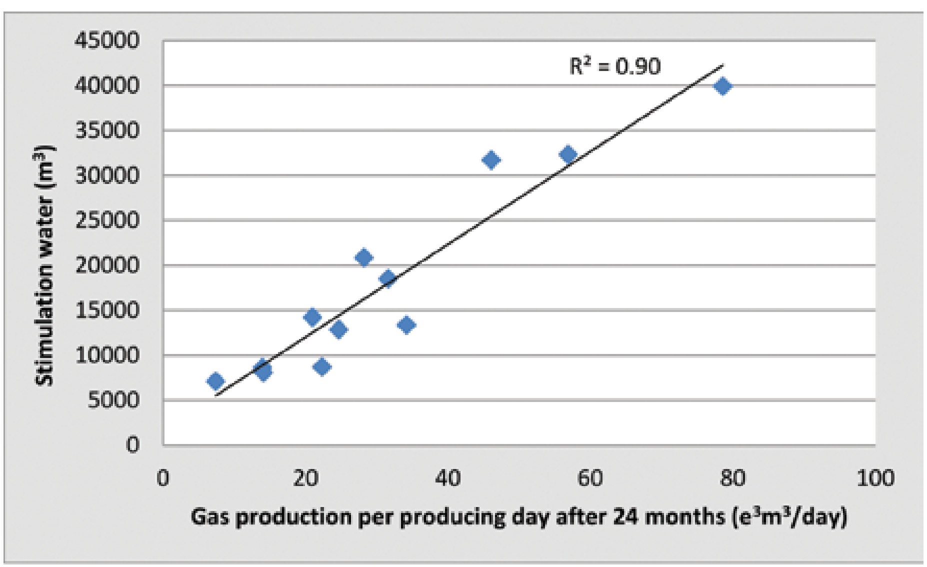

Figure 13. Relationship between stimulation volume for slickwater fractures in the Muskwa–Otter Park formation and later gas production after two years.

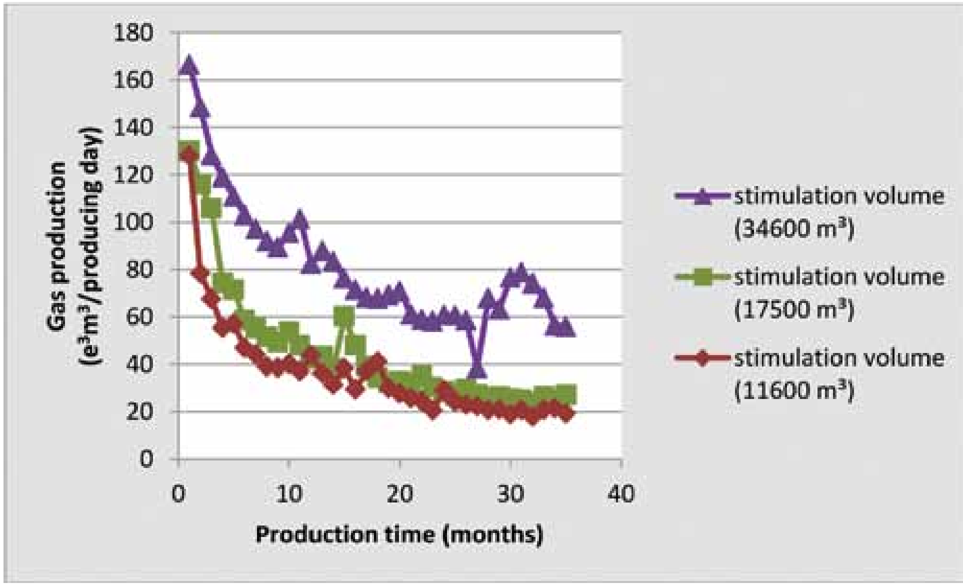

Figure 14. Representative production decline curves in the Muskwa–Otter Park shales for different stimulation volumes. Production curves are grouped according to the initial stimulation volumes as 11 600 m^3, 17 500 m^3 and 34 600 m^3, respectively.

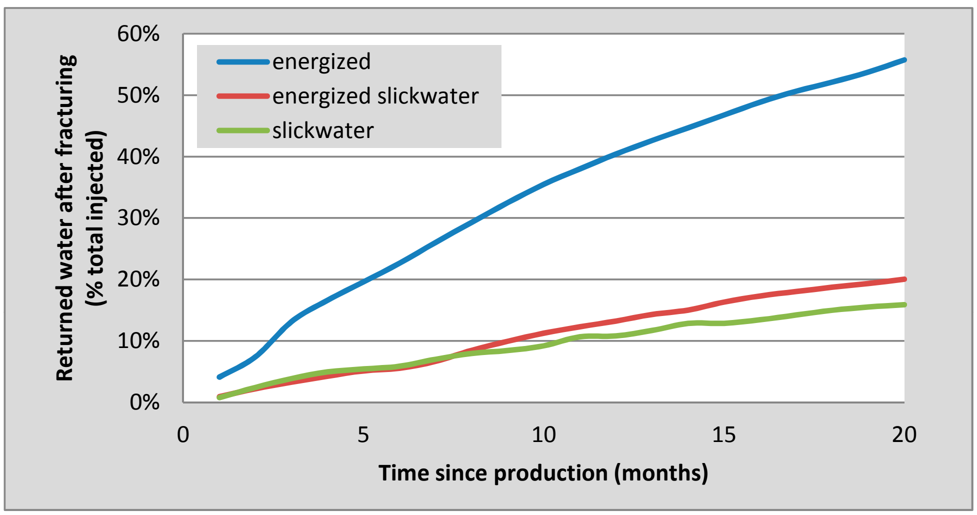

Figure 15. The rate of water return from hydraulic fracturing (as a percentage) over time, as categorized by fracture treatment type.

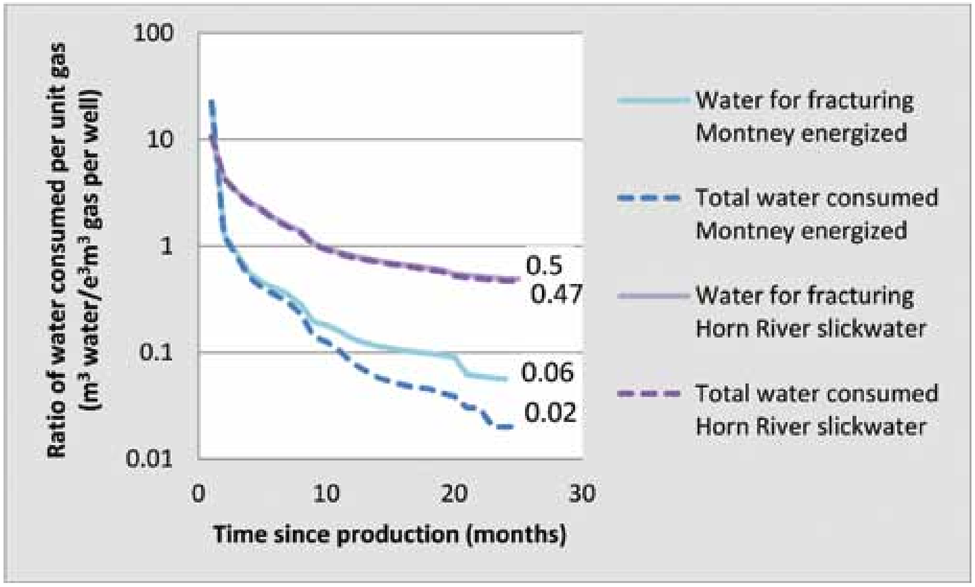

Figure 16. Water consumed to develop every 1000 m^3 gas for both the Montney trend and the Horn River Basin. The total water consumed is the initial water used for fracture stimulation less the return water.

(i.e., energized slickwater treatments) improved recovery slightly to 20%. The volume of return water for energized treatments was significant at 55% after 20 months. Data specific to energized wells in the Montney reveals that returned fluid exceeds 100% of that injected, which means that the returned water in the Montney Formation is a combination of both flowback fluid and produced water.

For the HRB, the ratio of the total water consumed per unit gas produced is not significantly different from the ratio of initial hydraulic fracturing water used for each unit gas produced (Fig. 16). This is because the return volumes are too low to mitigate overall consumption. Conversely, the small amount of water used for fracturing in the Montney (0.06 m^3 per unit gas) is substantially reduced by using return water (0.02 m^3 per unit gas). This metric of consumption becomes moot if saline water is used for fracturing.

DISCUSSION AND IMPLICATIONS

Water usage varies by basin (Fig. 17). The HRB and the Deep Basin have the highest water-use requirements; the Montney Basin has the lowest. This is expected, given the consistent use within each basin of their respective completion methods. Slickwater fractures are used for siliceous shale in the HRB and for sandstone and conglomerate across the Deep Basin (Table 1). By contrast, small amounts of water are needed for the energized fractures used in the softer siltstone and shale in the Montney Formation.

Despite the relatively small multistage hydraulic fracture database and disproportionate number of wells from the Montney Trend, available data from the other major basins were still sufficient to provide useful insight into some general trends in water usage in these basins. Data from the HRB and other more recent plays was limited because activity is more recent there and fracture information has not yet been entered and validated in the IRIS well database.

Montney Trend

Overall water usage for the Montney Trend was 1900 m^3 per well (Table 8). This volume fits well with other estimates in the literature (Dunk, 2010; Burke et al., 2011). This volume is consistent with water use in other basins that employ hydraulic fracturing. Fracture treatments in the Montney are primarily energized CO_2 treatments and generally have low water-use requirements.

The Montney showed trends of increasing the number of fracture stages (Fig. 6), fracture spacing (Fig. 8) and fracture length (Fig. 9); however, no overall correlation was found between gas production and any of these factors. It is unclear as to why this would be the case. Perhaps the production of condensates is driving the process. Subclassification of the data may better reveal trends and relationships.

The last finding of particular relevance to the Montney is the extent to which return water may influence consumption water. Energized wells in the Montney show returns of greater than 50% (Fig. 15). Returned water, if reused, could be an important factor in mitigating water demand for hydraulic fracturing in the Montney.

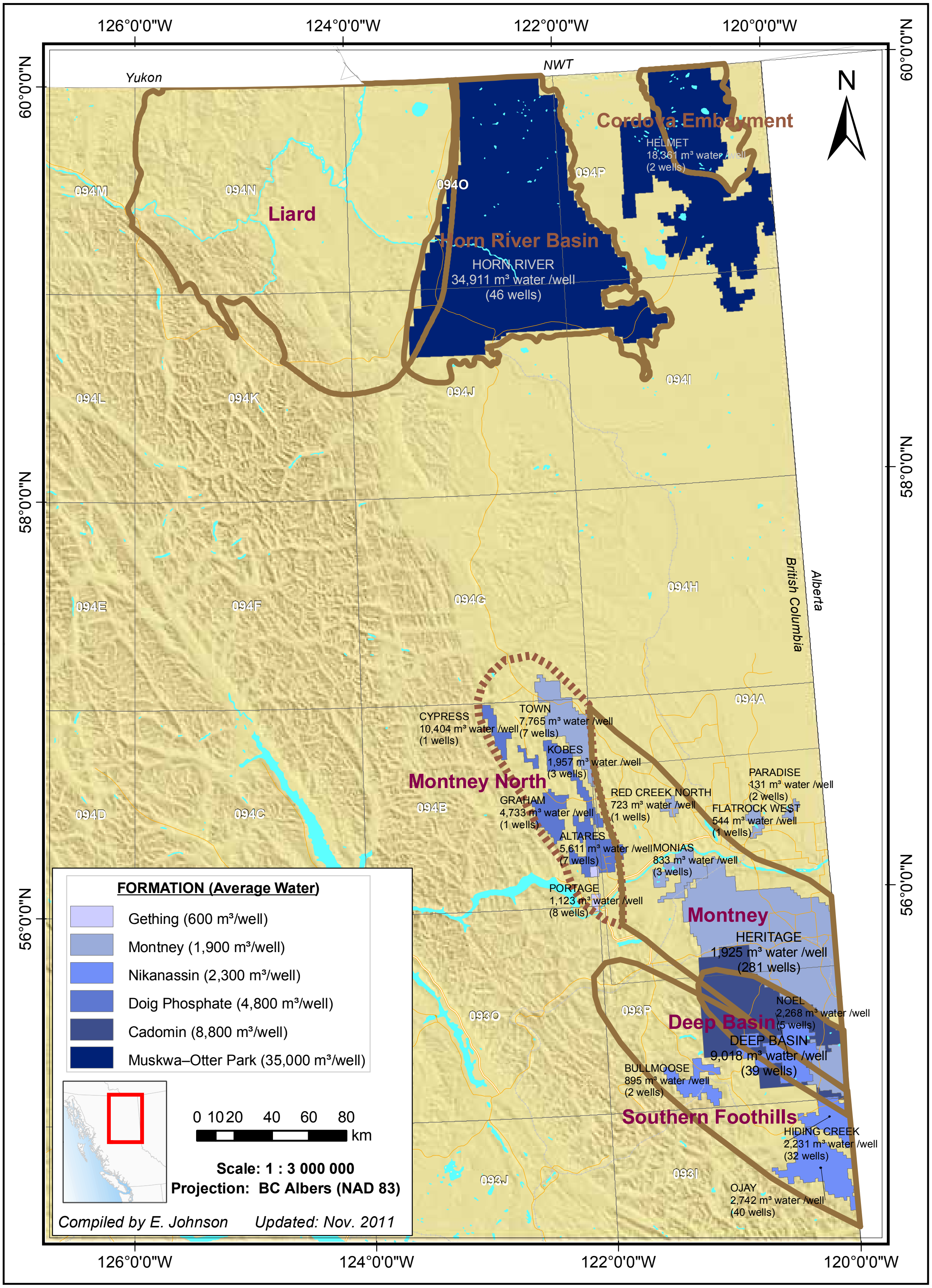

Figure 17. The formations being targeted in the five main basins. The water usage per well has been averaged by multistage wells in that formation and is represented by colours grading from light blue (lowest) to dark blue (highest).

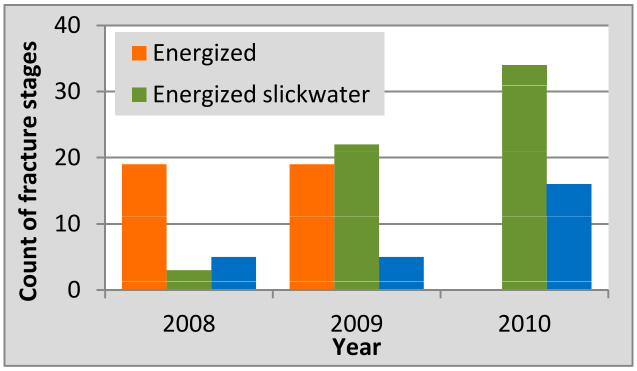

Figure 18. Montney North fracture treatment type as a function of time.

Horn River Basin

Overall water usage for the HRB was 30 000 m^3 per well (Table 8). This estimate is low because the average reflects the average of early wells that used few fractures with much smaller volumes. Still, the volume is an order of magnitude larger than that in the Montney. The primary reason for high water usage in the HRB is that high-volume slickwater treatments are almost exclusively used. Also, operators tend to have significantly more fracture stages per well. The trend in water usage has increased so sharply that average water per well value presented herein seems low.

The cumulative stimulation volume used for multi-stage wells in the HRB outpaced water consumption in the Montney Trend by 3.5:1 in 2010. The current trend for a high volume use in the HRB is expected to escalate because the best production is associated with wells that used the most water (Fig. 13, 14). Stimulation volume of water is a good proxy for stimulated reservoir volume, which means the more water used to fracture, the more gas produced. Further, water usage–related factors such as fracture length, number of completion stages and fracture spacing have not leveled off. Horizontal lengths in the Horn River Basin now extend up to 3 km (Stonehouse, 2011). Improvements in technology are enabling considerably more stages per well. Slickwater wells in the database have up to 28 stages but new OHMS technology allows for 40 to 60 stages per well. Service companies expect to be able to emplace more than 100 stages per well (Chandler, 2011; Themig, 2011).

Return water volumes are not likely to mitigate the need for increased stimulation water in the HRB. The rate of return water from slickwater wells is 17%. This rate of return is considerably less than the 30% indicated by Zelenev et al. (2010) and Burke et al. (2011). As a consequence, the volume of return water from slickwater operations in the HRB is unlikely to have a significant impact on water consumption rates.

The development of saline water resources is a potential source of water for gas-oriented fracturing operations in northeast British Columbia. Saline water can be substituted for freshwater in concentrations up to 100 000 ppm depending on the quality of the friction-reducing agent used (Blauch, 2010; Paktinat et al., 2011). Still, information is required to assess saline aquifer resources in the appropriate basins.

Montney North Trend

Overall, water use for the Montney North Trend was 5900 m^3 per well (Table 8). This value is considerably more than the 1900 m^3 per well determined for the Montney Trend. The reasons for this difference are that producers have different targets (the Doig Phosphate instead of the Nikanassin Group) and the Montney Formation is more shale rich in Montney North. Accordingly, different treatment types (with different water requirements) are needed to develop this region. Inconsistency in the treatment type across the basin may also reflect the fact that companies are still experimenting with treatment approaches in the region. Figure 18 shows the rapid shift in completion methods from energized towards slickwater.

Increasing water demand can be expected for the Montney North Trend as development in the region appears to be leaning towards both slickwater and energized slickwater fracturing. This evolution of treatment type in the Montney North has important implications for future expected water usage in the region because hybrid-energized slickwater treatments use five times the volume of water of energized treatments for every fracture stage (Table 5). Thus, the volume of water required to develop the Montney North could be more than an order of magnitude greater than the Montney Trend, depending on the completion method.

Deep Basin

Overall, water use for the Deep Basin was 9000 m^3 per well (Table 8). This basin has the second highest water usage for wells in northeast British Columbia (Fig. 17). The Cadomin Formation in the Deep Basin is not an unconventional shale gas target. The formation is composed of sandstone and conglomerate and has significantly lower pressures than other formations at similar depths. Given this geology, one would think that energized completions would be the treatment of choice. Instead, the trend in well completions here is towards slickwater fractures (Fig. 5).

The slickwater completions that have occurred in the Cadomin Formation have not been as effective as for those done in the more brittle Muskwa–Otter Park shales. Deep Basin operators use half the water per fracture stage compared to those in the HRB and show lower production rates (Table 8, Fig. 7). Development activity in the Deep Basin has not kept up with that in the HRB.

TABLE 8. AVERAGE WATER CONSUMPTION AND GAS PRODUCTION FOR SEVEN FORMATIONS IN NORTHEAST BRITISH COLUMBIA.

Formation	Region	Water per stage (m^3)	Main treatment type	Stages per well	Average water per wells (m^3)	Initial production rate (e^3m^3/day)	Main operator
MONTNEY	Montney	250	Energized	8	1900	90	Encana
	Montney North	1000	Variable	8	7800		Progress Energy
DOIG PHOSPHATE	Montney North	800	Variable	6	4800	32.4	Talisman Energy, Canbriam Energy
GETHING	Montney	40	Energized	10	400	0.5	Hudson's Hope Gas
	Montney North	90	Variable	12	1000		
		90	Variable	12	1000		
		90	Variable	12	1000		
	Southern Foothills	100	Slickwater	4	400		
MUSKWA–OTTER PARK	Horn River	2000	Slickwater	13	34900	27	Apache Canada
EVIE	Horn River	2100	Slickwater	10	19500	35.6	Stone Mountain Resources, EOG Resources
CADOMIN	Deep Basin	1100	Slickwater	9	8800	130	EnCana
NIKANASSIN	Montney	500	Variable	4	2100	97.5	Conoco Phillips
	Southern Foothills	500	Variable	6	2600		

Other basins

Little well data are available for the Cordova Embayment or the Liard Basin (Fig. 1). The geology of the Muskwa–Otter Park and Evie shales in the Cordova Embayment is similar to the HRB (Fig. 2). As such, one might expect that multistage slickwater fractures will be used in the Cordova Embayment. The Liard Basin is different in that several formations are likely to be drilled. The Besa River Formation contains some lateral equivalent to the HRB shale. The dominant completion method that will be used for development in the Liard is unclear at this time.

The Southern Foothills Nikanassin Group is composed of sandstone, siltstone, shale and coal. It has tight gas potential but is dissimilar from the other basins. The number of fracture stages per well is currently maintained at a low number. The approach to development at present seems somewhat experimental.

CONCLUSIONS

Research was undertaken on the multistage wells developed between 2005 and 2010 in northeast British Columbia. Wells with more than three hydraulic fractures were evaluated in terms of stimulation volume used, proppant required, the number of fractures, types of fractures, production, geographic distribution and geological factors.

Findings showed that water usage varied by basin with strong differences originating from the stimulation treatment method used. In general, the geology of the basin determines fracture treatment. High-volume water use is not limited to multistage fracturing of brittle shale in the HRB; it is also used to develop sandstone and conglomerate in the Deep Basin south of Dawson Creek. Even a small number of slickwater wells can substantially alter the cumulative water usage in a basin far more than a large number of energized wells. Increased stimulation volume greatly increased the estimated ultimate recovery from slickwater wells in the Muskwa–Otter Park shales in the HRB. This is driving water demand in the HRB.

Implications from the research are that water demand can be anticipated regionally through basin geology, treatment style for fracture stimulation and local trends in the numbers of completions per well. High water demand associated with multistage fracturing is not limited to shale basins but includes other geological settings. The location of high-volume wells is important in assessing regional water demand. These wells should be monitored closely because a few wells can make a large impact on cumulative water consumption. Data backlogs for the IRIS database could severely hamper trend analysis and prediction efforts. Water volume per well is dynamic and could rapidly vary by more than an order of magnitude with a subtle shift in technology. Greatly increased water demand is anticipated in the HRB. By extension, high water demand is also anticipated in the Cordova Embayment and Montney North Trend.

RECOMMENDATIONS

- Recommendation 1: Improved access to current well data and ongoing monitoring of well data on a basin-specific basis.[1] Priority to be given to the HRB and Montney North Trend, where water-use trends are escalating. The Montney North Trend should continue to be treated as a separate region from the Montney Trend to elucidate differences in water usage.
- Recommendation 2: Prioritization of research concerning identification of saline water sources for areas such as the HRB and Montney North, where high-volume water fracturing is occurring.
- Recommendation 3: Use of HRB water-usage estimates as a guide to potential water demand for Montney North, the Cordova Embayment, the Deep Basin and Liard regions until more information is known.

[1] Improved access includes up-to-date input validation of well data.

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POTENTIAL FOR FRESHWATER BEDROCK AQUIFERS IN NORTHEAST BRITISH COLUMBIA: REGIONAL DISTRIBUTION AND LITHOLOGY OF SURFACE AND SHALLOW SUBSURFACE BEDROCK UNITS (NTS 093I, O, P; 094A, B, G, H, I, J, N, O, P)

Janet Riddell[1]

ABSTRACT

Freshwater bedrock aquifers are hosted almost entirely by Cretaceous strata in northeast British Columbia. The most important prospective regional bedrock units for freshwater aquifers are the coarse clastic Cenomanian Dunvegan and Campanian Wapiti formations. Much of the Lower Cretaceous Fort St. John Group and the Upper Cretaceous Kotaneelee, Puskwaskau and Kaskapau formations are dominated by shale strata and generally behave as regional aquitards, but locally contain members that may host aquifers, including fractured shale sequences and coarse clastic intervals. In the Peace River valley, some of these aquifers are well known, but outside that region, hydrogeological data are sparse and many aquifers remain to be formally identified and delineated. Hydrocarbon exploration activity is occurring in new areas because of shale gas development. New exploration will generate lithological and geochemical data from areas where data is currently sparse, and will significantly improve our knowledge about the hydrostratigraphy of Cretaceous clastic units across northeast British Columbia.

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Key Words: Fresh water, Bedrock aquifers, Groundwater, Northeast British Columbia, Cretaceous, Jurassic, Dunvegan Formation, Wapiti Formation, Unconventional gas, Shale gas, Fort St. John Group, Kotaneelee Formation, Puskwaskau Formation, Kaskapau Formation, Montney, Horn River Basin, Bullhead Group, Cadomin Formation

INTRODUCTION

Bedrock aquifers are an important source of fresh water in British Columbia. The recent expansion of shale gas development in northeast British Columbia has significantly increased the demand for water in this region. In response, the British Columbia Ministry of Energy and Mines (MEM) has initiated several groundwater studies, including this study, which is a preliminary investigation of potential aquifer-hosting bedrock formations in the zone between 600 m depth and surface.

The MEM and its collaborators, the British Columbia Oil and Gas Commission (OGC) and Geoscience BC (GBC), are undertaking complementary water studies in British Columbia's natural gas–producing regions. Hayes (2010) and Hayes et al. (2011) evaluated deep saline aquifers in the Horn River Basin and the Montney play for their capabilities to produce the volumes of water necessary to support completions and to accept spent hydraulic fracturing (flow-back) fluids by deep well injection. Brown (2011) reported on the Montney Water Project, a GBC-sponsored collaboration that included projects directed at aquifer mapping and classification (Lowen, 2011), surficial mapping compilation (Hickin and Fournier, 2011) and delineation of paleovalleys that may host unconsolidated aquifers (Hickin, 2011). Wilford (2012) and Hickin and Best (2012) are expanding on this work in the Dawson Creek area.

In British Columbia, drilling and production regulations under the Oil and Gas Activities Act (2010) protect nonsaline groundwater by prohibiting hydraulic fracturing above 600 m depth and stipulates that surface casing must be set to a base of known fresh groundwater aquifers or to a depth of 600 m. The 600 m protection datum is conservative but necessary in the absence of an adequate database. Freshwater supply wells are rarely drilled to depths greater than 150 m. Drilling costs increase with depth; at depths greater than 150 m, other water sources become more cost effective.

Most of the oil and gas–producing region of northeast British Columbia is underlain at the surface and shallow subsurface (i.e., less than 600 m depth) by Cretaceous clastic sequences (Fig. 1) that were deposited along the western margin of the Western Canadian Sedimentary Basin (Irish, 1958; Stott and Taylor, 1968a, b; Stott, 1975, Thompson, 1975a–c; Taylor, 1979; McMechan 1994; Taylor and Stott, 1999). These Cretaceous units represent the primary target horizons for freshwater resource exploration. Oil and gas exploration target horizons occur at depths generally between 1000 and 2500 m and range in age from the Devonian to the earliest Late Cretaceous (Table 1). On the plains of northeast British Columbia, the structural geology is relatively simple, consisting of near-horizontal sedimentary strata. In the Rocky Mountain Foothills, the geology is more complex and pre-Cretaceous rocks occur at the surface as a result of uplift, folding and faulting along the deformation front (Taylor, 1972; Cecile et al., 2000; Hinds and Cecile, 2003). Pre-Cretaceous rock units occur at the surface at a few of the westernmost gas-producing fields and may host local aquifers.

This report identifies data sources and previous work that provide tools for freshwater resource exploration and describes characteristics of shallow (<600 m) bedrock units in terms of their predicted hydrostratigraphic properties (i.e., aquifer versus aquitard), lithology and distribution. Major widespread units are described first, followed by discussion of units of limited distribution grouped according to the specific geographic regions (Fig. 1 inset) where they occur.

PREVIOUS WORK AND DATA SOURCES: TOOLS FOR FRESHWATER RESOURCE EXPLORATION, MANAGEMENT AND PROTECTION

Five significant sources of information are available for shallow subsurface geology and water chemistry in northeast British Columbia: previous aquifer studies, surface geology maps, detailed stratigraphic studies of specific geological formations, water well logs and oil and gas exploration well records.

Previous aquifer studies

Mathews (1950, 1955) conducted preliminary investigations in the Peace River District for groundwater prospects for domestic and agricultural use. Mathews (1950) identified several surficial and bedrock-hosted aquifers and provided general comments about their yields and water quality. Mathews (1955) defined six physiographic units in the district and assessed their groundwater prospectivity. Ronneseth (1983) and Cowen (1998) compiled quantitative data on water well yields and water quality from surficial and bedrock-hosted aquifer units in the Peace River valley and commented on local and regional trends. Both noted that bedrock aquifers generally have lower water yields and quality than surficial aquifers, and that quality tends to be poorer on the plains and better in the Rocky Mountain Foothills. Lowen (2004, 2011) identified, delineated and classified developed aquifers in the Peace River region. Jones (1966), Barnes (1977), Hitchon (1990) and Bachu et al. (1993) conducted hydrogeological studies in correlative strata in the Peace River valley in adjacent Alberta.

Groundwater monitoring and aquifer classification studies are conducted by the British Columbia Ministry of Environment (MoE; http://www.env.gov.bc.ca/wsd/index.html). Aquifer classification mapping and classification is prioritized for regions with high domestic, agricultural and commercial water demands, especially where surface water supplies are restricted due to dry climate or low relief (for example, the Gulf Islands and the Okanagan Valley). Aquifers are classified according to their level of development and vulnerability to contamination (Berardinucci and Ronneseth, 2002; British Columbia Water Resources Atlas, 2012). In northeast British Columbia, the aquifers that have been delineated and classified to date are located in the Dawson Creek and Fort St. John areas. There are certainly many more bedrock aquifers throughout the rest of northeast British Columbia that have yet to be formally delineated because of data scarcity and previous relatively low demand. There is likely local and corporate knowledge about many of them among drillers and users.

Surface geology maps

The distribution of major geological units in the shallow subsurface can be predicted using bedrock geology maps. Bedrock geology mapping conducted by the Geological Survey of Canada is available for the all of northeast British Columbia at 1:250 000 scale (Irish, 1958; Stott and Taylor, 1968a, b; Taylor, 1972; Thompson, 1975a–c; Stott and Taylor, 1979; Taylor, 1979; Stott et al., 1983; McMechan, 1994; Taylor and Stott, 1999) and other regional scales (Cecile et al., 2000; McMechan, 2000; Okulitch et al., 2002). This mapping is compiled at the provincial scale on the British Columbia Ministry of Energy and Mines MapPlace website (MapPlace, 2012). The MapPlace compilation was used to construct Figure 1. Cretaceous rock units on Figure 1 are coloured to reflect their predicted potential to host aquifers.

Stratigraphic studies

Detailed stratigraphic studies on specific formations are abundant (for example, Fanti and Catuneanu [2010] for the Wapiti Formation, Hay and Plint [2009] for the Dunvegan Formation and many others referenced below). These studies can be valuable exploration tools as they provide descriptions of mappable markers in outcrop and in subsurface gamma-ray logs.

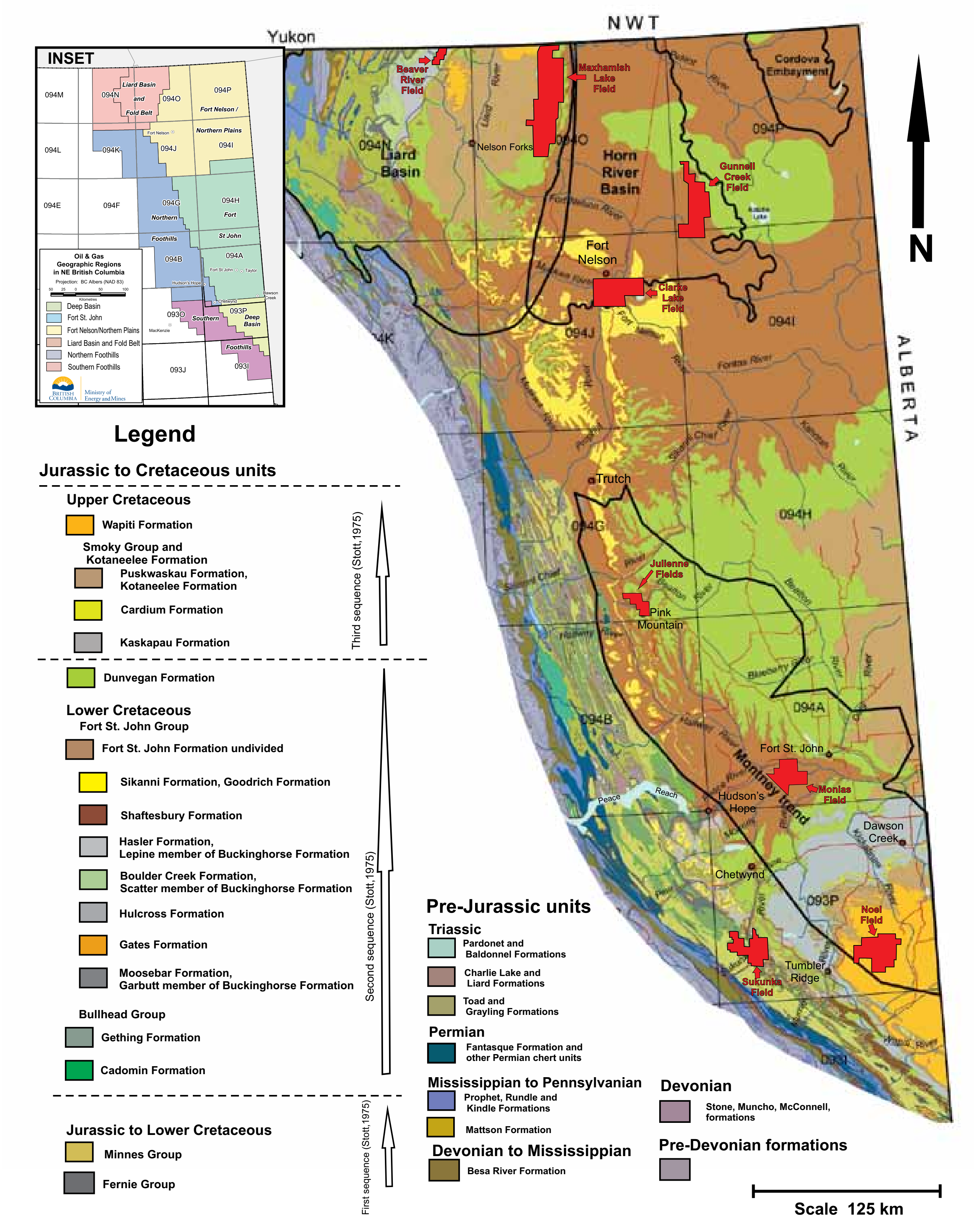

Figure 1. Bedrock geology map compilation of northeast British Columbia. Cretaceous bedrock units are coloured according to their predicted aquifer characteristics. Coarse clastic formations that can be expected to host aquifers are brighter hues of yellow, orange or green. For contrast, dominantly shaly formations that are expected to form aquitards are coloured dull grey or brown. The same colour scheme is used for Figure 2 and Table 1. The Montney trend and the Horn River Basin are active regions for shale gas development. The Liard Basin and the Cordova Embayment have shale gas potential. These regions overlap many conventional oil and gas plays. Digital geology base map by Massey et al. (2005). Inset: oil and gas geographic regions in northeast British Columbia (Adams, 2009).

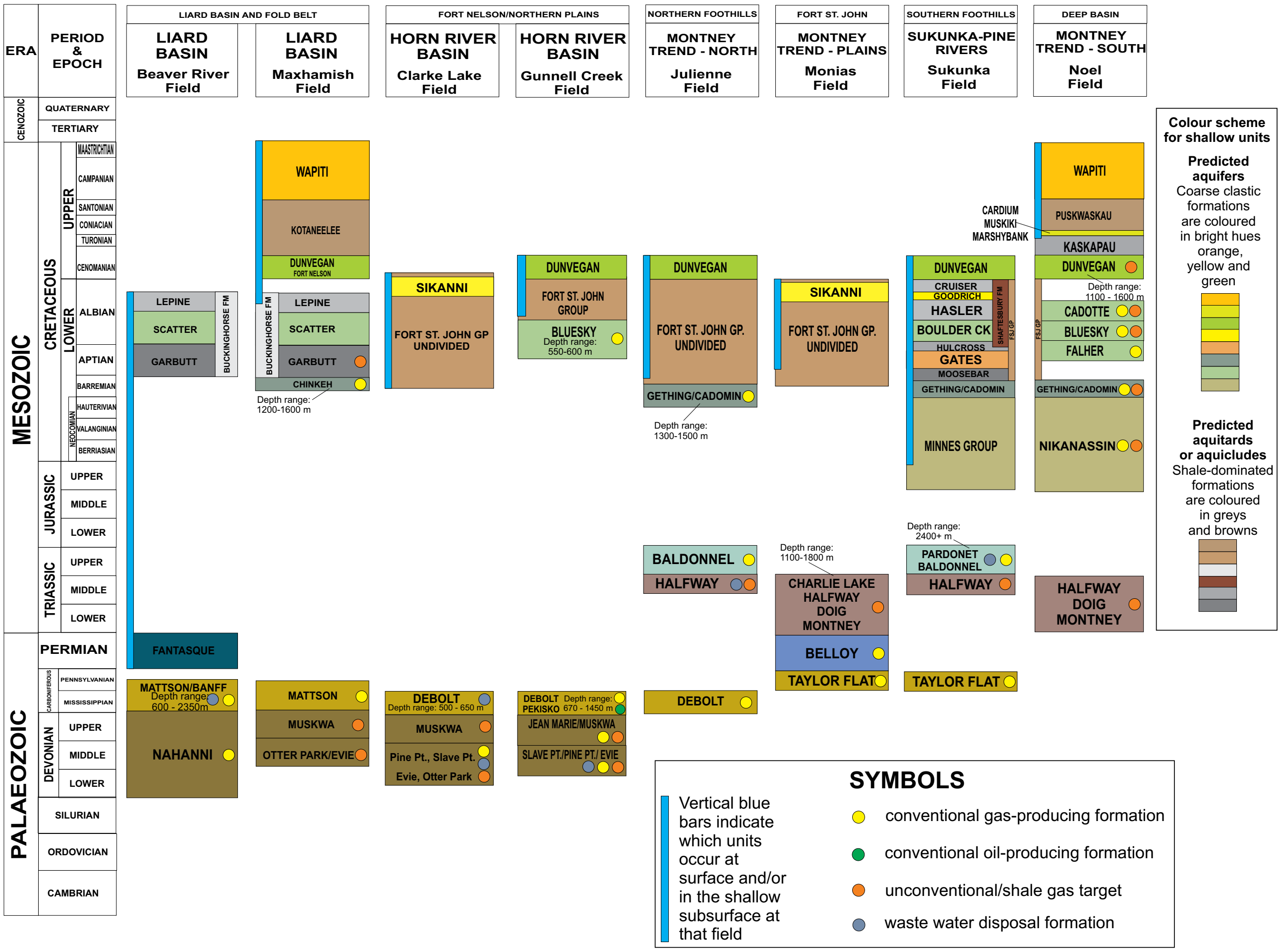

Table 1. Table of formations at eight selected gas fields in northeast British Columbia. Locations of selected gas fields are shown in red on Figure 1. Units occurring at surface or in the shallow subsurface are shown by a blue vertical bar. For reference, the target gas, oil or water disposal formations at the various fields are noted with coloured dots and the depth range of the shallowest producing formations are noted. Information on the target formations and their depths were determined using AccuMap® and geoSCOUT®. Sources: Stott (1975); British Columbia Ministry of Energy and Mines (2012).

Water well logs

Historical demand and exploitation dictates the level of knowledge of the aquifer characteristics for a particular geological formation. The WELLS online searchable database for British Columbia (British Columbia Ministry of Environment, 2012b), and its linked spatial counterpart, the British Columbia Water Resources Atlas (2012), are repositories for voluntarily submitted water well information, maintained by the British Columbia Ministry of Environment (MoE). These databases host valuable data for the Peace River region (including the southern end of the Montney trend) from water wells drilled for domestic, agricultural, municipal and industrial use.

Oil and gas exploration logs

At the time of this publication, more than 22 000 oil and gas exploration wells have been drilled and logged in northeast British Columbia. Exploration well logs include a wealth of subsurface geological, geochemical and geophysical data and are publicly available after a confidentiality period.

HYDROSTRATIGRAPHY OF JURASSIC AND CRETACEOUS GEOLOGICAL FORMATIONS IN NORTHEAST BRITISH COLUMBIA

The vast majority of freshwater bedrock aquifer potential in the oil and gas–producing regions of northeast British Columbia is hosted in Cretaceous coarse clastic units. Stott (1975) provides a summary of the development of three major Mesozoic clastic sequences, each formed by a major transgressive-regressive cycle. The lowest sequence includes marine shale of the Jurassic Fernie Formation, overlain by coarse clastic sediments of the Jurassic to Lower Cretaceous Minnes Group. Erosion preceded deposition of the second cycle, which includes Lower Cretaceous to early Cenomanian marine and nonmarine clastic rocks of the Bullhead and Fort St. John groups and the Dunvegan Formation. The third sequence includes mainly marine strata of the Smokey Group, deposited during major transgressions during the Turonian and Santonian stages of the Late Cretaceous, succeeded by mainly nonmarine coarse clastic sediments of the Campanian to Maastrichtian Wapiti Formation.

At a regional scale, coarse clastic regressive sequences (Bullhead Group, Dunvegan and Wapiti formations) can be viewed as potential aquifer hosts, and the marine shale units (Fort St. John Group, Kaskapau, Puskwaskau and Kotaneelee formations) as aquitards or aquicludes. Generalizations about aquifer characteristics at the formation scale, however, are not sufficiently accurate for groundwater exploration purposes because none of the Cretaceous formations is lithologically homogeneous. Within the three major, basin-wide regressive-transgressive cycles, many minor and spatially constrained cycles occurred. All of the coarse clastic formations contain shale members, and all of the shale formations contain continuous or lensoid coarse clastic members. In addition, fracture enhancement of porosity is seen in both shale and coarse clastic formations, producing local aquifers.

Major regional units

FIRST SEQUENCE: FERNIE–MINNES

Fernie Formation

The Jurassic Fernie Formation forms a significant regional aquitard (Bachu, 2002) in the Canadian Cordillera. It is an important marine shale unit that represents a major transgressive phase (Stott, 1975). The measured thickness of the Fernie Formation is highly variable due to its recessive character and its deformed nature. It generally does not exceed 300 m, but is reported to reach a thickness of 900 m in the western Rocky Mountain Foothills (Stott, 1975). The Fernie Formation has a limited extent at surface and in the shallow subsurface east of the deformed belt, but is present at shallow depths at the Murray gas field in the Southern Foothills (NTS 093I) and the Elbow Creek field north of the Halfway River (Fig. 1).

Minnes Group

The Late Jurassic to Early Cretaceous Minnes Group is a regressive sequence overlying the Fernie Formation that includes marine and nonmarine sandstone formations that may form small discontinuous aquifers. In British Columbia, the Minnes Group comprises the Monteith, Beattie Peaks, Monach, Bickford and Gorman Creek formations. The Minnes Group is exposed in the Rocky Mountain Foothills as far north as the Halfway River and is up to 2100 m thick (Stott, 1975). Minnes Group rocks are present at surface and in the shallow subsurface at the Brazion, Bullmoose, Murray, Burnt River and Sukunka fields of the Southern Foothills (NTS 093O, P), and at the Federal field and part of the Sikanni field in the Northern Foothills (NTS 094B and 094G, respectively). Minnes Group formations are age-equivalent to the Nikannassin Formation in the subsurface of the Peace River and Athabasca River regions.

After deposition of the Minnes Group, the sea retreated from the Alberta trough and extensive erosion and bevelling of the Fernie and Minnes groups occurred before deposition of the succeeding Bullhead Group (Stott, 1975).

SECOND SEQUENCE: BULLHEAD–FORT ST. JOHN–DUNVEGAN

Bullhead Group

The Bullhead Group was deposited in an alluvial-deltaic environment from Barremian to early Albian time (Stott, 1975). It includes a massive conglomerate of the Cadomin Formation and a coal-bearing sandstone of the Gething Formation. Both the Cadomin and the Gething formations have potential to host aquifers along the Rocky Mountain Foothills from the upper Halfway River (NTS 094B) to the British Columbia–Alberta border south of the Wapiti River (NTS 093I). The Bullhead Group correlates with the Lower Mannville aquifer of the southern Alberta plains (McLean, 1977).

The Cadomin Formation is dominantly a coarse (gravel to cobble) nonmarine conglomerate. Much of the Cadomin was deposited on a pediment surface (Stott, 1975; McLean, 1977) as a single thin conglomerate bed, resulting in a distinctive contiguous bed that forms an important marker throughout the Rocky Mountain Foothills. The Cadomin Formation ranges from 30 to 150 m in thickness in British Columbia.

The Gething Formation includes conglomerate, sandstone, siltstone and mudstone. It is dominantly nonmarine but includes marine members (Legun, 1990). It is generally coarser in the Peace River area and it thins and grades to finer sandstone and mudstone to the northeast. Its maximum thickness of 600 m (Stott, 1975) is found in the Southern Foothills, where it is an important coal-bearing unit.

The Cadomin and Gething formations are present at surface and in the shallow subsurface at the Pocketknife, Sikanni, Elbow Creek, Cypress and Federal fields at the north end of the Montney trend in the Northern Foothills, and at the Butler, Boulder, Brazion, Burnt River, Highhat Mountain, Sukunka, Bullmoose West and Murray fields of the Southern Foothills.

Along the east side of the northern Montney trend (for example, at the Julienne field (Table 1) the Gething and Cadomin formations are deeper and can be gas charged. On the plains, the formations of the Bullhead Group are too deeply buried to be freshwater exploration targets. The Cadomin Formation is a gas producer at the Cutbank field south of Swan Lake (NTS 093P) and in western Alberta. The age-equivalent Chinkeh Formation in the Liard River area is an important gas-producing unit in the Maxhamish field. The Gething Formation has been identified as a potential hydrocarbon target deep in the subsurface of the Kahntah River region, where its good reservoir properties are documented by Gingras et al. (2010).

Fort St. John Group

The Fort St. John Group is dominated by shale formations that record four transgressive events that occurred through Albian time (Stott, 1975). Regionally, much of the Fort St. John Group correlates with the Wilrich, Harmon and Shaftesbury aquitards of Alberta (Jones, 1966; Bachu, 2002). Other parts of the group include sandstone and siltstone formations that correlate with the Upper Mannville and Paddy aquifers.

Three aquifers hosted by rocks of the undivided Fort St. John Group in the Peace River valley (aquifers 765, 928 and 934) are delineated in the British Columbia Water Atlas and are described in detail by Lowen (2011). It is not clear in every case whether the water is produced from fractured shale, from sandstone formations or from both. Mathews (1950) and Cowen (1998) both noted that some shale units of the Fort St. John Group in the Peace River block produce sufficient water yields for commercial or agricultural use, and that water quality from shale beds tends to be poor due to high levels of dissolved salts and low levels of infiltration of fresh meteoric water. Available data on yields and water quality from sandstone units in the Fort St. John Group are mainly from the Peace River block (Mathews, 1950; Ronneseth, 1983; Cowen, 1998; Lowen, 2011) and are discussed in more detail below.

The Fort St. John Group lies above the Bullhead Group and below the Dunvegan Formation throughout most of northeast British Columbia. Where exposure is adequate, intervening coarse clastic units document regressive events within the dominantly shaly Fort St. John Group and allow for its subdivision into many formations. Formation nomenclature varies across northeastern British Columbia (Irish, 1958; Stott and Taylor, 1968a, b; Taylor, 1972; Stott and Taylor, 1979; Taylor, 1979; Stott et al., 1983; McMechan, 1994; Taylor and Stott, 1999; Cecile et al., 2000). Stott (1975) concisely illustrated the variation in nomenclature of the Fort St. John Group (and other Jura-Cretaceous formations) across northeast British Columbia with a series of formation tables and schematic cross-sections. One of these cross-sections is reproduced here (Fig. 2); it crosses northeast British Columbia from northwest (Liard River area) to southeast (Athabasca River in northeast Alberta). The image is coloured to match Figure 1 and Table 1 of this report. A helpful table of Fort St. John Group formations across northeast British Columbia and Alberta is provided by Leckie et al. (1994). Where outcrop is scarce or where shale units cannot be confidently distinguished, the undivided Fort St. John Group is mapped as a single unit (Fig. 1, 2, Table 1; Thompson, 1975a–c). This can cause border inconsistencies on large compilation maps (for example, Fig. 1; Okulitch et al., 2002).

Dunvegan Formation

The Dunvegan Formation is a widespread coarse clastic unit in northeastern British Columbia (Fig. 1) and northwestern Alberta, where it is the host for many bedrock aquifers (Mathews, 1950; Jones, 1966; Ronneseth, 1983; Cowen, 1998). The Dunvegan Formation is the most used bedrock aquifer host because it underlies the relatively populated Peace River valley and has supplied water demands from agriculture, communities and conventional oil and gas operations. Lowen (2011) delineated 12 aquifers hosted by the Dunvegan Formation in the Peace River valley. In that report, several hundreds of well records were examined and an average well yield of 0.6 L/s (9.5 gpm) was determined for Dunvegan-hosted wells. Lowen noted that the Dunvegan Formation is more productive in general than fractured shale units, and that in some locations the primary porosity is further enhanced by fracture porosity. One such enhanced well near Chetwynd can produce up to 14.3 L/s (227 gpm).

The Dunvegan Formation was deposited in Cenomanian time under terrestrial and shallow coastal marine conditions, including coastal plain, delta, lacustrine and fluvial environments. In British Columbia, the dominant lithology of the Dunvegan Formation is sandstone, except in the Liard River area, where it is commonly conglomeratic. The Dunvegan Formation ranges in thickness from approximately 170 m in the north along the Yukon border to approximately 270 m in the Southern Foothills between the Peace and Pine rivers (Stott, 1975). Mathews (1950) noted that the water quality from Dunvegan aquifers in the Peace River valley is highly variable, and that it generally deteriorates with depth. Water from deeper wells can be too saline for domestic or livestock use. Cowen (1998) observed that in the Peace River valley, the Dunvegan Formation hosts aquifers that yield satisfactory quality and quantities of groundwater; however, the productive zones are not laterally extensive and are commonly greatly vertically separated. This is likely to be the case with the Dunvegan Formation outside the Peace River valley as well, given the variety of depositional environments (i.e., fluvial channel, paleovalley, delta fronts, shallow coastal plains and minor marine transgressions) represented by the unit. This lateral and vertical variability is well described and illustrated by

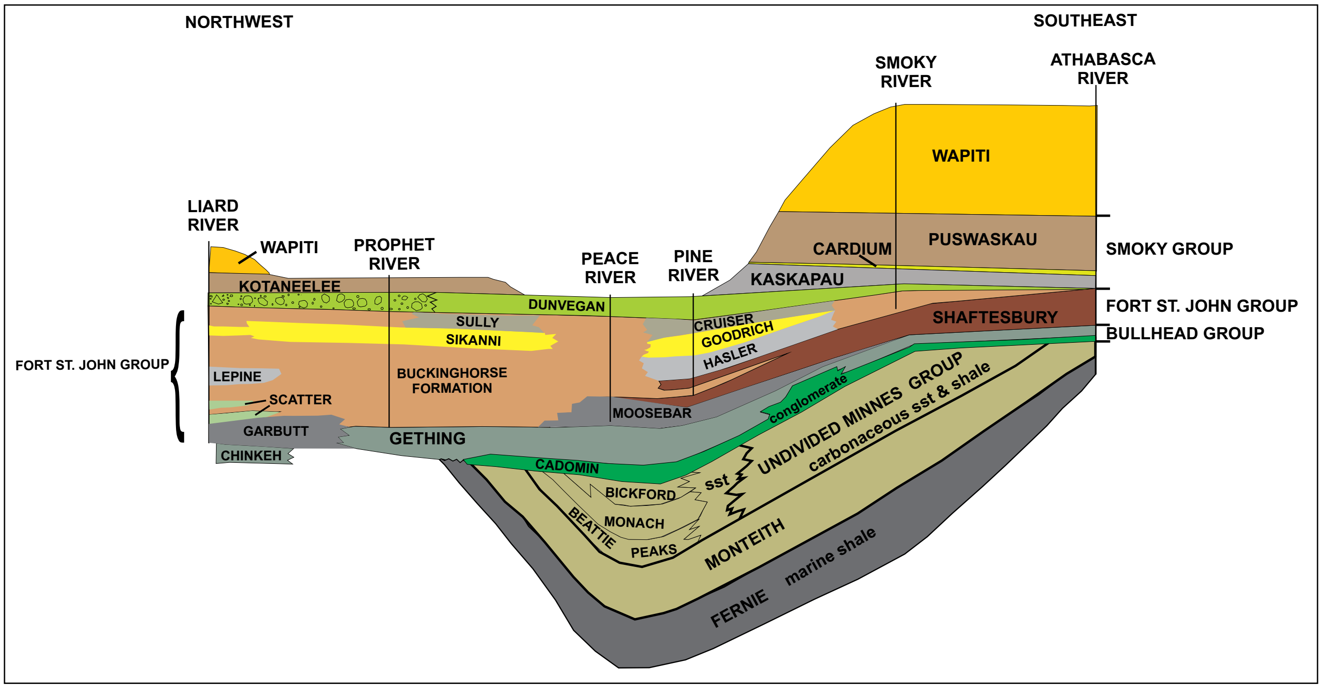

Figure 2. Schematic cross section of Stott (1975) from the Athabasca River (northwest Alberta) to the Liard River (northeast British Columbia). Colours have been added to the original figure to conform to Figure 1 of this report.

Bhattacharya (1994) and Hay and Plint (2009). This textural heterogeneity will likely make the Dunvegan Formation a difficult groundwater exploration target, especially in new areas where previous data and drilling experience are limited. Yields are likely better and more consistent in the Dunvegan Formation of the Liard and western Horn River basins, where it was deposited chiefly in alluvial fan environments and is more uniformly conglomeratic (Stott, 1975; Bhattacharya, 1994).

Hay and Plint (2009) provide descriptions and subsurface geophysical signatures of distinct Dunvegan Formation allomembers in Alberta and the Peace River area of British Columbia. These may prove to be useful for exploration elsewhere in northeast British Columbia.

The Dunvegan Formation is at or near surface over a vast area of northeast British Columbia (Fig. 1), including much of the Liard Basin between Toad River and Highway 77 (at the Maxhamish and Windflower fields), along the east side of the Horn River Basin to Kotcho Lake (for example, the Ootla, Gote, Cabin, Kotcho Lake, Tooga and Desan fields), at the oil and gas fields in much of the Sikanni Chief, Beatton and Blueberry and Doig watersheds, along the northeast flank of the Montney trend north of Fort St. John (from the Fort Wilder to Julienne Creek North) and along the Pine River (e.g., Groundbirch, Sunset Prairie, Septimus, Saturn, Tower Lake and Parkland fields).

In the Deep Basin region, the Dunvegan Formation is not prospective for fresh water; it is buried to depths greater than 600 m and is locally gas charged (Table 1).

THIRD SEQUENCE: SMOKY–KOTANEELEE–WAPITI

Smoky Group and Kotaneelee Formation

The Late Cretaceous Smoky Group represents mainly marine deposition that began the third major transgressive-regressive sequence in northeast British Columbia (Stott, 1975). Potential aquifer host formations locally occur within these marine shale-dominated sequences, particularly in the Deep Basin region (Fig. 1 inset).

The Smoky Group ranges in age from late Cenomanian to Campanian and is widely exposed at surface in northeast British Columbia. The Smoky Group includes two main marine shale units: the Turonian to Coniacian Kaskapau Formation and the Santonian Puskwaskau Formation, interrupted by intertidal and shallow marine sandstones (Stott, 1975), including the Cardium, Pouce Coupe, Doe Creek and Marshybank formations. In the Fort St. John and Liard areas, the Kotaneelee Formation (approximately equivalent to the Puskwaskau) marine shale is deposited directly on the Dunvegan Formation (Fig. 2); there, the first marine shale (Kaskapau Formation) and the intervening sandstone units are not preserved. Formations of the Smoky Group and Kotaneelee Formation are described in more detailed below in the Discussion.

Wapiti Formation

The youngest bedrock unit exposed at surface in northeast British Columbia is the Wapiti Formation. The Wapiti Formation is known to host aquifers in the Clayhurst and Kelly Lake (aquifers 444 and 621; British Columbia Water Resources Atlas, 2012) areas in British Columbia (Lowen, 2011) and in the Peace River region of Alberta (Jones, 1966). It has potential to host aquifers where it occurs elsewhere, including the Tupper Creek, Cutbank, Kelly, Noel, Hiding Creek and Noel gas fields in the Deep Basin, and in parts of the Maxhamish field in the Liard Basin.

Lowen (2011) reports generally moderate yields (up to 3.1 L/s or 50 gpm) in the Clayhurst and Kelly Lake aquifers. In the Mount Robson–Wapiti plains area of Alberta, Barnes (1977) noted a decrease in well yields from the Wapiti Formation in a southwest direction from the plains toward the disturbed belt, possibly due to the destruction of intergranular porosity by increased low-grade metamorphism associated with regional tectonism. Jones (1966) reported both intergranular and fracture permeability in Wapiti Formation–hosted aquifers in the Peace River District of Alberta, and water yields ranging from 0.3–6.3 L/s (5–100 gpm). Jones observed irregular aquifer distributions and abrupt variations in yields laterally and vertically in individual sandstone units within the Wapiti in the Peace River area of Alberta, possibly because porous zones are not planar, but are lens-shaped beds and channel deposits. Both Barnes (1977) and Lowen (2011) reported spot high iron concentrations in the water from Wapiti Formation water wells.

The Wapiti Formation is exposed at surface in the Dawson Creek (NTS 093P) and Monkman Pass (NTS 093I) map areas, where it ranges from 0 to 450 m in thickness and consists of continentally derived sandstone, shale and coal (Stott, 1975). In the Liard Basin (NTS 094N, O) on the British Columbia–Yukon border, the Wapiti is poorly exposed at surface near Maxhamish Lake and west of the Beaver River field (Stott and Taylor, 1968a). There, only the lower part of the formation is preserved, where it consists of coarse-grained conglomeratic sandstone. The top of the Wapiti Formation is not preserved anywhere in British Columbia.

The Wapiti Formation represents a major Campanian to Maastrichtian regression that deposited a nonmarine clastic wedge, following marine shale sedimentation of the Puswaskau Formation in the southern plains and the Kotaneelee Formation in the Liard area (Stott, 1975). The work of Fanti and Catuneanu (2010) in the Wapiti Formation of west-central Alberta and into the Deep Basin of northeast British Columbia identify and describe a fluvial sequence, basal channel-fill deposits that grade into floodplain deposits, channelized sediments and extensive overbank facies. Fanti and Catuneanu (2009) provide detailed descriptions of mappable markers in outcrop and in subsurface gamma-ray logs for the Wapiti Formation in the Deep Basin region and adjacent Alberta.

DISCUSSION: LOCAL VARIABILITY OF SHALLOW BEDROCK UNITS BY OIL AND GAS REGION

Local variability within the above-described major regional units is concisely outlined and illustrated by Stott (1975). In some parts of northeast British Columbia, local formations or members have the potential to be important hydrostratigraphic units (whether as aquifers or aquitards). A map of the oil and gas geographic regions of northeast British Columbia appears as an inset on Figure 1.

Deep Basin area

This region includes areas east of the deformation front to the Alberta border and south of Dawson Creek and Highway 97. There, the Upper Cretaceous Kaskapau, Marshybank, Muskiki, Cardium, Puskwaskau and Wapiti formations (Stott and Taylor, 1979, McMechan, 1994) are present at surface and shallow subsurface. The stratigraphy of the Noel gas field (Table 1) is representative of much of the region.

KASKAPAU FORMATION

The Kaskapau Formation is dominantly a marine mudstone unit that overlies the Dunvegan Formation in much of the Dawson Creek (NTS 093P) and Monkman Pass (NTS 093I) map areas. It forms a regional aquitard unit (Hitchon, 1990; Bachu, 2002) but grades laterally on its eastern and western borders into shallow marine or deltaic sandstones that form local aquifers. These subunits locally include the 2 m thick Doe Creek sandstone (Mathews, 1950; Jones, 1966; Plint and Kreitner, 2007) and the 9 m thick Pouce Coupe sandstone (Mathews, 1950; Canadian Geoscience Knowledge Network, 2012) near the Alberta border south of Dawson Creek, and Dickbusch, Trapper, Tuskoola, Wartenbe and Mt. Robert sandstones in the Tumbler Ridge area of the Southern Foothills (McMechan, 1994; Varban and Plint, 2005). These western sandstone tongues represent the western shoreface facies of the basin and are 15–50 m thick (Varban and Plint, 2005).

The Kaskapau Formation ranges in thickness from 300 to 550 m along the British Columbia–Alberta border to a maximum of approximately 670 m at the deformation front (Varban and Plint, 2005). It ranges in age from Late Cenomanian to Middle Turonian. It correlates with the Second White Speckled Shale unit of the plains of Alberta and Saskatchewan (Leckie et al., 1994).

Mathews (1950) noted that wells and springs in the Pouce Coupe sandstone member of the Kaskapau Formation yield good-quality water at the Doe River and Seven Mile Corner locations north of Dawson Creek. Lowen (2004, 2011) has documented the Groundbirch-Progress aquifer (aquifer 591; British Columbia Water Resources Atlas, 2012) as being hosted by the Kaskapau Formation (unspecified member) and reports variable productivity (from 0 to 3.15 L/s [50 gpm]) and variable water quality over 99 wells. The Dawson Creek–Arras aquifer (aquifer 593; British Columbia Water Resources Atlas, 2012) is hosted in the Kaskapau (unspecified member) and the overlying Cardium Formation. Lowen (2011) reported a median well yield of 0.32 L/s (5 gpm) from aquifer 593, with no reported quality issues.

CARDIUM FORMATION

The Cardium Formation hosts known aquifers in the Peace River valley near the British Columbia–Alberta border (Mathews, 1950; Jones, 1966; Hitchon, 1990). It lies between black marine shale of the Kaskapau and Muskiki formations and is exposed at surface in escarpments from south of Dawson Creek to Tumbler Ridge (McMechan, 1994). Mathews (1950) reported production of good-quality water from the Cardium Formation at three locations between Dawson Creek and Tomslake. Lowen (2011) identified the Cardium Formation as the host for part of the Dawson Creek–Arras aquifer (aquifer 593; British Columbia Water Resources Atlas, 2012).

The Cardium Formation is an intertidal shallow marine unit that is dominated by fine-grained marine sandstone and includes lesser mudstone and conglomerate (Stott, 1975; McMechan, 1994). It can be traced in subsurface logs through the southeast quadrant of the Dawson Creek map area (NTS 093P). In British Columbia, the Cardium Formation is approximately 20 m thick near the Alberta border and thickens to the southwest to a maximum of approximately 100 m along the deformation front (Canadian Geoscience Knowledge Network, 2012). Details of the internal stratigraphy, correlations, distribution of important conglomeratic members and their subsurface wireline log signatures are described by Hart and Plint (2003).

The Cardium Formation is an important oil-producing unit in Alberta, notably at the Pembina field (Krause et al., 1994).

MUSKIKI FORMATION

The Late Cretaceous Muskiki Formation is dominantly a rusty-weathering pyritic shale unit (Leckie et al., 1994) and is likely to behave as an aquitard. It is exposed in river escarpments from southwest of Dawson Creek, continuing southeast to the British Columbia–Alberta border (NTS 093O, P; Stott and Taylor, 1979; McMechan, 1994). It lies over the Cardium Formation sandstone and under the Marshybank Formation. The Muskiki Formation is generally less than 95 m thick and thins toward the Southern Foothills (Plint, 1990).

MARSHYBANK FORMATION

In British Columbia, the Marshybank Formation consists of basal marine sandstone overlain by nonmarine strata and may host aquifers. It has a maximum thickness of approximately 50 m and is exposed southwest of Dawson Creek, continuing southeast to the Alberta border (Plint, 1990; McMechan, 1994). It overlies the Muskiki Formation.

BADHEART FORMATION

The Badheart Formation is a medium- to coarse-grained marine sandstone unit of Coniacian age (Late Cretaceous), which may host aquifers in the Peace River region of Alberta (Jones, 1966). In British Columbia, the distribution of the Badheart Formation is confined to the northeast corner of the Monkman Pass map area (NTS 093I), where it underlies the Wapiti Formation (Stott and Taylor, 1979). The Badheart Formation in British Columbia is a few metres thick and is a potential aquifer host in the southernmost Deep Basin and Southern Foothills.

PUSKWASKAU FORMATION

The Puskwaskau Formation underlies the Wapiti Formation and is dominantly a shaly unit that is expected to behave generally as an aquitard. It is Santonian in age and occurs in the southeast quadrant of the Dawson Creek map area (NTS 093O) and the northeastern corner of the Monkman Pass map area (NTS 093I). It is also exposed north of the Peace River in the Fort St. John region. Hu and Plint (2009) detail the stratigraphy of the Puskwaskau Formation and describe subsurface log signatures of allomembers. The formation ranges from <70 to >340 m thick. Silty and sandy layers occur within the 14 allomembers, which may have potential as thin, localized, laterally limited aquifers.

An aquifer south of Pouce Coupe (aquifer 622; British Columbia Water Resources Atlas, 2012) is identified by Lowen (2011) as being hosted by the Puskwaskau Formation. This aquifer is near surface at the Swan Lake gas field. The Puskwaskau Formation there includes dark grey shale, calcareous shale and siltstone (McMechan, 1994). Lowen (2011) notes a wide variety of hydraulic responses across this aquifer, but with generally moderate well yields between 0.06 and 6.31 L/s (1–100 gpm), and averaging 0.95 L/s (15 gpm). Hard water was reported in some well records from this aquifer.

Southern Foothills

This region includes areas along and west of the deformation front and south of Peace Reach (Fig. 1, inset). The stratigraphy of the Sukunka field (Table 1) is representative of much of the region. Rock units exposed at the surface include the Minnes Group, the Gething and Cadomin formations of the Bullhead Group, several local formations of the Fort St. John Group and the Dunvegan Formation. These units are present at the surface and shallow subsurface at the following oil and gas fields: Stone Creek, Commotion, Highhat Mountain, Boulder, Brazion, Burnt River Sukunka, Gwillim, Bullmoose, Wolverine, Murray, Grizzly North, Grizzly South and Red Deer.

Local units of the Fort St. John Group are described below.

MOOSEBAR FORMATION

The Moosebar Formation overlies the Bullhead Group and consists of dark grey sideritic marine shale (McMechan, 1994). It is equivalent to the Wilrich aquitard in the subsurface of the Peace River plains and is part of the Garbutt Formation of the Liard region. The Moosebar Formation is approximately 289 m thick near Hudson's Hope and thins towards the southeast to 43 m at the British Columbia–Alberta border (Stott, 1975).

GATES FORMATION

The Gates Formation is a coarse clastic unit. Lowen (2011) delineates an aquifer (aquifer 441; British Columbia Ministry of Environment, 2012b) hosted by the Gates Formation at Lynx Creek, northeast of Hudson's Hope. Based on 16 wells, the average yield from the Lynx Creek aquifer is 0.63 L/s (10 gpm).

The Gates Formation lies between the marine shales of the Moosebar and Hasler formations. It was deposited in alluvial-deltaic environments (Stott, 1975) and includes sandstone, shale, coal, siltstone and mudstone (McMechan, 1994). It is 20 m thick near Hudson's Hope and thickens towards the southeast to 263 m approaching the British Columbia–Alberta border (Canadian Geoscience Knowledge Network, 2012). The Gates Formation is time equivalent to the Scatter Formation of the Liard region. Wadsworth et al. (2003) demonstrated methods for high-resolution stratigraphic correlation of facies in the Gates Formation using available wireline logs and subsurface cores.

SHAFTESBURY FORMATION AND EQUIVALENTS

A single unit, the dominantly shaly Shaftesbury Formation (Stott and Taylor, 1979), represents the entire Albian stage in the Monkman Pass map area (NTS 093I). Regionally, the Shaftesbury Formation is an important aquitard (Bachu, 2002). To the north and west, regressive episodes produced tongues of coarse clastic sedimentary strata within the shale. Stott et al. (1983) and McMechan (1994) distinguish five formations (Hulcross, Boulder Creek, Hasler, Goodrich and Cruiser) within the Albian section. Of these formations, the coarse clastic Boulder Creek and Goodrich formations may host aquifers.

BOULDER CREEK FORMATION

The Boulder Creek Formation has potential to host aquifers. It is a well-sorted marine sandstone up to 280 m thick and gradationally overlies the Hulcross shale (Fig. 2). The Boulder Creek Formation correlates with the Cadotte member of the Peace River plains and the upper part of the Scatter member of the Liard area (Stott, 1975).

GOODRICH FORMATION

The Goodrich Formation is composed of sandstone deposited in near-shore and delta-front environments and represents a potential aquifer. It overlies the Hasler shale (Table 1, Fig. 2) and is up to 390 m thick. The Goodrich Formation correlates with the Sikanni sandstone unit north of the Peace River (Stott, 1975).

HULCROSS, HASLER AND CRUISER FORMATIONS

The Hulcross, Hasler and Cruiser formations are all marine shale that can be generally expected to behave as aquitards. The Hulcross overlies the Gates sandstone and ranges from 0 to 135 m thick (Canadian Geoscience Knowledge Network, 2012). It is correlative with the Harmon member in the subsurface of the Peace River plains, and is part of the Scatter Formation in the Liard region (Stott, 1975). The Hasler Formation shale lies on the Boulder Creek Formation and is 250–265 m thick. It is equivalent to the Lepine Formation in the Liard area. The Cruiser Formation shale overlies the Goodrich sandstone, is 105–230 m thick (Canadian Geoscience Knowledge Network, 2012) and is equivalent to the Sully Formation of the Fort St. John Group north of Peace River. An aquifer in the Chetwynd area (aquifer 627; British Columbia Ministry of Environment, 2012b) is hosted by the Cruiser Formation in fractured shale. Lowen (2011) reports an average well yield of 1 L/s (16 gpm) from this aquifer, with no documented water quality concerns.

Fort St. John and Fort Nelson/Northern Plains regions

Over much of the plains regions of northeast British Columbia, the Dunvegan Formation and formations of the Fort St. John Group are exposed at the surface. Stratigraphic columns for the Gunnell Creek and Monias fields (Table 1) represent the shallow bedrock geology for parts of these regions. The stratigraphy at the Gunnell Creek field is representative of much the eastern side of the Horn River Basin and the Cordova Embayment. The stratigraphy at the

Monias field is representative of the northeastern margin of the Montney trend. At some wells in the Monias field, the sandy Sikanni Formation can be distinguished in the shallow subsurface within the dominantly shaly Fort St. John Group.

SIKANNI FORMATION

The Sikanni Formation is a sandstone unit within the upper Fort St. John Group that has potential to host aquifers along the part of the Montney trend north of the Peace River. The Sikanni Formation was deposited in near-shore to delta-front environments in the late Albian. It is up to 300 m thick, and thins and shales out to the east under the plains. It is equivalent to the Goodrich Formation sandstone south of the Peace River (Stott, 1975). Webb et al. (2003) provide detailed descriptions of mappable markers in subsurface wireline logs for the upper part of the Fort St. John Group from the Peace River to the Liard area.

Northern Foothills

The surface geology of the Northern Foothills is represented on Figure 2 by stratigraphic columns for the Clarke Lake field in the southern Horn River Basin and the Julienne field in the northern Montney trend. The Dunvegan Formation and Fort St. John Group are the important surface and shallow subsurface units. In much of this area, the Fort St. John Group is mapped as an undivided unit; however, along the eastern edge of the Northern Foothills from the Halfway River to the Liard River, the sandy Sikanni Formation is distinguishable (Stott and Taylor, 1968a, b; Taylor, 1979; Taylor and Stott, 1999). The Sikanni Formation has potential to host aquifers. It is described above in the ‘Fort St. John and Fort Nelson/Northern Plains’ section above. The Sikanni Formation is present at surface and shallow subsurface in the Clarke Lake area (Evie Bank, Roger, Clarke Lake, Klua, Hoffard and Milo fields), near Trutch and along the Prophet River (Adsett, Bougie, Trutch, Caribou and Green Creek fields), and along the northwest edge of the Montney trend (at the Lily Lake, Cypress, Chowade, Daiber, Graham, Butler, Farrell Creek West and Altares fields).

Liard Basin and Fold Belt

Shallow bedrock stratigraphy varies considerably across the Liard Basin as the geological structure becomes increasingly complex to the west. On the eastern edge of the Liard Basin, the shallow stratigraphy is much like the plains, as represented by the stratigraphic column for the Maxhamish field (Table 1), with near-horizontal strata ranging from the latest Cretaceous Wapiti Formation down to the Albian Lepine member of the Fort St. John Group (Fig. 1, 2). In the Liard River region, the Dunvegan Formation was deposited in alluvial fan environments (Stott, 1975; Bhattacharya, 1994) and contains more conglomerate than it does farther south, which may prove to increase its prospectivity as an aquifer. To the west, increasingly older strata are brought to surface along a number of steep north-striking faults (Taylor and Stott, 1999; Walsh, 2004). At the Beaver River field, the youngest surface formations are Lower Cretaceous Lepine, Scatter and Garbutt formations. The oldest is the Permian Fantasque Formation (Table 1), which is exposed in an anticline (Taylor and Stott, 1999).

FANTASQUE FORMATION

The Permian Fantasque Formation is a bedded chert up to 55 m thick (Canadian Geoscience Knowledge Network, 2012). It is exposed at the surface in the centre of the anticline that underlies the Beaver River gas field. Its potential to host aquifers is unknown.

BUCKINGHORSE FORMATION: GARBUTT, SCATTER AND LEPINE FORMATIONS

The upper part of the Fort St. John Group in the Liard River area includes the Lepine, Scatter, and Garbutt formations, which are sometimes grouped together as the Aptian to Albian Buckinghorse Formation. The Scatter Formation is composed of deltaic sandstone and has potential to host aquifers. It is approximately equivalent to the Gates and Boulder Creek sandstones (Stott, 1975). Its thickness ranges from 60 to 375 m (Canadian Geoscience Knowledge Network, 2012).The Garbutt and Lepine formations are dominated by marine shale and correlate with the Moosebar and Hasler shales, respectively. Leckie and Potocki (1998) describe the stratigraphy of the Scatter and Garbutt formations in the Liard Basin and demonstrate how they can be distinguished on wireline logs.

The Garbutt Formation has been evaluated for shale gas potential (Ferri et al., 2011), but at the date of this publication, no shale gas has been produced from this unit.

KOTANEELEE FORMATION

The Late Cretaceous Kotaneelee Formation is exposed on both sides of the Liard River in the Liard Basin near the British Columbia–Yukon border. The Kotaneelee Formation is dominated by marine shale and is expected to generally behave as an aquitard. It is 152–305 m thick (Canadian Geoscience Knowledge Network, 2012) and is equivalent to the Puskwaskau Formation of the Deep Basin and eastern Fort St. John regions (Stott, 1975).

CONCLUSIONS

- Freshwater bedrock aquifers are mainly hosted by Cretaceous strata in northeast British Columbia. The most important prospective regional bedrock units for freshwater aquifers are the coarse clastic Wapiti and Dunvegan formations. Other less extensive units locally host significant local bedrock aquifers.
- In the Peace River valley, bedrock aquifers have provided fresh water to meet domestic, agricultural and commercial demands. Some of these aquifers have been delineated and studied. Certainly many more aquifers exist in northeast British Columbia that have not yet been formally identified or delineated because of low data density.
- Bedrock aquifer yields in the Peace River area are generally much lower than those of surficial aquifers. Most bedrock aquifer yields are not sufficient to supply the volumes required for major industrial use, but can be adequate for domestic needs. Fracture porosity, however, can substantially enhance yields in both coarse clastic and shale units. Bedrock units with significant yields may yet be discovered outside the Peace River valley as shale gas development continues.
- The Kotaneelee, Puskwaskau and Kaskapau formations and the majority of the Fort St. John Group are mainly shale units that can be expected to behave as regional aquitards; however, minor coarse clastic units within these formations may host small aquifers locally. Fractured shale units are known to host freshwater aquifers in the Peace River valley and may be present in other regions.
- Water quality is generally better (lower in dissolved solids) in the Rocky Mountain Foothills and poorer on the plains. This characterization is supported in the Peace River valley, where significant data exist and it is reasonable to expect that it will hold true throughout northeast British Columbia.
- The depth to the base of fresh groundwater is unknown almost everywhere in northeast British Columbia because of the data gap between the base of water wells (generally less than 150 m deep) and top of logged and sampled oil and gas exploration wells (generally greater than 300 m deep). This data gap can be addressed by obtaining new lithological and geochemical data from the upper few hundred metres in a representative number of exploration wells in oil and gas fields. Exploration activity occurring in previously undeveloped areas will provide opportunities to obtain new lithological and aqueous geochemistry data where information has previously been absent or limited.
- Detailed stratigraphic studies have been published on many of the bedrock formations that are prospective for fresh groundwater. These can be valuable exploration tools; they provide descriptions of mappable outcrop and subsurface log markers in outcrop and in subsurface gamma-ray logs.

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COLLABORATIVE INTERAGENCY WATER PROJECTS IN BRITISH COLUMBIA: INTRODUCTION TO THE NORTHEAST BRITISH COLUMBIA AQUIFER PROJECT AND STREAMFLOW MODELLING DECISION SUPPORT TOOL

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ABSTRACT

Allocation of water to domestic, agricultural and industrial uses that is mindful of environmental requirements requires knowledge of the surface and below-ground water resources. The allocation of water in northeastern British Columbia has recently become significant due to demands associated with the development of the unconventional shale gas resource through hydraulic fracturing.

To address the lack of surface water information in northeast British Columbia, a streamflow modelling project has been initiated to provide information to government agencies and water licence applicants. Groundwater aquifers in the Montney gas play area are being described using traditional and geophysical investigation techniques.

The projects involve provincial and federal government agencies, the British Columbia Oil and Gas Commission, Simon Fraser University, private well owners and the oil and gas industry. This paper provides an overview of these projects.

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Key Words: Water, Groundwater, Hydrogeology, Aquifer, Water wells, Observation wells, Montney gas play, Shale gas, Unconventional gas, Northeast British Columbia Aquifer Project, Hydrology Modelling and Decision-Support Tool, Groundbirch paleovalley

INTRODUCTION

Water is a valued resource in British Columbia and there are a variety of stakeholders concerned with its sustainable use. The Northeast British Columbia Aquifer Project and Streamflow Modelling Decision Support Tool Project are two interagency collaborative initiatives directed at understanding water source options for industrial, domestic, agricultural and environmental use in British Columbia's traditional oil and gas development region. These projects are a collaboration of the British Columbia Ministry of Forests, Lands and Natural Resource Operations (FLNRO), the British Columbia Ministry of Environment (MoE), the British Columbia Ministry of Energy and Mines (MEM), the British Columbia Oil and Gas Commission (OGC), Simon Fraser University (SFU), Geoscience BC (GBC) and the Geological Survey of Canada (GSC).

Shale gas development is a substantial contributor to British Columbia's energy inventory and development is increasing in the Horn River Basin, the Liard Basin, the Cordova Embayment and the Montney gas play area (Fig. 1). To develop this unconventional shale gas resource, gas wells are stimulated through hydraulic fracturing, whereby the relatively impermeable shale is fractured, providing a conduit for the gas to flow from the rock to the wellbore. Hydraulic fracturing requires substantial quantities of water (Johnson, 2012); therefore, secure water supplies could be a limiting factor in development. Industry, the public and various levels of government are seeking sufficient information to appropriately manage these resources. Two collaborative projects have been initiated to begin addressing ground- and surface-water sustainability: the Northeast British Columbia Aquifer Project and the Streamflow Modelling Decision Support Tool.

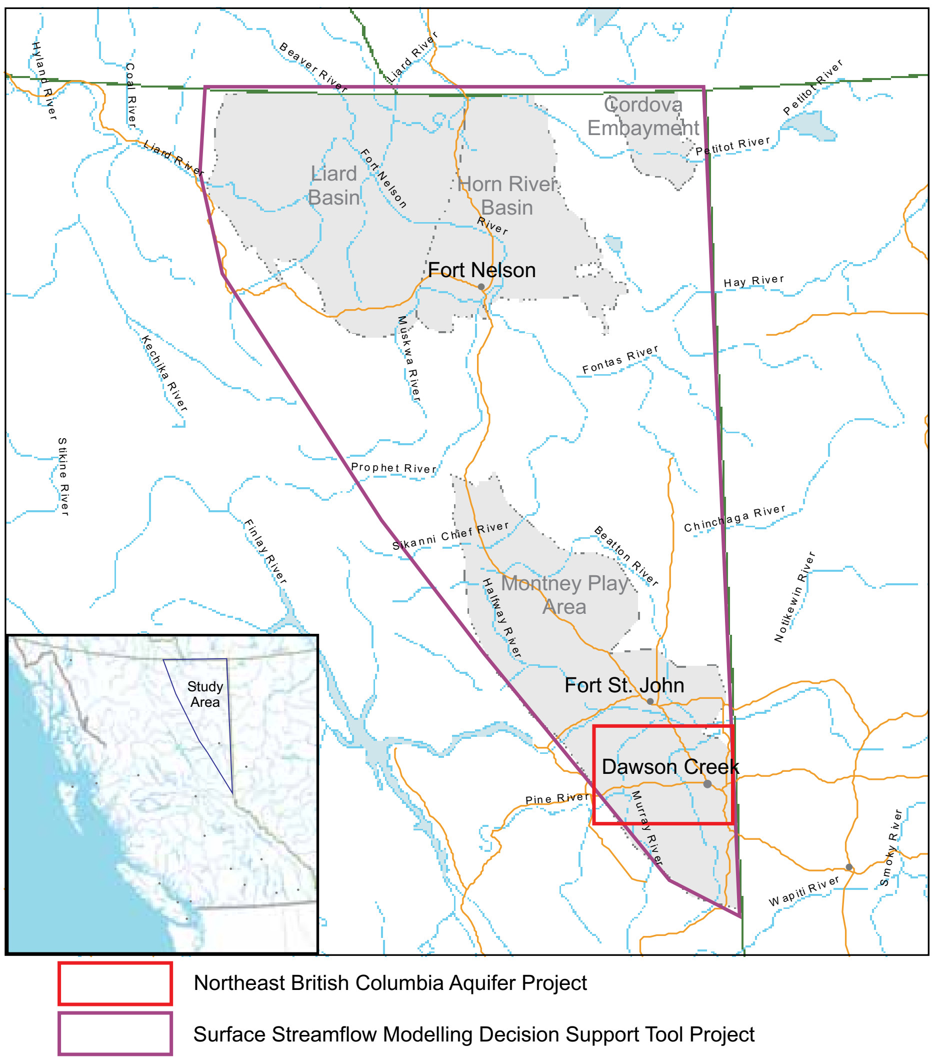

Figure 1. The Northeast British Columbia Aquifer Project is being conducted in the Dawson Creek area within the Montney gas play area (red box). The Streamflow Modelling Decision Support Tool Project is being conducted across northeast British Columbia (purple polygon).

NORTHEAST BRITISH COLUMBIA AQUIFER PROJECT

This project is in the process of exploring groundwater aquifers in the Montney gas play area from two different, but complementary, perspectives. One component of the project focuses on traditional groundwater investigations using groundwater wells to determine stratigraphy, water chemistry, water table elevations and fluctuations over time, and the hydraulic characteristics of aquifers. Each drilled well provides a one-dimensional view of aquifers. Interpolating between a series of wells allows for a more extensive description of an aquifer. The second component of the project investigates aquifers using geophysical techniques to delineate the geological units that define the aquifers. A series of lines are run across the landscape enabling a two-dimensional delineation of subsurface aquifers. Interpolating between a series of lines allows for a three-dimensional description of the aquifers. Hydraulic characteristics of the aquifers and the subsurface calibration of the geophysics are determined using groundwater wells (this is where the two approaches are complementary—in fact, essential). The project includes four components: 1) a well water survey, 2) expansion of the British Columbia Observation Well Network, 3) the geological framework of the Groundbirch paleovalley and 4) a groundwater level (GWL) interface data update. In the following sections, we introduce each of these components.

Water well survey

Basic water well information and water chemistry are essential for understanding groundwater systems. A survey of more than 100 water wells in the study area was initiated with the objective of having at least one sample well per 20 km^2. The survey involved several steps: updating well records for the area, establishing contact with well owners and undertaking well sampling and measurement.

Well records for the area are not complete; in some cases information was lacking, whereas in other cases the wells had not been used. Where well logs were available, the information was not of consistent quality. These data are critical for understanding the hydrogeology of the area and were verified or added during discussions with well owners (depth of well, depth to water at time of drilling, geology and type of aquifer).

Establishing contact with the well owners was challenging. Many individuals were only home at night, resulting in long days for team members. Some individuals were suspicious of any research to do with their groundwater, whereas others had already participated in other well water sampling projects sponsored by the industry. As a result, a short brochure was prepared that explained the project and provided contact information (Fig. 2). In addition, a cover letter was prepared, specifically requesting participation in the project and stressing that the source of any groundwater information would be kept confidential.

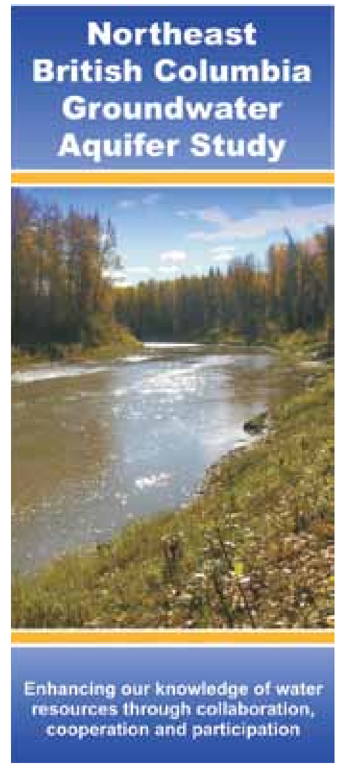

Figure 2. A three-panel public information brochure for the Northeast British Columbia Aquifer Project was distributed to landowners within the study area.

Fieldwork focused on the physical and chemical nature of water in each well (Fig. 3). Physical aspects included depth to groundwater using an ultrasonic meter (Ravensgate Sonic 200U Well Depth Sounder). The elevation of the well was established using a precision GPS unit (Magellan MobileMapper CX). A multiparameter flow-through meter (YSI Pro Plus) was used in the field to determine pH, electrical conductivity, dissolved oxygen and oxidation/reduction potential. Samples were shipped to SFU and analyzed for anions, cations, isotopes, trace metals, alkalinity, total dissolved solids and nutrients. Given the scope of the project—to determine the physical aspects of aquifers in the study area—we are not sampling or analyzing for volatile organic compounds (VOCs, BTEX, i.e., benzene, toluene, ethylbenzene and xylenes). Well owners were asked a series of questions related to level of use, historical water sampling, proximity to other water wells or oil and gas wells, land use around the well and if they were interested in potentially having their well pump tested/slug tested at a later date.

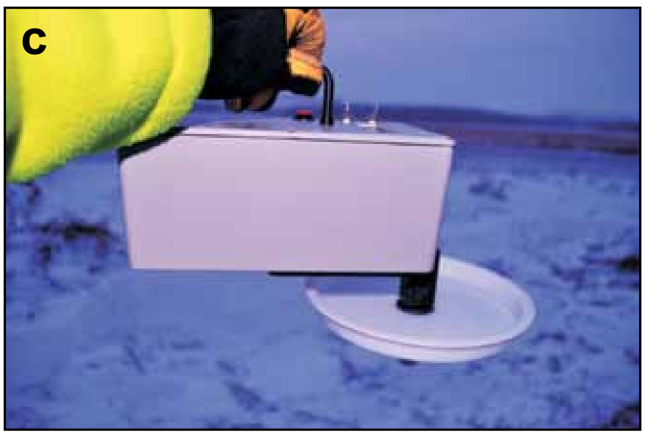

Figure 3. a) Wells included in the water well survey were visited by a contractor and measurements and samples were collected; b) the location and elevation (±50 cm) of each well was determined by precision GPS measurement; c) the static water level was established using a handheld ultrasonic meter; d) a multiparameter flow-through meter was used to determine pH, electrical conductivity, dissolved oxygen and oxidation/reduction potential.

Expansion of British Columbia Observation Well Network

The Government of British Columbia maintains a provincial network of approximately 140 groundwater observation wells. The wells are monitored regularly for groundwater level and groundwater chemistry to determine, over the long-term, whether aquifers are being impacted through natural and human-induced factors (Janicki, 2011). Most of the observation wells in British Columbia are concentrated in heavily populated southern regions where groundwater usage has historically been most intense. Only two observation wells are located in northeastern British Columbia, where most of the province's oil and gas development takes place. Neither of these wells are within the Montney gas play area.

Informed decisions regarding water resource allocation and authorizations cannot be made without a clear understanding of the water resource. The Government of British Columbia is currently exploring ways to modernize the Water Act, which will include formula-based in-stream flow assessment for surface allocations and regulating groundwater use (British Columbia Ministry of Environment, 2010). It is recognized that water authorizations or approvals granted may be compromised by the lack of information. The Northeast British Columbia Aquifer Project, in conjunction with funding through the Climate Action, Clean Energy (CACE) initiative, constructed six new observation wells in the rural areas surrounding Dawson Creek (Fig. 4). The publicly available observation well data will provide fundamental information on aquifer water levels necessary for responsible resource allocation and authorization.

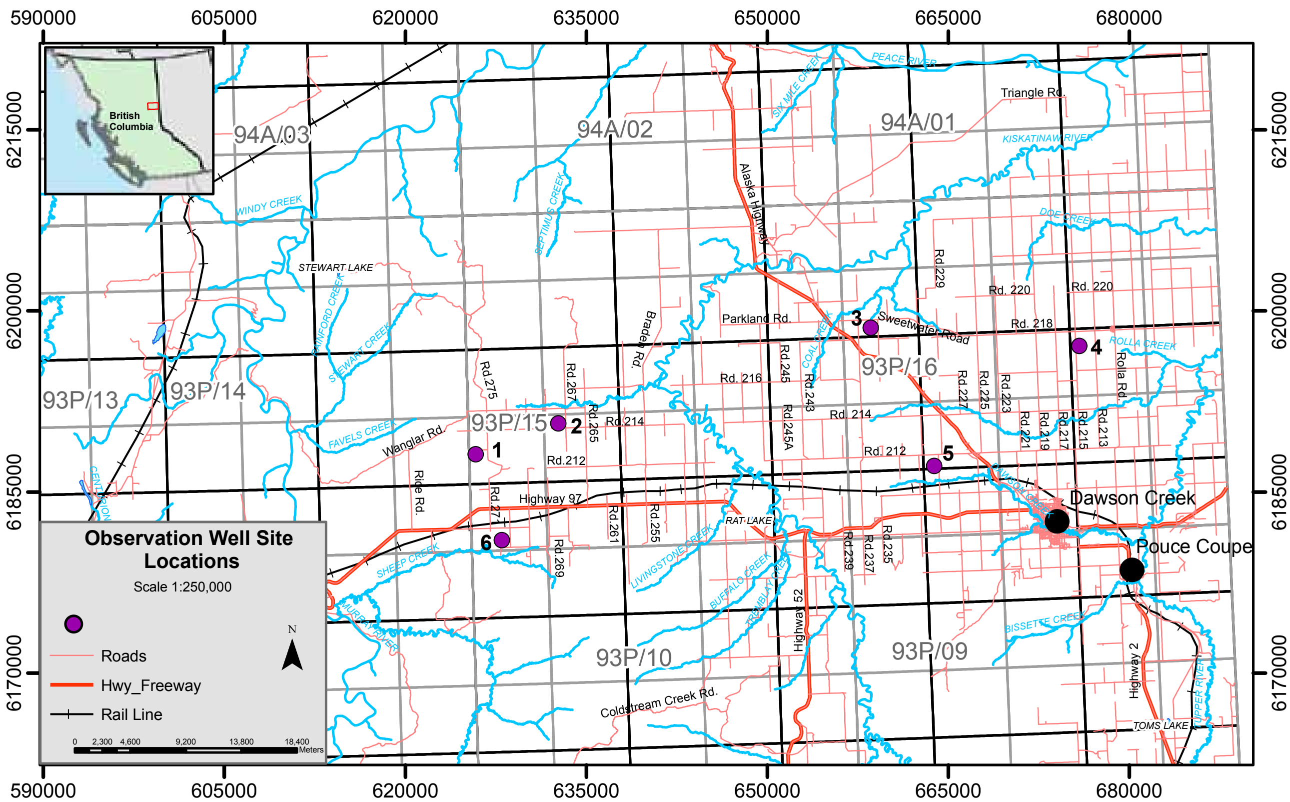

Figure 4. All of the new observation wells were constructed in the rural area around Dawson Creek.

The six observation wells were constructed in November 2011 and will be equipped with water-level monitoring equipment. Production capability and basic aquifer parameters (transmissivity, hydraulic conductivity, etc.) will be determined during the upcoming field season. Water samples will also be collected, analyzed and included with the water well survey (described above).

REGIONAL HYDROGEOLOGY

Mapping completed by the MoE (Berardinucci and Ronneseth, 2002) indicates the presence of several unconsolidated aquifers of limited extent overlying more widespread bedrock aquifers. The unconsolidated aquifers are mapped as confined sand and gravel of glacial or preglacial age (Hickin and Best, 2012), whereas the bedrock aquifer is identified as the Kaskapau Formation of Upper Cretaceous age (Glass, 1990). At surface, and overlying the aquifers, is a thick layer of impermeable clay. Vulnerability of aquifers in the area has been classified as low to moderate using the British Columbia Ministry of Environment Aquifer Classification System (Lowen, 2011). A review of water well records on the MoE website indicates that the likely source of groundwater for water wells in the study area is from bedrock aquifers, although the presence of suitable aquifer materials, such as gravel, is reported at shallower depths in some locations. The observation well drilling program included completing wells in both shallow unconsolidated and deeper bedrock aquifers, depending on geological conditions.

LOCATION SELECTION

Six observation well locations were selected using the following criteria:

- within the Montney play trend and in proximity to recent shale gas activity;
- within a vulnerable aquifer(s) as mapped by the MoE;
- access along a British Columbia Ministry of Transportation and Infrastructure road rights-of-way;
- south of the Peace River within a MoE priority area for new observation wells;
- a good chance of water production based on nearby water well records;
- reasonable depth to bedrock so that no individual well would be overly expensive; and
- establishment of three wells within a single aquifer so groundwater flow and gradient can be determined.

Figure 4 shows the location of the observation wells. The observation well at location 6 was selected to test the aquifer potential of the Groundbirch paleovalley and was expected to be deeper than the other five observation wells (Hickin, 2011). This well had polyvinyl chloride (PVC) casing installed and was logged with downhole geophysical instruments. The results will be correlated with a ground-based geophysical program designed to characterize the paleovalley (see below; Hickin and Best, 2012).

DRILLING AND COMPLETION

The six observation wells were drilled in late November and early December 2011 using an air-rotary drilling rig (Fig. 5) with a casing hammer. Drilling began with either an auger or an oversized bit of 19 cm (7.5 in.; water-well drilling operations use Imperial units). After roughly 3 m (10 ft.) of penetration, steel casing was pounded into the ground with the casing hammer. Drill cuttings were collected from the end of a discharge hose every 3 m (10 ft.) and logged.

Figure 5. In November 2011, six new water observation wells were drilled along on road rights-of-way using an air rotary water well drilling rig with a casing hammer.

After bedrock was encountered, the remainder of the hole was drilled open-hole. After reaching total depth of the borehole, a 12.7 cm (5 in.) PVC liner was inserted from the bottom of the borehole to near the ground surface. The lowest 6–12 m (20–40 ft.) of the liner was screened or perforated to allow inflow of groundwater. Approximately 75 cm (2.5 ft.) of steel casing remained above ground level as a 'stick-up' (Fig. 6). A MoE-issued well identification plate (Table 1, well plate number) was welded onto the side of each observation well casing. The well was then developed and an approximate measurement of the well yield was made using a stopwatch and bucket. Several days after drilling and completing the construction of the observation wells, the total depth and static water level were measured using a wet tape (Heron Instruments dipper-T water tape). Observation wells 1–6 have been incorporated into the MoE observation well network database and assigned well tag numbers (WTN) and observation well numbers (Table 1).

Figure 6. Following completion, approximately 1.5 m of steel casing remained above ground to mark the well. The casing was tagged with a well number and a lock cap was installed.

RESULTS

All wells recovered water but locations 1, 4 and 6 were particularly productive, based on informal measurements using a stopwatch and a bucket. Location 3 was drilled considerably deeper than expected in order to intersect the water table. Only location 6, which was drilled within the interpreted Groundbirch paleovalley, encountered a small volume of groundwater in a gravel bed of indeterminate extent at roughly 40 m (130 ft.) of depth. In this same well, a more significant aquifer was intersected at the bedrock sediment interface at approximately 80 m.

All wells were screened in bedrock and were constructed with a surface seal with a minimum of 4.5 m (approximately 15 ft.) in length. Bedrock generally consists of weathered carbonaceous shale with interbeds of siltstone and fine-grained sandstone. Water is likely contained within both the thin sandstone interbeds and secondary pore space created by weathering and jointing.

Geological framework of the paleovalley

Delineation of the geological framework within the Groundbirch paleovalley will aid in modelling the hydrogeology of the unconsolidated aquifers within this feature. This will be achieved by integrating three geophysical surveys with other geological datasets. A downhole electromagnetic and gamma survey was conducted in the recently drilled 85 m deep British Columbia observation well, constructed with a nonconductive casing (location 6 described above; Fig. 4). The detailed geology provided from this well was used to calibrate the other surveys. A ground-based time-domain electromagnetic survey was conducted in February 2012 and a shallow seismic reflection survey is anticipated to be carried out in the spring of 2012. These surveys will provide 2D sections across the paleovalley. This information will be augmented with field data from

TABLE 1. GENERAL PARAMETERS FOR SIX NEW OBSERVATION WELLS.

Location	Well Plate Number	Well Tag Number*	Easting (NAD83)	Northing	Total Depth		Depth to Bedrock		Depth to Uphole Aquifer		Screened Interval		Estimated Well Yield		Static water level below ground	
					(metres)	(feet)	(metres)	(feet)	(metres)	(feet)	(metres)	(feet)	litres/second	US gallons/minute	(metres)	(feet)
1	31673	104707	626795	6188502	31.7	104	6.1	20	-	-	25.6-31.7	84-104	2.3	30	19.6	64
2	31674	104708	633333	6189602	25.6	84	13.7	45	-	-	18.6-24.7	61-81	1.5	20	5.2	17
3	31676	104709	659162	6198993	91.4	300	18.3	60	-	-	79.2-91.4	260-300	0.02	0.25	57.3	188
4	31677	104710	673846	6196989	65.6	84	8.5	28	-	-	18.2-24.4	60-80	2.3	30	surface	surface
5	31675	104711	664182	6187977	48.8	160	21.3	70	-	-	42.7-48.8	140-160	0.4	5	19.2	63
6	31672	104712	628709	6180490	85.3	280	79.9	262	40.8	134	73.8-79.9	242-262	0.75	10	21.9	72

* Well data can be accessed using the Well Tag Number at the link below:
http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/index.html

Well locations can be found on a map using Well Tag Numbers using the following link:
http://webmaps.gov.bc.ca/imf5/imf.jsp?site=wrbc

an exposure of the paleovalley succession along the Coldstream River canyon, together with water well data from the MoE's WELLS database, the latter of which houses British Columbia's water well information (see Hickin and Best [2012] for details on this component of the project).

Groundwater level interface data update

British Columbia's observation wells provide data on groundwater-level fluctuations and groundwater quality information on developed aquifers in British Columbia. Water-level data from observation wells are continuously collected via instrumentation in the well. The water-level data is referenced from ground level and the data is downloaded by regional staff. Data are checked and validated for errors and omissions before being published and stored on the groundwater level (GWL) website.

Validated groundwater data collected from the Provincial Groundwater Observation Well Network are available in tabular, graphical and csv formats through the GWL public interface (https://a100.gov.bc.ca/pub/gwl/). Although the central database stores unvalidated data, it is not made available through the GWL public interface. The development of satellite telemetry equipment allows for the near–real-time upload of groundwater level data from across the province, potentially providing users with timely data on the condition of more than 55 aquifers throughout British Columbia. Unfortunately, near–real-time data from observation wells retrofitted with satellite telemetry equipment cannot be displayed in the GWL because it is unvalidated and thus, is not available to the public. The GWL public interface is currently being updated to include validated and unvalidated data in its outputs using support from the British Columbia Ministry of Forests, Lands and Natural Resource Operations and the British Columbia Ministry of Environment. This will allow for improved management of groundwater resources and support the Government of British Columbia's open-data initiative.

HYDROLOGY MODELLING AND DECISION-SUPPORT TOOL DEVELOPMENT FOR WATER ALLOCATION, NORTHEAST BRITISH COLUMBIA

The British Columbia Oil and Gas Commission (OGC), with support from Geoscience BC and the British Columbia Ministry of Forests, Lands and Natural Resource Operations, is undertaking a hydrology modelling project in northeast British Columbia. This project follows a pilot project undertaken in early 2011 by Chapman and Kerr (2011). The pilot project used available gridded climate data and land cover and vegetation data within the Horn River and Liard Basin gas play areas to model discharge in several watersheds. From the success of the pilot project, it was concluded that there is utility in pursuing a monthly water-balance modelling approach. The current project is now extending and fine-tuning the hydrology modelling to all of northeast British Columbia. The objective of the project is to complete overview hydrology modelling for northeast British Columbia and to produce a GIS-based decision-support tool, which would be used to provide estimates to guide water license applicants and short-term water-use approval decisions (British Columbia Water Act, Section (8) – Short Term Water Use).

Study area

This study encompasses the area of northeast British Columbia that includes the unconventional Montney gas play area, the Liard Basin, the Horn River Basin and the Cordova Embayment, from south of Dawson Creek to the Yukon and Northwest Territories boundary in the north, and east of the Rocky Mountains (Fig. 7). The total area in British Columbia under study is approximately 175 500 km^2.

The streamflow regime is typically nival (snowmelt dominated), with a sustained cold winter period characterized by low rates of streamflow and competent river ice, followed by a spring freshet from approximately mid-April to late June, characterized by high rates of streamflow as the winter's accumulated snow melts. After the spring

Figure 7. There are more than 55 hydrometric stations throughout northeast British Columbia and adjacent Northwest Territories and Alberta.

freshet period, river levels generally recede slowly through the summer and autumn until the winter freeze. Frontal or convective storm systems bring varying amounts of rain from late spring to autumn, often resulting in temporary increases in river levels and discharge, and occasionally producing flooding (which is randomly distributed in the watersheds within the study area).

Data

The water balance model takes a 'conservation of mass approach' and follows a concept originally applied by Solomon et al. (1968) and Moore et al. (2011). Key inputs to the model for northeast British Columbia are monthly and annual precipitation and temperature grids from the ClimateWNA program (Wang et al., 2012), which are derived from the PRISM methodology (Daly et al., 2008); gridded evapotranspiration data produced by the Consultative Group for International Agricultural Research (CGIAR); land cover and vegetation mapping from Natural Resources Canada and the Province of British Columbia; and hydrometric data from the Water Survey of Canada.

Actual evapotranspiration data produced by CGIAR modelling accounts for water availability using a modified Hargreaves (Trabucco and Zomer, 2010) approach and takes climate inputs from the WorldClim database—a 1 km gridded climate surface representing the time period of 1950–2000 (Hijmans et al., 2005; Trabucco and Zomer, 2010). Within the CGIAR data, evapotranspiration is adjusted according to soil moisture content factors and assumes agronomic land cover. Evapotranspiration values were obtained from several sources (Chapman, 1988, Spittlehouse, 1989; Liu et al., 2003; Barr et al., 2007) and were adjusted within the model.

Model calibration

Estimates of monthly and annual runoff were derived using the simple continuity equation: Q = P–ET, where Q = annual runoff (mm), P = annual precipitation (mm) and ET = annual evapotranspiration (mm). Exploratory spatial data analysis was a large component of this work, and as such the end result will be a product that represents the hydrology of northeast British Columbia as effectively as possible given available data.

The results of the annual runoff modelling were calibrated against hydrometric data collected by the Water Survey of Canada. A total of 55 hydrometric stations were selected for calibration. Not included were gauges on very large drainages (e.g., Peace River, Liard River), lake outlet stations or stations on drainages with manmade controls. The stations are located in British Columbia, western Alberta and the southern Northwest Territories and in several cases the watersheds cross provincial/territorial borders. Although the objective of this work was only to create estimates for ungauged drainages in British Columbia, these transborder stations and stations wholly located in adjacent jurisdictions provided critical representation of portions of British Columbia that are ungauged.

Significant variability and error exists in the natural processes represented by all components of the model and the hydrometric data to which model results are compared. A multivariate regression technique was used to remove some modelling error. Results for the annual runoff modelling indicate a median error of 3.7%, with 78% of the calibration basins having estimates within ±20% of the measured mean annual runoff. A statistical model was then used based on a multivariate regression technique to distribute the modeled annual runoff to individual months of the year. In general, the monthly runoff modelling is quite good, with hydrograph fits that are visually accurate (Fig. 8) and with reasonable statistics (median Nash-Sutcliffe efficiency = 0.90, with 58% of the calibration basins having Nash-Sutcliffe efficiency statistics of greater than 0.90).

Project workshop

A workshop was held on January 11, 2012 to review and comment on the modelling approach and the proposed decision support tool. Participating in the workshop were scientists, managers and operational staff from provincial ministries (FLNRO, MEM and MoE), a federal ministry (Environment Canada–Water Survey of Canada), industry (Nexen, Esso and Conoco-Philips), Geoscience BC, FORREX, the OGC and academia (The University of British Columbia and University of Victoria). The objectives of the workshop were to receive scientific and operational input on the model and tool, gauge support for the approach in using the model and tool, and to communicate the project to stakeholders. This was a successful workshop with fully engaged discussion and constructive suggestions presented.

Summary

The hydrology modelling approach outlined in this paper is yielding consistent and reliable estimates of annual and monthly runoff for rivers in northeast British Columbia. The modelling is not yet complete and further enhancements based on workshop input are being tested. Included in the enhancement is the ability to locate a point of interest on a river and generate runoff data for that point based on the upstream watershed. This multipoint ability within a watershed will allow for point-specific identification of water availability. It is anticipated that the modelling will be completed by early 2012.

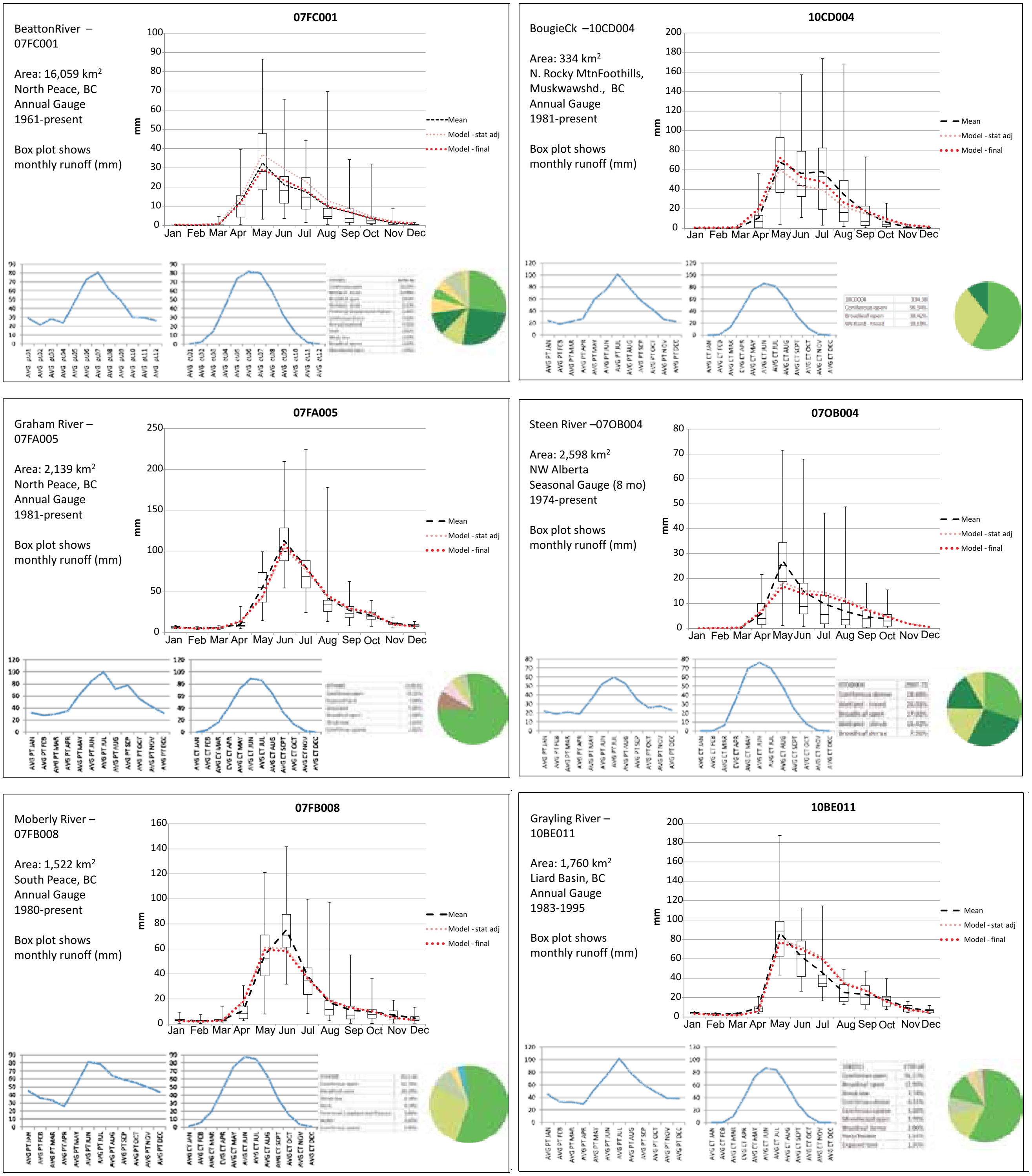

Figure 8. Several examples show how the modelled data fits the average monthly discharge measured at the hydrometric stations. The blue plots on the bottom left of each example show modelled precipitation (mm) and modelled actual evapotransporation (AET). The pie chart shows the proportion of each vegetation cover category within the watershed (the pie size is proportional to the table provided and is read from the 12 o'clock position clockwise).

ACKNOWLEDGMENTS

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STRATIGRAPHY AND PROPOSED GEOPHYSICAL SURVEY OF THE GROUNDBIRCH PALEOVALLEY: A CONTRIBUTION TO THE COLLABORATIVE NORTHEAST BRITISH COLUMBIA AQUIFER PROJECT

Adrian Hickin[1] and Melvyn E. Best[2]

ABSTRACT

In northeast British Columbia, the increasing pressure on water supply that supports domestic, agriculture and industrial activities has made water a valuable resource. The increasing rural population and expansion of industrial development have led to an escalating need to understand water systems and availability. To this end, the British Columbia Ministry of Forests, Lands and Natural Resource Operations has partnered with the British Columbia Ministry of Energy and Mines, the British Columbia Ministry of Environment, Simon Fraser University and the Geological Survey of Canada to investigate shallow bedrock and unconsolidated groundwater aquifers within the Montney natural gas play. One component of this project is to delineate the geological framework of the unconsolidated aquifers within the Groundbirch paleovalley. This will be achieved by integrating three geophysical surveys with other geological datasets. Downhole electromagnetic and gamma surveys will be conducted in a recently drilled 85 m deep British Columbia observation well constructed with a nonconductive casing. The detailed geology provided by this well will be used to calibrate the other surveys. A ground-based time-domain electromagnetic survey and a shallow seismic reflection survey will be carried out to provide two-dimensional sections across the paleovalley. This information will be supplemented by field data from an exposure of the paleovalley succession along the Coldstream River canyon, along with water well data from the British Columbia Ministry of Environment's WELLS database, the latter of which houses British Columbia's water well information.

Hickin, A. and Best, M.E. (2012): Stratigraphy and proposed geophysical survey of the Groundbirch paleovalley: a contribution to the collaborative Northeast British Columbia Aquifer Project; *in* Geoscience Reports 2012, *British Columbia Ministry of Energy and Mines*, pages 91-103.

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Key Words: Groundbirch paleovalley, Aquifer, Hydrogeology, Quaternary geology, Elecromagnetic survey, Shallow seismic survey, Downhole geophysics

INTRODUCTION

Water is a valued resource in British Columbia. There is, however, increasing pressure on water supplies from a variety of stakeholders in various regions of the province. In northeast British Columbia, water supports domestic, agriculture and industrial activities. As populations grow and industry expands, there is an increasing need to understand water systems and availability so that best management practices can be developed to ensure equitable use, economic development and sustainability of this valuable resource. In 2011, the British Columbia Ministry of Forests, Lands and Natural Resource Operations (FLNRO) partnered with the British Columbia Ministry of Energy and Mines (MEM), the British Columbia Ministry of Environment (MoE), Simon Fraser University (SFU) and the Geological Survey of Canada (GSC) to investigate shallow bedrock and unconsolidated groundwater aquifers in the rural area surrounding Dawson Creek falling within the Montney natural gas play (Wilford et al., 2012). This collaborative project includes three main objectives:

- to characterize the water chemistry of bedrock and unconsolidated aquifers;
- to expand the British Columbia Observation Well Network in oil and gas regions;
- to delineate the geological framework of the unconsolidated aquifers.

Objectives 1 and 2 are discussed in Wilford et al. (2012). This paper introduces objective 3; it discusses the impetus for this part of the project and provides some preliminary results.

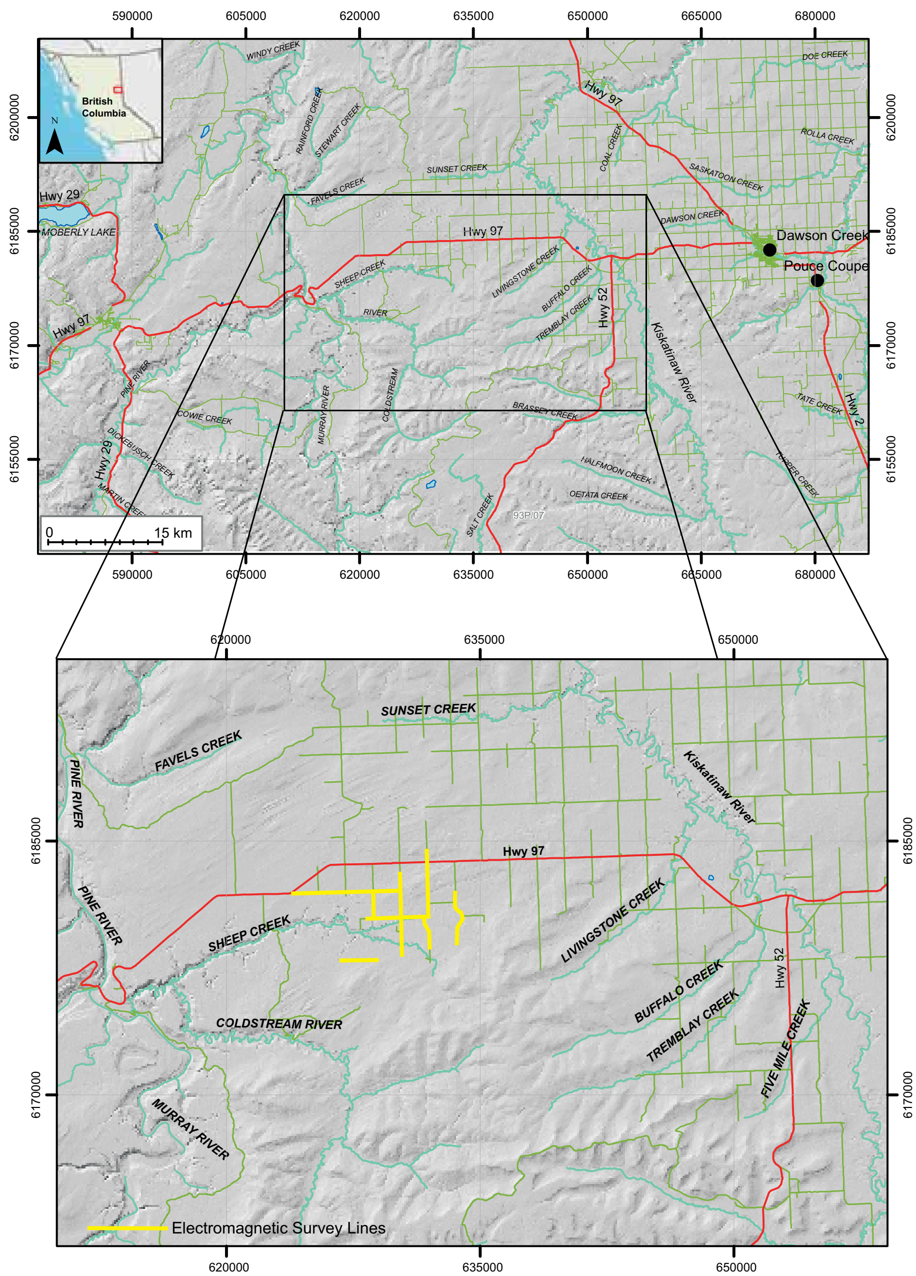


Figure 1. The study area is located in the Groundbirch area of northeast British Columbia.

Natural gas production from shale and other impermeable deposits has become a significant contribution to British Columbia's energy inventory (Adams, 2012). Petroleum exploration and production is also an essential component of British Columbia's economy. The Canadian Association of Petroleum Producers (CAPP) indicates that the oil and gas sector was responsible for more than $8 billion[1] of capital investment in British Columbia in 2010 (Canadian Association of Petroleum Producers, 2012). The province received more than $8.4 billion in oil and gas royalties for the fiscal years from 2005 to 2011 (Chapman et al., 2011). Although land sale activity has declined recently, cumulative land sale bonus revenue since 2005 exceeds $6.8 billion (Chapman et al., 2011). Development of these resources is possible through hydraulic fracturing and advances in horizontal drilling. Because hydraulic fracturing requires significant quantities of water, industry and government are working to evaluate all source-water options. A comprehensive understanding of water availability will aid in developing water sourcing and usage strategies that balance economic benefit with sustainability.

The study area is located in northeastern British Columbia and encompasses the region between the British Columbia–Alberta border and east to the Murray–Pine

[1] Net cash expenditures include geophysical and geological exploration and drilling, development drilling, field equipment, gas plants, operating wells and flow lines.

rivers (Fig. 1). Dawson Creek is the largest settlement in the region (population approximately 11 000) and the region is dominantly agricultural land and boreal forest. The area has a long history of oil and gas activity, with the first wells drilled as early as 1920 and significant activity continuing from the 1950s through to present (Janicki, 2008). The region has been the centre of recent natural gas activity and has received international attention because natural gas producers have been targeting the Triassic Montney Formation, a world-class shale and tight natural gas play.

Although hydraulic fracturing is often identified as a relatively new technology in shale and tight gas development, this stimulation technique has been used in British Columbia for more than 40 years to increase production efficiency from reservoirs. The difference between historic practices and current activity is the increase in the scale associated with shale gas development. With the advent of horizontal drilling and advances in hydraulic fracturing, producers are now able to economically recover natural gas from rocks not previously considered reservoirs because of low permeability (e.g., unconventional shale and tight gas). In the Montney play area, the target horizon is located approximately 2.5–3.5 km below the ground surface (Fig. 2). To liberate gas from the relatively impermeable shale and siltstone, long horizontal sections are drilled into the formation and the rock is hydraulically fractured, thereby providing conduits (increasing the permeability) for gas to move from the rock to the wellbore. Fracturing is achieved by pumping large volumes of water (Johnson and Johnson, 2012) at high pressure into the horizontal wellbore and out into the rock. Induced fractures in the rock are prevented from closing by incorporating proppants such as quartz sand with the hydraulic fluid as it is being injected into the fractures. Every production well in this play area uses hydraulic fracturing to induce economic production of natural gas. As development continues to expand, water management will be of paramount concern for industry, government and regulators.

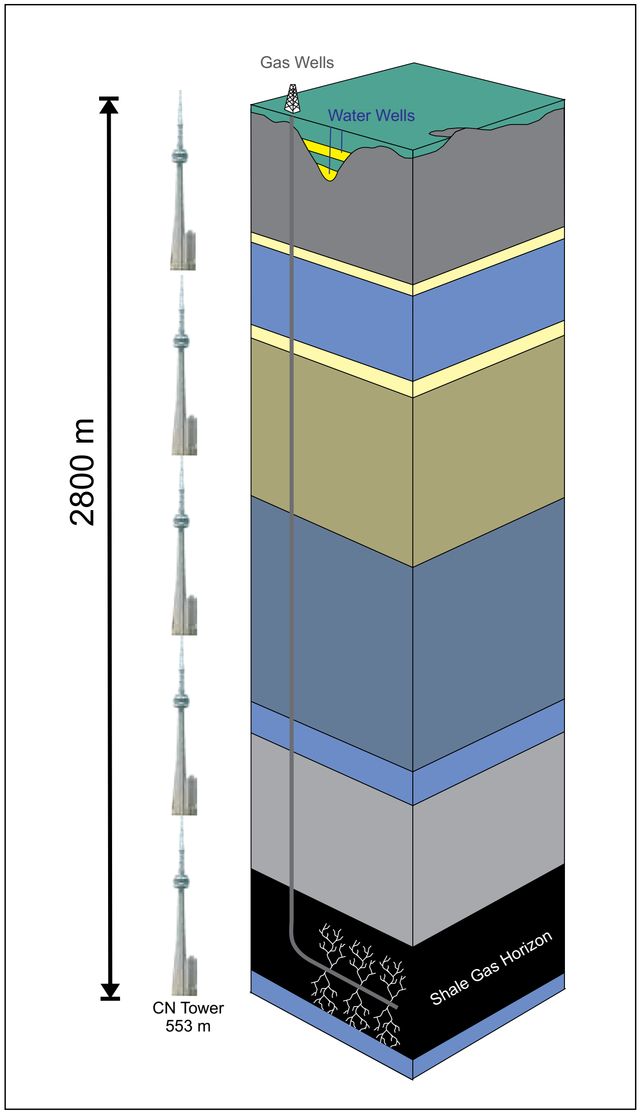


Figure 2. Hydraulic fracturing of the Montney Formation occurs between 2.5 and 3.5 km below the ground surface. This is the equivalent of five CN Towers, one on top of another, underground. Groundwater wells in the area are typically less than 250 m deep.

WATER SOURCES

Three natural sources of water are available for industrial use: surface, shallow subsurface (<600 m) and deep saline (<1000 m) water. Surface water, which includes lakes and rivers, continues to be the most abundant and most commonly used source. Shallow subsurface water may also be a significant source in the future. Saline water (or formation water) from deep underground reservoirs (well below drinking water) may also represent a potential source (e.g., Debolt Formation water has recently been used for hydraulic fracturing in the Horn River Basin, north of the study area; Hayes et al., 2011).

An inventory of water sources in the Montney play area was recently undertaken by Geoscience BC and partners (Brown, 2011) from which much of this study has evolved. Geoscience BC's collaborative initiative involved industry and various government agency partners, including MEM, MoE and FLNRO. Activities focused on compiling and analyzing publically available data. One of the projects in Geoscience BC's initiative involved a modelling exercise that assessed surface water resources through the collection of climate and precipitation data, stream flow, lake volume and related hydrometric information (Foundry Spatial, 2011). Analysis was aimed at determining surface water availability and seasonal variation at a watershed level. Another initiative updated MoE's WELLS database (which houses the province's water-well information) with previously unsubmitted water-well records from the Montney play area. These data were integral in aquifer classification (Lowen, 2011) and bedrock topography mapping (Hickin, 2011). The work by Lowen (2011) and Hickin (2011) confirmed the geometry of a buried paleovalley in the Groundbirch area, which is the focus of the work proposed in this study.

GROUNDBIRCH PALEOVALLEY

Buried Cenozoic paleovalleys are relatively common in northeast British Columbia (Mathews, 1978, 1980; Hickin et al., 2008; Hartman and Clague, 2008; Hickin, 2011). In many cases, these paleovalleys may contain late Neogene and late Pleistocene sediments (Reimchen and Rutter, 1972; Mathews, 1978; Edwards and Schafe, 1996; Hickin et al., 2008). Some paleovalleys are buried with little or no surface expression (Pawlowicz et al., 2005, 2007; Hickin et al., 2008), while others, like those within the study area, occur within modern bedrock-controlled valleys (Mathews, 1978). Since deglaciation, many of these paleovalleys have been incised by 150–250 m, exposing the sediments of the paleovalley-fill succession and bedrock.

Cowen (1998) suggested that buried paleovalleys in the Peace Region are significant sources of groundwater because they typically have higher yields than other potential aquifers. Buried paleovalleys are host to significant accumulations of heterogeneous sediment. Depending on the stratigraphy and hydrogeological constraints, coarse-grained units within the succession may be host to both confined and unconfined aquifers. The thickness, lateral extent and connectivity of these horizons are integral to understanding groundwater availability.

Hickin (2011) delineated nine paleovalleys in the Montney play area, including the Groundbirch paleovalley (GPV; Fig. 3), which was originally identified by Callan (1970). The bedrock topography, model by Hickin (2011), predicts the GPV to be approximately 6000 m wide, 100 m deep and trending west-southwest from the Kiskatinaw River to the Pine–Murray river confluence, paralleling Highway 97. This paleovalley has, in part, been described by Cowen (1998) but is depicted as a tributary of the Kiskatinaw paleovalley. Cowen (1998) reports good-quality fresh water hosted within interglacial sand and gravel of the GPV. His test drilling indicates that the local stratigraphy differs from that presented by Callan (1970) and that the basal gravel and related aquifer expected at the bedrock contact was not present in their drillholes. This suggests that there may be several aquifers at various elevations within the valley-fill succession and the geology is complex.

The GPV is exposed along the canyon sections of Coldstream River and Sheep Creek (Fig. 1). At the mouth of Coldstream River, there is a nearly continuous, 170 m thick section of valley-fill sediments and underlying bedrock exposed along a 3 km stretch of the canyon (Fig. 4, 5). This section provides an opportunity to observe the bedrock and six unconsolidated stratigraphic units that may be potential aquifers elsewhere in the buried paleovalley (Fig. 6).

COLDSTREAM RIVER SECTION

Cretaceous

UNIT 1: BEDROCK (DUNVEGAN FORMATION)

The GPV has incised into Cretaceous bedrock, through shale of the Kaskapau Formation, into the underlying Dunvegan Formation (Stott, 1961; McMechan, 1994). Dunvegan rocks at the base of the Coldstream River canyon include flat-lying, well-bedded, recessive fine-grained mudstone with interbedded 1–2 m thick resistant sandstone beds (Fig. 7). The Dunvegan Formation is interpreted as a succession of shingled, nonmarine to marine deltaic sediments consisting of mudstone, sandstone and conglomerate (Bhattacharya, 1989, 1993; Bhattacharya and Walker, 1991; Plint, 2000; Plint el al., 2001). Despite significant variation in the texture of the Dunvegan Formation, it has been identified by Mathews (1955), Jones (1966), Cowen (1998) and Lowen (2011) as a significant bedrock aquifer (Riddell, 2012). Hayes et al. (2011) suggest, however, that this unit has limited aquifer potential deeper in the subsurface. Fractures, joints and near-surface weathering may have created the shallow productive water zones of this unit, although coarse-grained facies should be considered as potential aquifers.

Pre-glacial/Interglacial

UNIT 2: SAND AND GRAVEL

The lowest and oldest unconsolidated unit preserved in this section is poorly exposed. Where encountered, it consists of partially cemented, oxidized and indurated interbedded sand and gravel (Fig. 8). The gravel is clast supported, poorly sorted, pebble to small cobble sized with a coarse sand matrix. In some places it is open-framework gravel; in other places, matrix is present. The medium to coarse sand occurs as moderately sorted, stratified lenses. The unit has a maximum thickness of 2–3 m where exposed, but both upper and lower contacts were obscured. The unit is discontinuous and where exposed could not be traced laterally for more than 40 m. It is interpreted to be a nonglacial fluvial deposit and would have excellent aquifer potential where present in the subsurface.

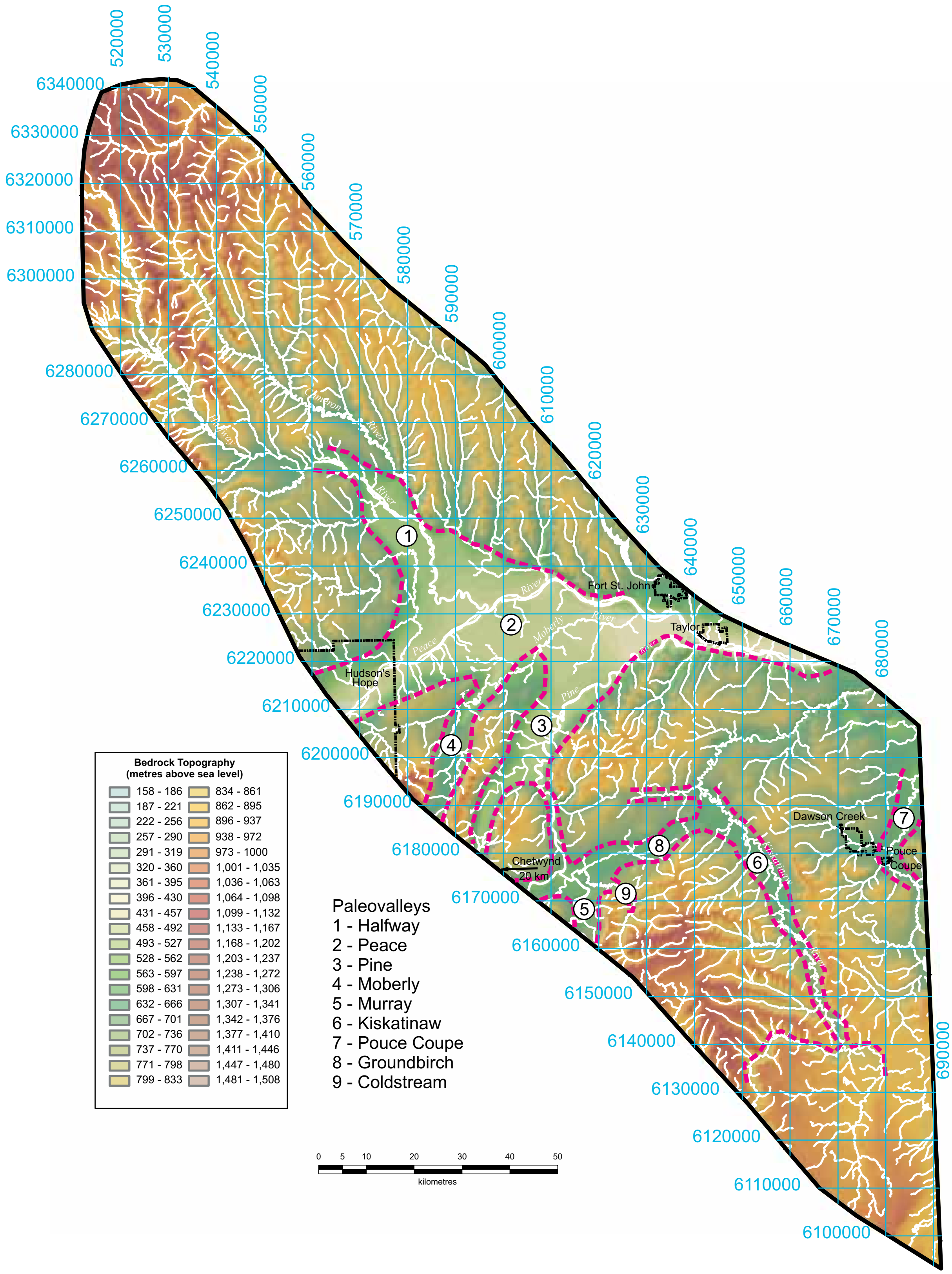
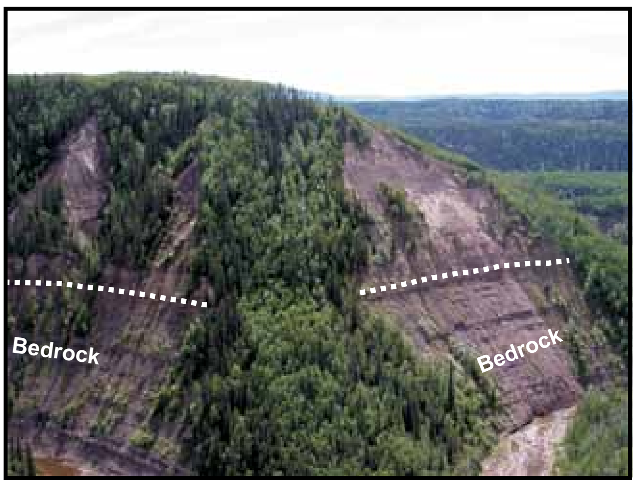


Figure 3. The Groundbirch paleovalley is one of nine paleovalleys identified from bedrock topography mapping by Hickin (2011).

Figure 4. Incision of the Coldstream River near its confluence with the Murray River has exposed the valley-fill succession of the Groundbirch Paleovalley. These exposures provide an excellent opportunity to observe the character and relationship of the stratigraphic units within the succession.



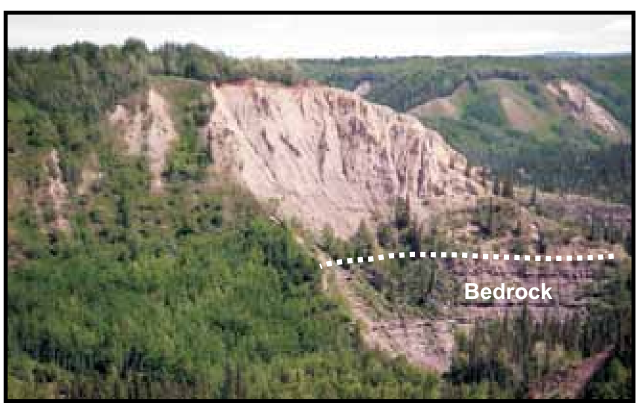


Figure 5. a) The south side of Coldstream River canyon exposes Dunvegan Formation bedrock, overlain by Groundbirch paleovalley-fill sediments; b) the north side of Coldstream River canyon has a thicker and likely more complete section of GPV-fill succession.

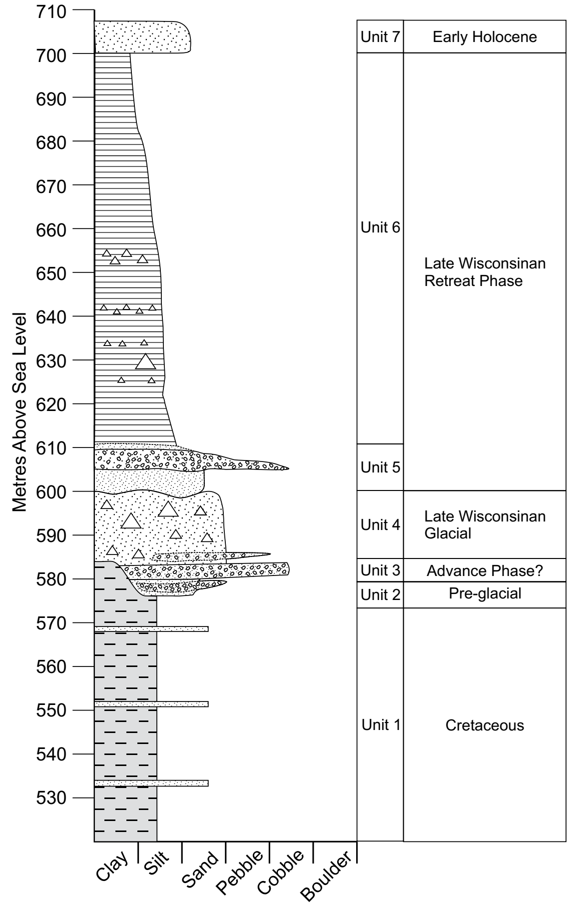


Figure 6. An idealized composite stratigraphic section of the Groundbirch paleovalley-fill succession that consists of seven units.

Figure 7. Dunvegan Formation bedrock is exposed at the base of the Coldstream River section.

Preglacial–Late Wisconsinan: Advance phase (?)

UNIT 3: SAND AND GRAVEL

Unit 3 consists of clast-supported, moderately oxidized, poorly sorted, pebble- to cobble-sized gravel in a silt to granule matrix (Fig. 9). It is 6 m thick at its maximum but pinches and swells laterally or is absent. It was observed along the north-facing canyon wall where it extends laterally for 150 m as a discontinuous body at the bedrock contact. The lower contact is sharp and presumed to be erosional. The matrix is poorly sorted and ranges from silt to granule in size, coarse sand being the modal size. Modal clast size is large pebble but ranges from small pebbles to cobbles. Clast lithologies are dominantly sandstone and silicified mudstone with abundant quartzite and no lithologies associated with eastern provenance (i.e., Canadian Shield; Mathews, 1980). This unit is interpreted to be a nonglacial fluvial deposit that transitions to an advance-phase glaciofluvial deposit. It would be an excellent host for an aquifer if present in the subsurface.

Late Wisconsinan: Glacial phase

UNIT 4: DIAMICT

Unit 4 is a matrix-supported, poorly sorted, granule to boulder diamict (Fig. 10). Matrix textures range from silty clay to sand. Clasts are well faceted, striated and have a glacial origin. The unit is 12–20 m thick and laterally extensive for kilometres (Fig. 10). It has either a sharp lower contact with bedrock or has an intercalated, gradational contact with the gravel of unit 3 (Fig. 10d). The diamict is interpreted as till associated with Late Wisconsinan glaciations. This unit is predicted to have limited porosity or permeability and is expected to be an aquitard/aquiclude in the stratigraphic succession.

Late Wisconsinan: Retreat phase

UNIT 5: SAND AND GRAVEL

Unit 5 consists of coarsening-upward medium sand to gravel at its base that transitions to a fining-upward succession of subhorizontally stratified, clast-supported, moderately sorted, pebble to small cobble gravel (Fig. 11). The lower contact is obscured; however, it is estimated that the unit consists of approximately 5 m of medium sand and 5 m of gravel. The gravel subunit could only be traced laterally for 25 m and was not observed above the exposure on the north-facing wall of the canyon. Unit 5 is interpreted to be a glaciofluvial or subaqueous deposit associated with retreating ice within Glacial Lake Peace (Mathews, 1980). The unit would be an excellent aquifer if present in the subsurface.

UNIT 6: CLAY, SILT, SAND AND DIAMICT

Unit 6 is a regionally extensive succession that makes up the majority of the Coldstream section. It generally fines upwards and consists of well-bedded, horizontally stratified clay, silt and diamict. In this section, the unit ranges from 70 to 100 m thick (Fig. 12a). The lower contact is conformable both over the diamict of unit 4 and over the gravel of unit 5 (Fig. 12b). The base of the unit, above unit 5, consists of sand with abundant type-A and type-B climbing ripples (Fig. 12c) indicative of a high bedload (Ashley et al., 1982) and likely associated with density underflows common in glaciolacustrine environments. Upsection, the unit transitions to horizontally stratified silt and sand with abundant dropstones as large as boulders (Fig. 12d). In general, the succession continues to fine upwards to rhythmically bedded silt, sand and clay, although throughout the middle portion of the unit, there are numerous beds of diamict (Fig. 12e, f). These are likely debris-flow diamicts or ice-rafted debris. Toward the top of the section, the unit consists of silt and clay with minor sand and no dropstones or diamict. This package is interpreted to represent waterlain sediment of a glaciolacustrine environment. This unit is heterolithological with a variety of sedimentary structures that reflect variation in ice position, seasonality, ice cover and location within the basin. The complexity of the unit means that its aquifer potential is unpredictable. Lowen (2011) indicates that in places this unit might be a main aquifer in the Peace Region, but this would depend on the local texture and thickness of potential water-bearing horizons.

Early Holocene

UNIT 7: SANDY SILT

Unit 7 occurs at the top of the section and is marked by a colour change where the sediment is heavily oxidized in bands (Fig. 13). This unit is uniform, poorly sorted sandy silt. Oxidized horizons are moderately indurated. Although the banding implies some stratification, it mimics topography, which suggests that the colour change results from diagenetic or pedogenic processes. Unit 7 is 5–6 m thick and the lower contact is gradational, marked by a subtle transition from rhythmically bedded silt and fine sand to sandy silt. This unit is interpreted to have an eolian origin, and is perhaps loess.

Figure 8. Unit 2 is the oldest unit in the Groundbirch paleovalley succession. It consists of sand and gravel and is likely a pre-Late Wisconsinan fluvial unit.

Figure 9. a) Weathered face of unit 9 showing the abundance of white quartzite and silicified siltstone clasts that comprise this preglacial/advanced-phase gravel; b) cleaned section of unit 9 shows the abundant matrix and the oxidation associated with this unit.

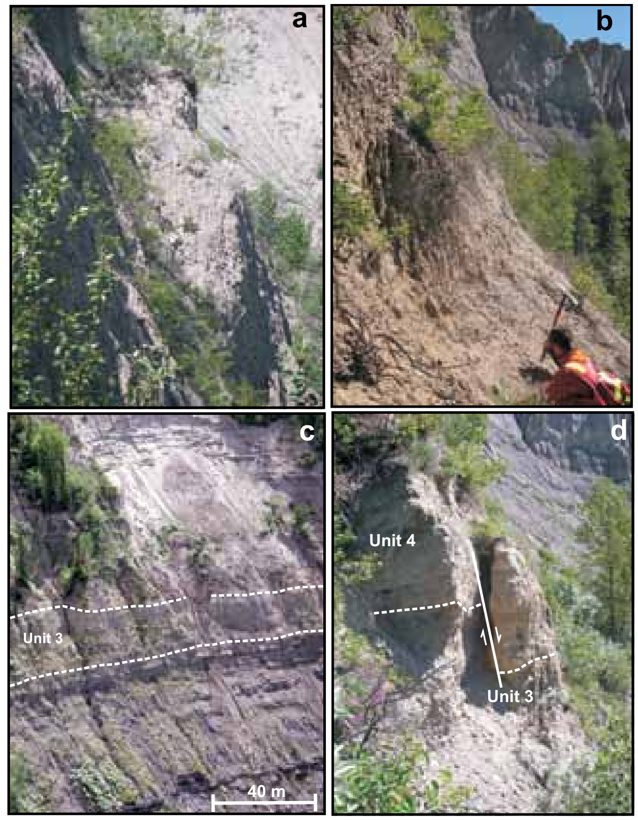


Figure 10. Unit 4 is a diamict: a) it forms competent vertical cliffs towards the base of the Coldstream River section; b) it consists of grey to brown diamict; c) it is laterally extensive and can be traced for kilometres on the south side of the Coldstream River canyon (north-facing exposure); d) the low contact is conformable and intercalated with unit 3.

DISCUSSION AND PROPOSED WORK

The Groundbirch paleovalley was identified in several studies as an important groundwater feature (Callan, 1970; Cowen, 1998; Lowen, 2004, 2011). These same studies suggest that there is a need for a more thorough groundwater evaluation to understand the aquifers in this groundwater system. Although there is abundant water-well information available in this area from the MoE WELLS database, the quality of the geological data is questionable. Discrepancies between the stratigraphy presented by Callan (1970) and that presented by Cowen (1998) indicate units vary from place to place and geology is unpredictable. This complexity is clearly apparent in the lower Coldstream River section where coarse-grained units are laterally discontinuous. Given the importance of this area in terms of economic development and water stewardship, more information on the geological framework that hosts the groundwater system is necessary. To address this, several geophysical surveys are proposed as part of the Northeast British Columbia Aquifer Project (Wilford et al., 2012).

1) Borehole electromagnetic (EM) and gamma surveys

One of the new observation wells drilled in a deep section of the paleovalley (85 m) was constructed with a polyvinyl chloride (PVC) casing (Fig. 1). The nonconductive casing will allow an EM-39 (Geonics Ltd.) slim-hole induction tool and a gamma probe to log the electrical and natural radioactivity of the valley-fill sediments. From these data, detailed lithological information can be inferred. The information will be combined with data from the Coldstream River section and used to calibrate the surface geophysical surveys.

Figure 11. Unit 5 is a sand and gravel unit: a) the upper portion of unit 5 consists of a fining-upward gravel; b) the gravel in this unit is pebble to cobble sized and consists mainly sandstone and mudstone clasts of a western provenance.

2) Ground-based EM survey

Electromagnetic surveys have been used in hydrogeological investigations since the 1970s (Reynolds, 1997). For this survey, the ProTEM 47 (Geonics Ltd.) will be implemented, using a 100 m square transmitter loop with the receiver located at the centre of the loop (McNeil, 1994). This instrument is a time-domain EM system that measures voltage as a function of time after the current in a transmitter loop has been switched off. The change in voltage of the decaying signal is used to model the electrical properties (resistivity) of the subsurface. The resistivity of the layers is related to grain size, water content and water salinity. Because the anticipated depth of investigation is approximately 100 m, the ProTEM 47 was selected for two main reasons: 1) the method is nondestructive and after a measurement is collected, i.e., there is no surface disturbance and 2) this instrument is more portable than the larger ProTEM 57 because it is battery operated and needs no external power source (e.g., a generator), which increases the efficiency of data collection.

Measurements will be combined and a one-dimensional layered-earth model will be generated using Interpex software (Interpex Ltd., Golden, Colorado). The one-dimensional depth models will be integrated into two-dimensional resistivity sections to provide a representation of the geology within the valley fill and offer insight into the geometry and extent of potential water-bearing horizons.

3) Shallow reflection seismic survey

A shallow reflection seismic survey has been proposed for a later phase of the project. The seismic data will complement the EM survey by providing information on the location of boundaries between lithological units of contrasting acoustic impedance. This provides information on the geometry of the paleovalley and the architecture of the valley-fill sediments, which is critical to hydrogeological investigations (Rabbel, 2006). By combining the two surveys, information on both the texture and valley-fill architecture can be deduced (Hickin et al., 2009). The ideal seismic method is the land streamer–Minivib system developed by the GSC (Pugin et al., 2009a, b). This system uses a Minivib (Industrial Vehicles International Inc.) vibrating source consisting of a 140 kg mass that sweeps through a frequency range of 10–550 Hz (Pugin et al., 2009b). The Minivib tows a land streamer array of small metal sleds, equipped with a three-component geophone (Fig. 14). The land streamer approach eliminates the need to set geophones and the vibrating source eliminates the necessity for a percussion source. Data acquisition is very efficient; the system can collect 1000 records per day (4–8 km/day). Fortuitously, many of the roads in the Groundbirch area are oriented perpendicular to the trend of the GPV, which offers an excellent opportunity to image multiple cross-sections across the buried valley.

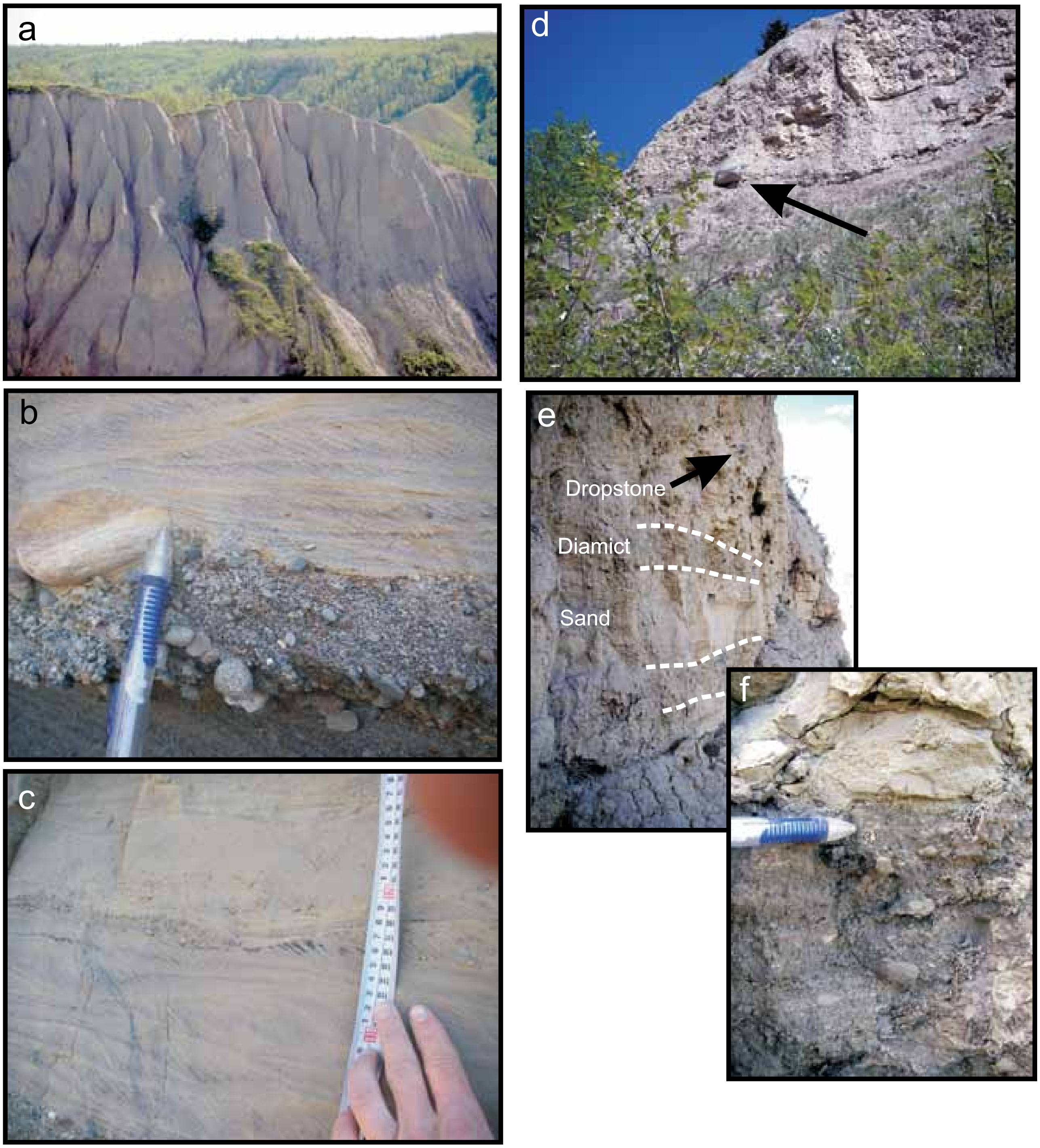


Figure 12. Unit 6 is a hetrolithologic glaciolacustrine unit: a) the unit is the thickest (70–100 m) and most voluminous unit in the Groundbirch paleovalley succession; b) the lower contact is conformable over unit 5; c) the lower part of unit 6 consists of sand with well-developed climbing ripples likely associated with underflows; the ripples are highlighted by sand-sized fragments of black coal; d) the middle part of unit 6 has an abundance of dropstones, some of which can be large boulders (indicated by the arrow); e) the bulk of the middle portion consists of interbedded sand, silt and diamict with common dropstones; f) laterally continuous, massive, matrix-supported diamict beds are commonly interbedded with sandy glaciaolacustrine deposits of unit 6; the diamict likely represents subaqueous debris flows and ice-rafted debris.

Figure 13. Unit 7 is the youngest unit in the succession and is demarcated by a distinct colour change (oxidation) at the top of the section. There is only a very subtle decrease in the grain size between the top of unit 6 and the base of unit 7. The origin of this unit is speculated to be eolian.

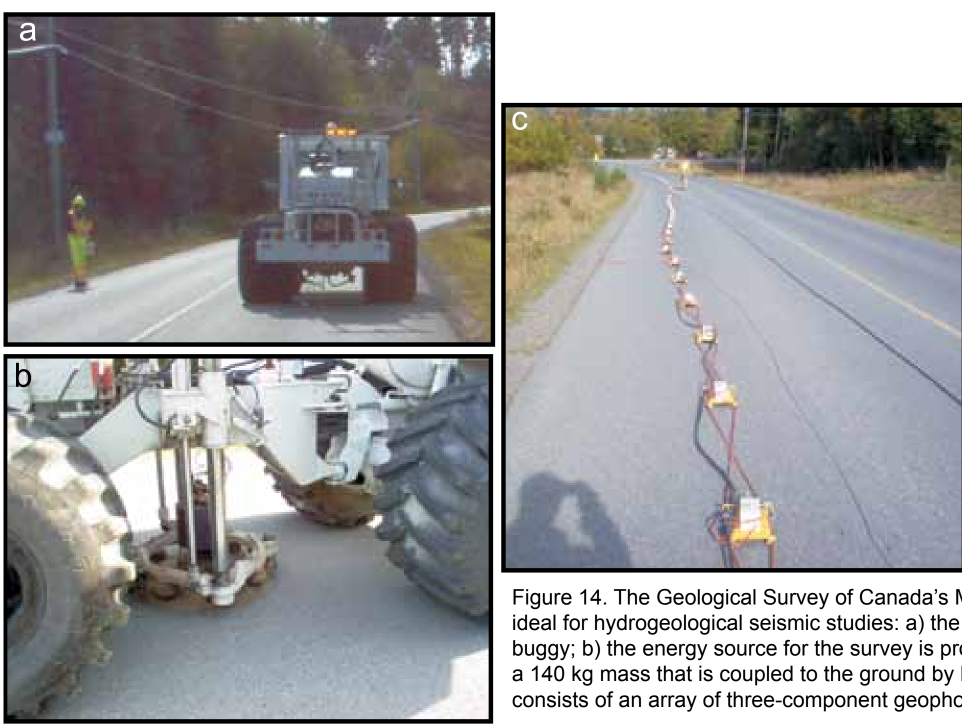


Figure 14. The Geological Survey of Canada's Minivib with land streamer is ideal for hydrogeological seismic studies: a) the vibrator is mounted on a Minivib buggy; b) the energy source for the survey is provided by a vibrator, consisting of a 140 kg mass that is coupled to the ground by hydraulics; c) the land streamer consists of an array of three-component geophones mounted on metal sleds.

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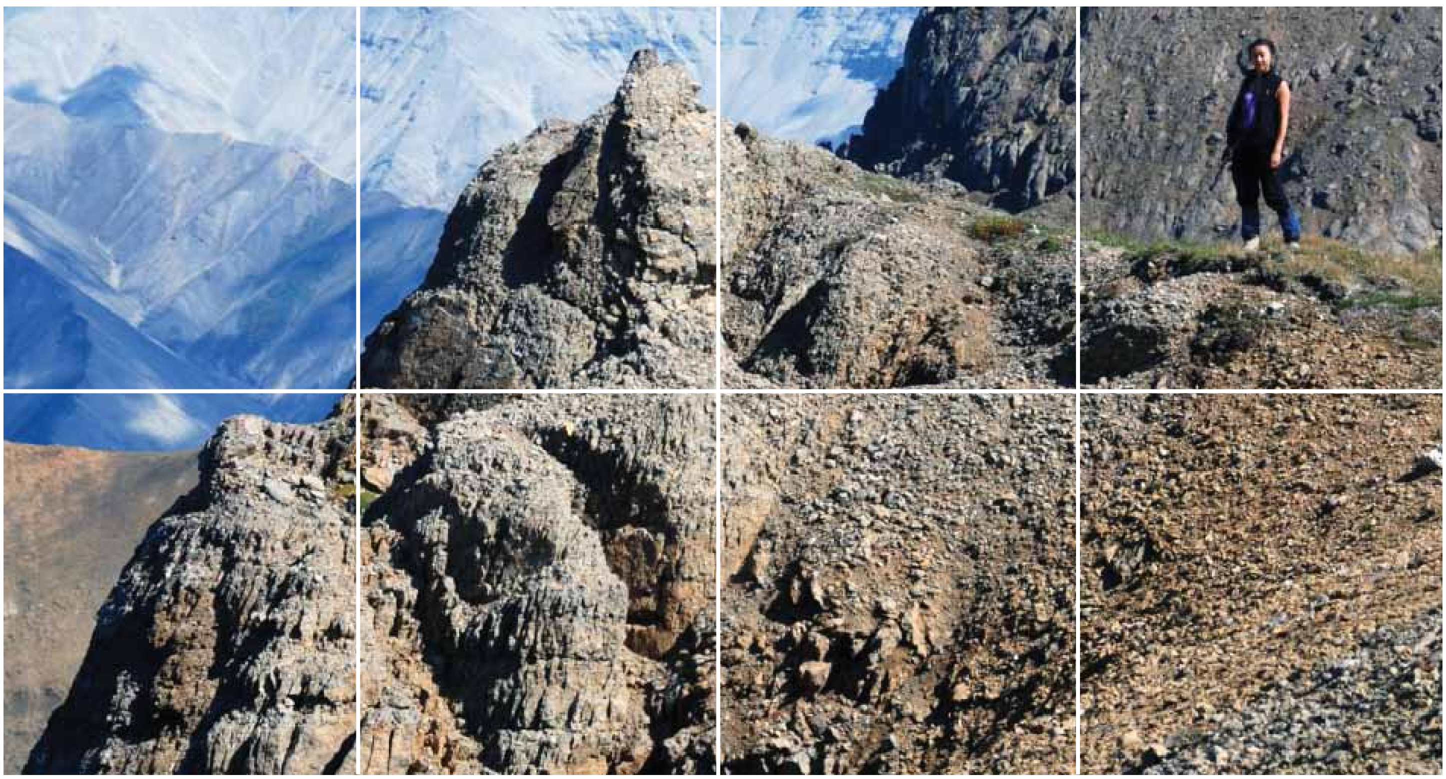

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