Stratigraphic Correlation and Sedimentary Provenance of Triassic Natural Gas–Bearing Rocks in Northeastern British Columbia (NTS 094B): Correlation of Outcrop to the Subsurface

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Golding, M.L., Zonneveld, J-P., Orchard, M.J., Ferri, F. and Mortensen, J.K. (2011): Stratigraphic correlation and sedimentary provenance of Triassic natural gas–bearing rocks in northeastern British Columbia (NTS 094B): correlation of outcrop to the subsurface; *in* Geoscience BC Summary of Activities 2010, Geoscience BC, Report 2011-1, p. 229–238.

Introduction

Triassic rocks of the Western Canada Sedimentary Basin (WCSB) in northeastern British Columbia contain large reserves of natural gas that are an important resource for the province. Their equivalents in Alberta have long been developed for oil and gas; the lower-most of these units are known as the Montney and Doig formations in the subsurface. The equivalents in BC, however, have not been as extensively studied or developed as those in Alberta. Previous work has concentrated on the sedimentology and biostratigraphy of the surface equivalents to the Montney and Doig formations, namely the Grayling, Toad and Liard formations in northeastern BC. This project aims to build on this work by studying outcrop sections in the Halfway River map area (NTS 094B), paying particular attention to the sedimentology of the sections, and collection of samples for biostratigraphic and detrital zircon studies. This in turn will allow improved correlation of hydrocarbon-bearing rocks across BC, with the potential to increase exploration in the areas surrounding the city of Fort St. John. It will also lead to an increased understanding of sedimentation pathways during the deposition of Triassic rocks in the WCSB, which will help to determine the distribution of sedimentary facies amenable to hydrocarbon generation and accumulation.

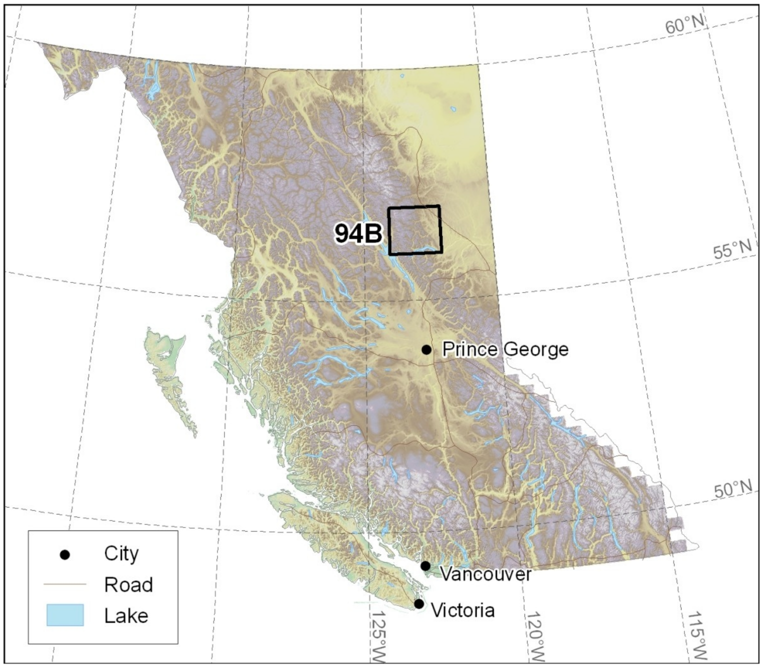

Figure 1. Location of the Halfway River map area (NTS 094B), northeastern British Columbia.

In addition to being productive hydrocarbon reserves, the Triassic rocks of the WCSB were deposited at an important time in the assembly of the North American Cordillera. It has previously been argued that convergence between the passive margin of North America and the outboard pericratonic terranes began some time during the Jurassic (Monger and Price, 2002). Evidence from the Yukon, however, has suggested that this convergence may have begun as long ago as the Late Permian (Nelson et al., 2006; Ber-

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Keywords: *Triassic, Western Canada Sedimentary Basin, correlation, conodont, detrital zircon, sedimentary provenance, Doig phosphate zone, South Halfway, Williston Lake*

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anek et al., 2010b). This theory is based in part upon the timing of emplacement of intrusions in Yukon-Tanana terrane, as well as the presence of detrital zircons in Triassic sediments that could only have been sourced from that terrane. The collection of detrital zircon samples from northeastern BC will help determine whether accretion began at a similar time farther south. The well-defined biostratigraphic timescale for the Triassic in BC will allow the timing of this event to be better constrained.

Fieldwork was undertaken in the summer of 2009, with a single section studied south of the Halfway River (Figure 2), named the South Halfway section. A detailed report of this work was published in Ferri et al. (2010). Since that time, work on the biostratigraphy of the section has been completed, and preliminary results from the detrital zircon samples are reported here.

This paper also provides an update on fieldwork conducted along the east arm of Williston Lake (Figure 3) during the summer of 2010. Eight Triassic sections were examined, namely Beattie Ledge, East Carbon Creek, Folded Hill, Glacier Spur, Brown Hill, Black Bear Ridge, Ne-parle-pas Point and Ursula Creek. Although these sites have been well studied in the past (Whiteaves, 1889; McLearn, 1930, 1940, 1941a, 1941b; Tozer, 1967; Irish, 1970; Thompson, 1989; Gibson and Edwards, 1990, 1992; Zonneveld, 2010), no sampling for detrital zircon dating was carried out at that time. The well-established conodont and ammonoid biostratigraphy of these sections (Orchard and Tozer, 1997) make them well suited for a study of the timing of changes in sedimentary transport pathways. Conodont samples have also been collected from some of these localities in order to improve the biostratigraphic record of these sections and hence improve correlations within Triassic strata throughout northeastern BC.

Triassic Stratigraphy of Northeastern British Columbia

Figure 4 is a stratigraphic chart showing the different Triassic formations recognized in northeastern BC, as well as their equivalents in the subsurface to the east (Peace River and Alberta/BC) and in Alberta farther to the southeast (Foothills–Bow/Sukunka rivers).

The oldest formation studied and sampled during fieldwork on this project is the Toad Formation, at South Halfway (Figure 2), Ursula Creek, Brown Hill and Glacier Spur (localities 16, 10, 9, Figure 3). This formation consists of argillaceous to calcareous siltstone, silty shale, silty limestone and dolostone, as well as very fine grained sandstone (Thompson, 1989). It spans the Smithian (Early Triassic) to the Ladinian (Middle Triassic), and it is equivalent to the Montney and lower Doig formations in the subsurface (Zonneveld, 2010).

Above the Toad Formation lies the Liard Formation, which consists of fine to coarse sandstone, calcareous and dolomitic siltstone and sandy to silty dolostone and limestone (Thompson, 1989). It was examined and sampled at South Halfway (Figure 2), Glacier Spur, Folded Hill and Beattie Ledge (localities 9, 8, 3, Figure 3). It ranges in age from the Ladinian to the Carnian, and is the surface equivalent of the upper Doig and Halfway formations (Zonneveld, 2010).

The Charlie Lake Formation overlies the Liard Formation and consists of calcareous and dolomitic siltstone and sandstone, dolostone, limestone and evaporite (Zonneveld, 2010). The formation retains its name in the subsurface, and is considered to be Ladinian–Carnian in age (Zonneveld, 2010). No samples were collected from this formation.

The Charlie Lake Formation is in turn overlain by the Baldonnel Formation, which is characterized by a sequence of limestone, dolostone and siltstone (Zonneveld, 2010). This unit is named after its subsurface equivalent. The age of this formation ranges from upper Carnian to lower Norian in the east, and from lower Carnian to upper Carnian in the west (Zonneveld, 2010). It was observed and sampled at East Carbon Creek (locality 4, Figure 3).

The Ludington Formation is the western deep-water equivalent of the Liard, Charlie Lake and Baldonnel formations (Gibson, 1993), and as such is only found in the most westerly outcrops. Samples were collected from this formation at Ursula Creek (locality 16, Figure 3). It consists primarily of dolostone, limestone and calcareous siltstone and is Ladinian–Carnian in age (Zonneveld, 2010).

The youngest part of the Triassic is represented by the Pardonet Formation, which was studied and sampled at Ne-parle-pas Point and Black Bear Ridge (localities 15, 12, Figure 3). This formation consists of limestone, dolostone, calcareous silt and shale (Zonneveld, 2010). This unit can also be traced into the subsurface, and it is Norian to Rhaetian in age (Zonneveld, 2010).

South Halfway Section

The South Halfway section is located approximately 2 km south of the Halfway River, with the base of the measured section at 473870E 631169N (Zone 10, NAD 83; Figure 2). The section has previously been described by Gibson (1971) and Ferri et al. (2010). In the summer of 2009, the section was investigated by two of the authors (Golding and Ferri). The section consists of 643 m of the Toad and Liard formations with stratigraphically higher outcrops of the Charlie Lake, Baldonnel and Pardonet formations. A detailed report of this work was published in Ferri et al. (2010). Since that time, work on the biostratigraphy of the section has been completed, and preliminary results from the detrital zircon samples are reported here.

Biostratigraphy

Eighteen conodont samples were collected from throughout the section, but only one was productive (sample 09-OF-SH15). This sample was taken from sandy carbonate near the base of the Liard Formation, at a distance of 627 m above the base of the section, as defined in Ferri et al. (2010). The conodonts belong to two species—*Neogondolella liardensis* Orchard and *Budurovignathus mungoensis* (Diebel). Both of these species are indicative of the sutherlandi and desatoyense zones. Although a number of ammonoids and bivalves were collected in situ, it has not been possible to identify these due to poor preservation. However, one ammonoid collected from scree above the

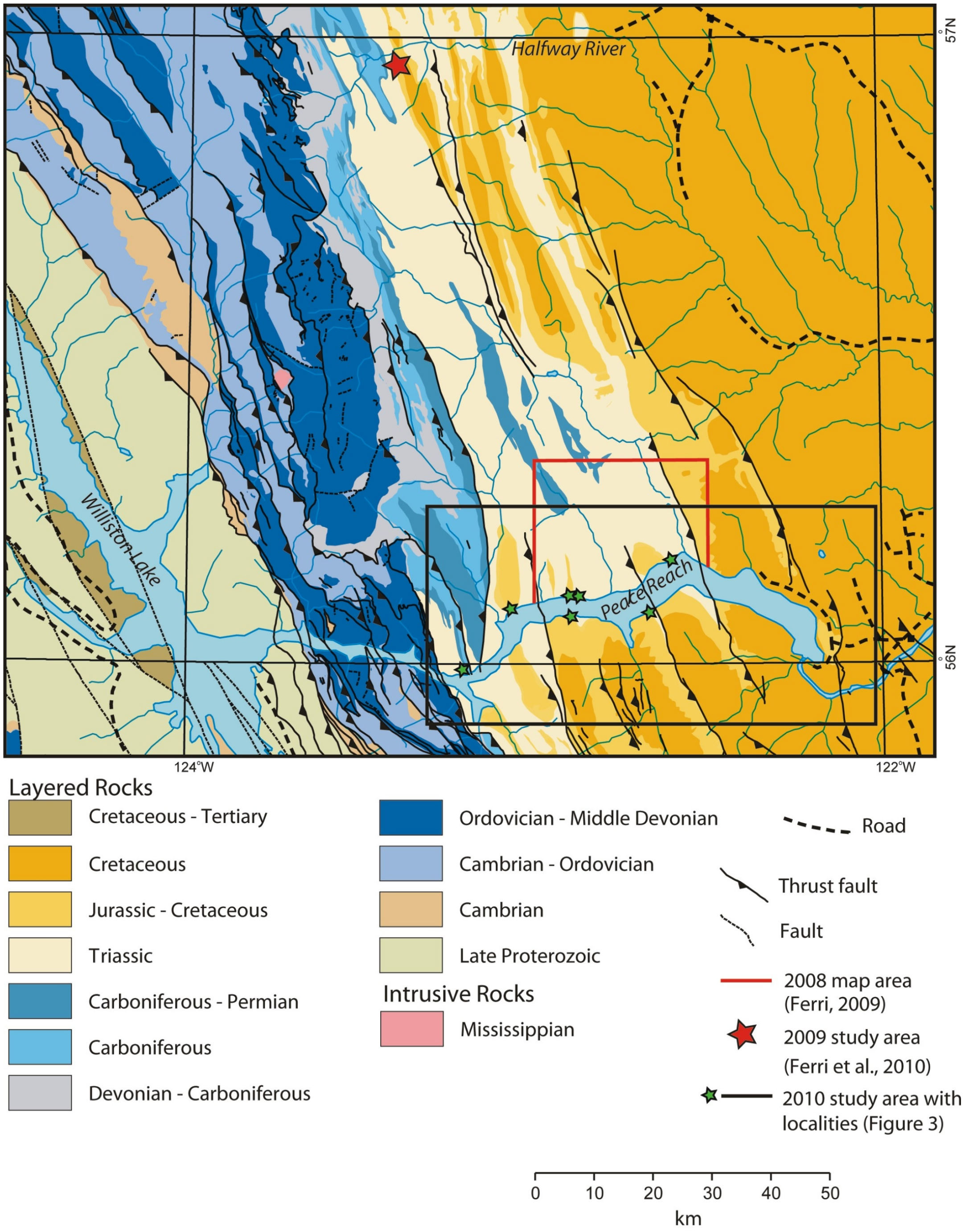

Figure 2. Regional geology of the Halfway River map area, northeastern British Columbia, showing the location of the 2010 study area, the South Halfway section (studied in 2009), as well as the location of work carried out by the authors in 2008 (see Ferri, 2009). After Ferri et al. (2010).

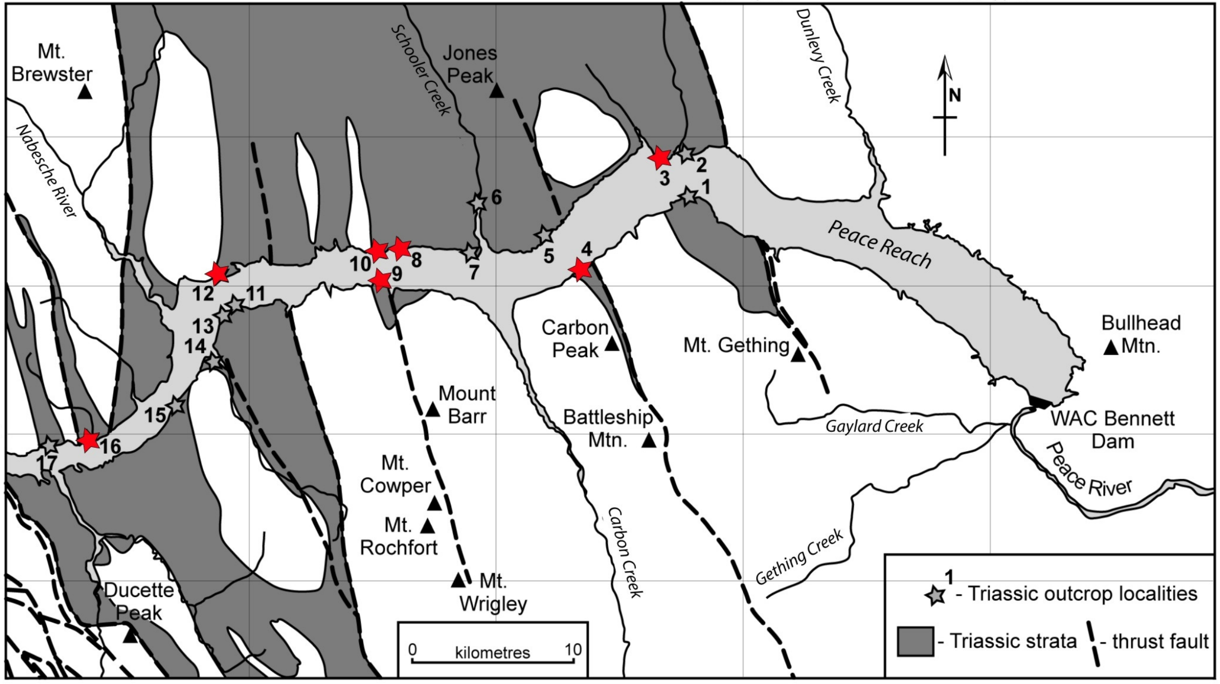

Figure 3. Map of Peace Reach in the Halfway River map area, northeastern British Columbia, showing the distribution of Triassic outcrop and the location of Williston Lake sections (after Zonneveld, 2010). Those sections studied in 2010 are highlighted by red stars: Beattie Ledge (3); East Carbon Creek (4); Folded Hill (8); Glacier Spur (9); Brown Hill (10); Black Bear Ridge (12); Ne-parle-pas Point (15); and Ursula Creek (16).

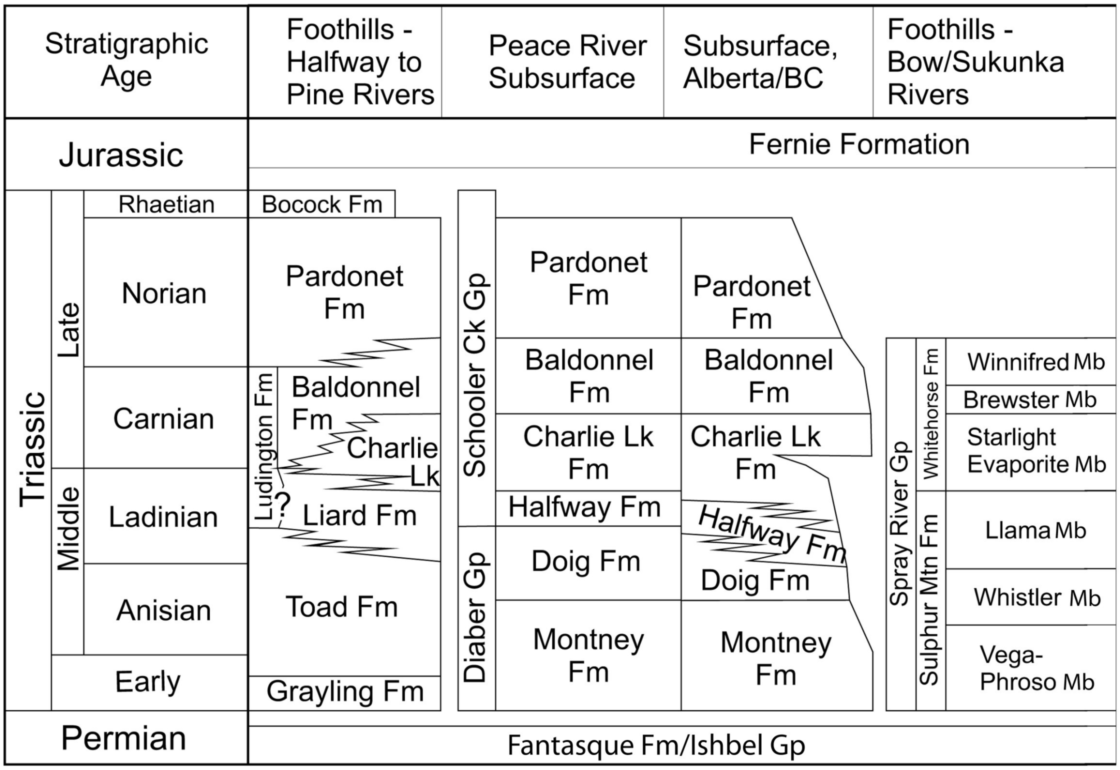

Figure 4. Triassic formations in British Columbia and their correlations with those in the subsurface and in southern Alberta (modified from Ferri, 2009). Abbreviations: Ck, Creek; Fm, Formation; Gp, Group; Lk, Lake; Mb, Member; Mtn, Mountain.

highest conodont sample is identifiable as *Nathorstites macconnelli* (Whiteaves). This is indicative of the sutherlandi zone, which is consistent with the conodonts collected from stratigraphically lower in the section. The sutherlandi zone, as defined by Tozer (1994), consists of two subzones and is the youngest zone of the Ladinian; however, work on conodonts from BC and Nevada (summarized in Orchard, 2010) indicates that the younger subzone is Carnian in age. This is the subzone that contains *Nathorstites macconnelli*. Therefore, at the South Halfway section, the base of the Liard Formation either occurs within the uppermost Ladinian or the lowermost Carnian. The formation is at least in part Carnian. It is interesting to note that within the scree below the sample of *Nathorstites* there is a large accumulation of terebratulid brachiopods, which are also found below the occurrence of *Nathorstites* on Williston Lake, more than 60 km to the south. McLearn (1947) described the distribution of the *Nathorstites* fauna across BC.

Detrital Zircons

Six detrital zircon samples were collected from throughout the section. The majority of the rock sampled was siltstone, and the very small grain size of the contained zircons made them very difficult to analyze. The most interesting of the preliminary results comes from sample SH02-Z, collected 421 m above the base of the section. Although some of the grains from sample SH02-Z are of Proterozoic age, at least one grain is Devonian in age. This could indicate derivation from the Ellesmerian orogenic wedge to the north (e.g., Beranek et al., 2010a), from Devonian igneous rocks within the Yukon-Tanana terrane, or from a more local origin. However, with only one grain present it is not possible to distinguish the possible source areas based on the zircon data alone. The sample originates 206 m below the only firm age constraint in the section (dated conodont sample 09-OF-SH15 at 627 m) and so the timing of Devonian input into the WCSB is poorly constrained. Further attempts will be made to obtain datable zircons from sample SH02-Z and also SH04-Z and SH05-Z, which are closer to the location of the dated conodont sample 09-OF-SH15.

Correlation with the Subsurface

The gamma-ray logs that were generated for the section enable its correlation with other sections both at the surface and in the subsurface. A preliminary correlation has been published by Ferri et al. (2010), based upon the recognition of the Doig phosphate zone. Phosphate is commonly associated with radioactive elements including U, K and Th. The Doig phosphate zone therefore shows up as a spike at the Montney-Doig boundary in the gamma-ray logs, as shown in Figure 5. This is particularly sharp in the more easterly sections, but becomes more diffuse to the west, possibly indicating that the Doig Formation is condensed in the east, and the lower boundary may be unconformable. The Doig phosphate zone has previously been assigned an age from Spathian to Anisian (Zonneveld, 2010), and although the top of the spike at the South Halfway section is 327 m below the conodont sample 09-OF-SH15 that yielded a Ladinian–Carnian age, it is consistent with the age range that has previously been suggested.

Williston Lake Sections

In the summer of 2010, three of the authors (Golding, Zonneveld and Orchard) conducted fieldwork on Peace Reach, the eastern extension of Williston Lake in the Halfway River map area (NTS 094B; Figure 3). Eight Triassic sections were examined, namely Beattie Ledge, East Carbon Creek, Folded Hill, Glacier Spur, Brown Hill, Black Bear Ridge, Ne-parle-pas Point and Ursula Creek. Samples were obtained for both detrital zircon and conodont analysis, and collection focused on the parts of the sections that were considered most likely to be productive. Detrital zircon samples were collected from the coarsest sediment present, whilst conodont samples were collected from carbonates where knowledge of the fauna present was incomplete in order to improve the biostratigraphic record of these sections and hence improve correlations within Triassic strata throughout northeastern BC.

Sampled sections range in age from Smithian to Rhaetian. The Late Permian is the earliest time that the accretion of the pericratonic terranes has been postulated (Beranek et al., 2010b), however evidence for convergence during the Triassic would be earlier than has previously been suggested for the Cordillera (Monger and Price, 2002).

The following descriptions of examined sections are discussed by geographic locality, from west to east (Figure 4). Stratigraphic logs of the sections were published in Zonneveld (2010), and measurements refer to the distance above the base of the sections as defined in those logs.

Ursula Creek

The section at Ursula Creek is located near the western end of Peace Reach (locality 16, Figure 3). This location was chosen because it is one of the most westerly outcrops of Triassic rocks in the WCSB, and as such is more likely to contain evidence for sediment transport from the west, if any such evidence is present. The sediments at this section consist primarily of shale and siltstone of the Grayling and Toad formations with carbonates belonging to the Ludington Formation above. Four detrital zircon samples were collected from coarse beds located 78.90, 85.20, 124.9 and 129.55 m above the base of the section. These samples were all taken from the Toad Formation and fit into a well-defined biostratigraphic timescale that ranges from Smithian to Ladinian in age.

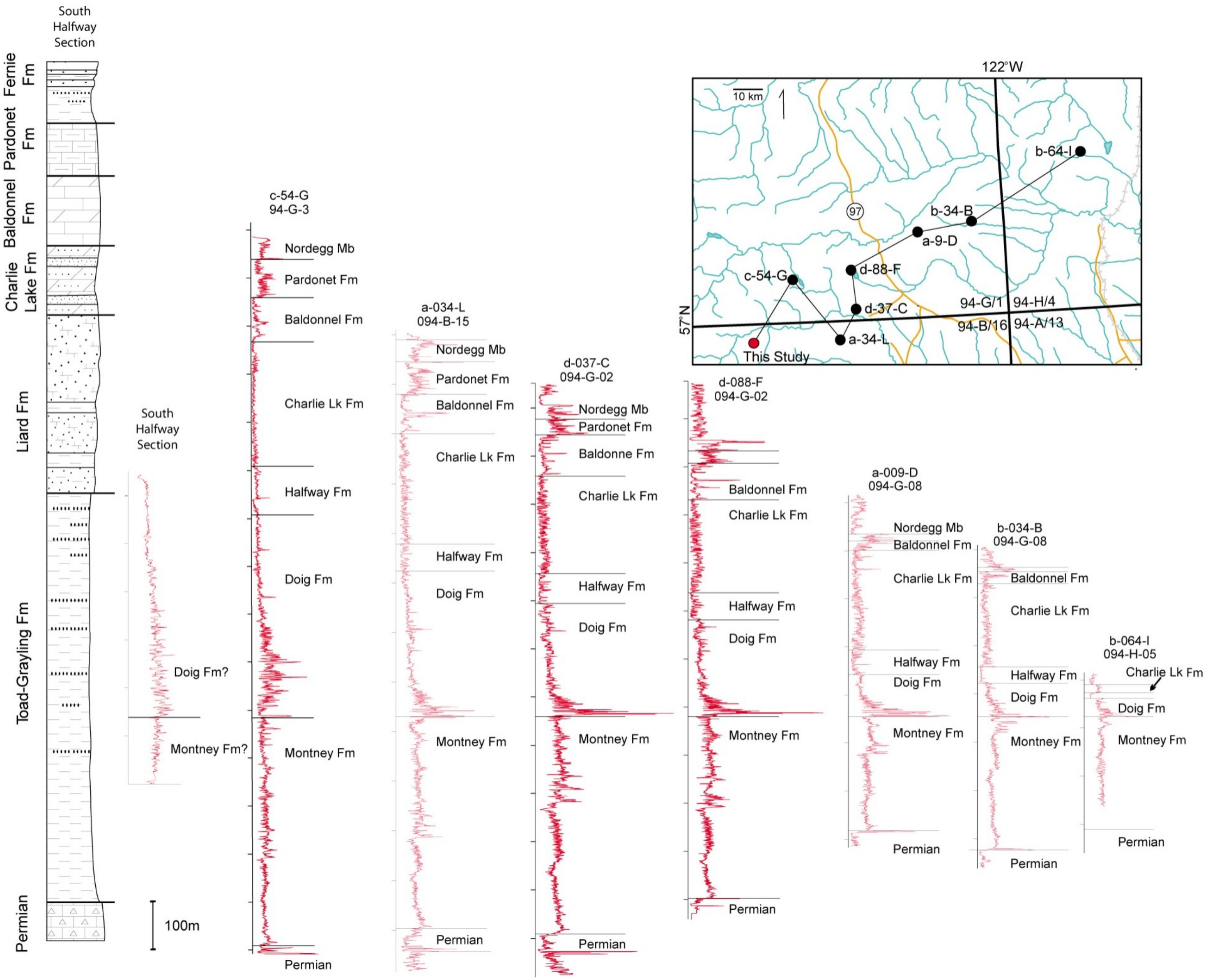

Figure 5. Correlation of lithological and gamma-ray logs of the South Halfway section with gamma-ray logs from subsurface wells to the east, northeastern British Columbia. The Doig phosphate zone shows up as a prominent spike in the readings near to the Montney-Doig boundary, although it becomes less pronounced in the more westerly logs. Locations of the logs shown on map (inset). After Ferri et al. (2010).

Ne-parle-pas Point

The Ne-parle-pas Point section (locality 15, Figure 3) is located farther to the east of Ursula Creek, and was chosen for investigation because of three coarse lag beds within the Pardonet Formation. These beds are located 41.2, 42.5 and 51 m above the base of the measured section and were sampled for detrital zircon geochronology. The Pardonet Formation here consists of shale and silt punctuated by coarser beds, and it has previously been dated to the Norian stage.

Black Bear Ridge

The section at Black Bear Ridge (locality 12, Figure 3) has been extensively studied due to the presence of a complete Carnian-Norian boundary section, and it is a candidate for the Global Boundary Stratotype Section and Point for this boundary (Orchard et al., 2001). The oldest unit present at Black Bear Ridge is the Ludington Formation, which consists of calcareous and dolomitic siltstone. This is overlain by turbidites belonging to the Pardonet Formation. This study focused on the upper part of the Pardonet Formation, which has been dated to the Rhaetian. This is the youngest section that was examined on Williston Lake. If detrital zircons sampled from this section suggest transport from the west during the Rhaetian, it would push back the currently accepted date for the final accretion of the outboard terranes from the Early Jurassic. In the Yukon, westerly derived sediment from the Late Permian onwards have been detected but it is not clear whether sediment input occurred as early in BC.

One detrital zircon sample was collected from a granule lag bed, 242 m above the base of the measured section. The last occurrence of *Monotis* is below the lag bed. However, the age of the section above the lag bed is poorly constrained due to difficulty in obtaining productive conodont samples, and as such, four additional conodont samples were collected in an attempt to improve the resolution of the biostratigraphic timescale. Two were from shale, 242.8 and 243.8 m above the base of the measured section, and two were from calcareous nodules that were 242.8 and 244.05 m above the base.

Brown Hill

The Brown Hill section is located farther east of Black Bear Ridge (locality 10, Figure 3). Here, calcareous siltstones and fine sandstones of the Toad Formation are overlain by fine to medium sandstone and carbonate of the Liard Formation, which is in turn overlain by carbonates, evaporites and crossbedded sandstones belonging to the Charlie Lake Formation. The upper part of the section consists of carbonate and calcareous sandstone of the Baldonnel Formation overlain by sandstone, shale and nodular and bioclastic limestone belonging to the Pardonet Formation. Two samples were collected for detrital zircon dating from beds located 191 and 239 m above the base of the measured section. These samples are from fine sandstone of the Toad Formation (Anisian to Ladinian in age).

Glacier Spur

Glacier Spur is located across the lake from Brown Hill (locality 9, Figure 3). The section is 370 m thick, and is the most extensively sampled of all the sections. At the base of the section is the Toad Formation, consisting of interbedded siltstone and shale. Above this are fine to medium sandstones and carbonates of the Liard Formation as well as carbonates and evaporites belonging to the Charlie Lake Formation. Five detrital zircon samples were collected from coarse sand beds at 122.6, 149.0, 255, 293.8 and 304 m above the base of the measured section, and five conodont samples were collected from calcareous beds at 129, 235, 312.3, 312.7, 313 and 319.3 m above the base. The samples all come from the Liard Formation, which is dated to the Ladinian. The collection of a large number of detrital zircon and conodont samples will hopefully allow the timing of any changes in sedimentary provenance to be tightly constrained. Although conodont samples have previously been collected from this section, the current samples should help to better constrain the age ranges present.

Folded Hill

Folded Hill is located just east of the Brown Hill locality (locality 8, Figure 3). The section consists of shale, siltstone and sandstone belonging to the Toad Formation, overlain by shale, fine to medium sandstone and minor carbonate of the Liard Formation, which is intercalated with fine sandstone of the Charlie Lake Formation. One detrital zircon sample was collected from a coarse sand bed located 203 m above the base of the measured section. This sample was taken from the Liard Formation (Ladinian in age).

East Carbon Creek

Farther to the east, there is a section at East Carbon Creek (locality 4, Figure 3). At the base of the section, there is fine sandstone and carbonate of the Charlie Lake Formation, which transitions into calcareous siltstone, sandstone and carbonate of the Baldonnel Formation. Again, one sample was collected for detrital zircon analysis from a granule lag bed located 76 m above the base of the measured section. This sample comes from the Baldonnel Formation (Carnian in age).

Beattie Ledge

The easternmost section investigated was Beattie Ledge (locality 3, Figure 3). Here there is siltstone and fine sandstone of the Toad Formation, intercalated with fine to coarse sandstone and carbonate biostromes of the Liard Formation. This unit is in turn intercalated with sandstone, carbonate and evaporite of the Charlie Lake Formation. No detrital zircon samples were collected from this section. Instead, two conodont samples were collected from 36 and 48.5 m above the base of the measured section. These were taken from the Liard Formation, which is Ladinian in age. The samples were collected from beds that also contained an abundant ammonoid fauna, which was collected by L. Krystyn (University of Vienna, Austria) and M. Balini (University of Milan, Italy), and will complement the age determinations of the conodont samples. An improved understanding of the age of these beds will aid in the correlation of this section with others on the lake and elsewhere in northeastern BC.

Conclusions and Future Work

The work that was begun in 2009 has thus far enabled correlation of the South Halfway section with other sections both in the subsurface to the east and with the sections on Williston Lake to the south. This correlation is based partly on gamma-ray logs and partly on biostratigraphy, and the combination of these techniques holds promise for more precise and widespread correlation of these rocks in the future. The age of the Doig phosphate zone has been confirmed as older than Ladinian within the western part of the WCSB. A single detrital zircon from the South Halfway section indicates the deposition of sediment derived from a Devonian source, possibly the Ellesmerian orogenic wedge to the north. Additional dating of detrital zircon samples close to a conodont sample indicative of the sutherlandi zone will hopefully provide confirmation of this finding and constrain the timing of this sediment input.

Samples collected from Williston Lake will be processed for detrital zircon dating and conodont analysis. This will build on the initial observations from the South Halfway section and indicate if and when changes in sedimentation took place in northeastern BC in the Triassic. More samples will be collected in the autumn of 2010 from core housed in the BC Ministry of Energy's storage facility in the community of Charlie Lake, to allow correlation between surface outcrop and subsurface sections. The resulting data will have implications for the timing of changes in Triassic sedimentary facies and provenance of these natural gas–bearing rocks in BC, which will in turn allow more detailed models of the distribution of facies to be made. This, combined with the improved correlation of Triassic rocks across BC, will help to determine the location and nature of likely hydrocarbon-bearing rocks in the province.

Acknowledgments

Funding for this project is being supplied by Geoscience BC. The BC Ministry of Energy provided field support during the summer of 2009. An earlier version of this manuscript was reviewed by L. Beranek and his comments helped to improve the final copy.

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