Biostratigraphic and Sedimentological Studies of Natural Gas-Bearing Triassic Strata in the Halfway River Map Area (NTS 094B), Northeastern British Columbia: Progress Report

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Introduction

The western part of the Western Canada Sedimentary Basin (WCSB) in northeastern British Columbia includes one of the most complete sections of Triassic strata found anywhere in the world (e.g., Gibson and Barclay, 1989; Gordey et al., 1991; Davies, 1997). This sequence represents an important source of hydrocarbons, and is thought to contain more than 37% of BC's conventional gas reserves. Although there is currently a high level of industry interest in the Triassic package in northeastern BC, much of this region remains significantly underexplored due to difficulties in accessibility and a lack of available infrastructure. The current exploitation success of unconventional natural gas reservoirs within the lower part of the Triassic succession is expected to significantly increase recoverable resources and further enhance the economic importance of this package within the province. In comparison to other hydrocarbon reservoir or source sequences within the WCSB, the Triassic has received very little study, and the nature and depositional setting of much of the Triassic section is not well understood.

A detailed study of Triassic strata in the Halfway River map area (NTS 094 B) in northeastern BC (Figure 1) was started with the goal of better understanding the stratigraphic and sedimentological framework, together with the paleotectonic setting of this economically important succession. This work represents a Ph.D. study by M. Golding, based at the University of British Columbia, and is being carried out in conjunction with a multiyear BC Ministry of Energy, Mines and Petroleum Resources (MEMPR) geological mapping project in the Foothills of the Halfway River map area where the bulk of surface exposures are of Triassic age (Ferri, 2009). The current study has two main components: 1) detailed biostratigraphic characterization of the Triassic sequence, mainly using conodonts to provide age constraints; and 2) provenance studies of the Triassic units, employing both field-based sedimentology and chemical and isotopic analysis. Geoscience BC has provided funding for a one-year reconnaissance-level study of key portions of the Triassic section in the Halfway River map area. The focus of an additional two years of fieldwork, which are planned for this project, will be based in part on results of the initial scoping study.

Two weeks of fieldwork were carried out by M. Golding and F. Ferri in August of 2009. A section of Lower and Middle Triassic rocks south of the Halfway River was examined. This section was chosen by BC MEMPR to characterize Montney and Doig formations equivalent strata (the Toad and Grayling formations) in hopes of better understanding subsurface exposures of these rocks along the eastern Foothills. BC MEMPR collected samples for geochemical and geophysical testing. Vitrinite reflectance will be determined to delineate thermal maturity and several other geochemical analyses (e.g., total organic carbon, etc., by Rock Eval™) will be undertaken to determine hydrocarbon potential. Gamma-ray measurements were taken along the length of the section to allow correlation between the section and other sections in the subsurface. A detailed description of the section, local geology, and geochemical and geophysical results will be available in a BC MEMPR report later in 2010. Collected samples will also be processed for conodonts and detrital zircon geochronology to better constrain the depositional age of these units and the

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Keywords: *Triassic, Western Canada Sedimentary Basin, conodont, detrital zircon, sediment provenance, Halfway River*

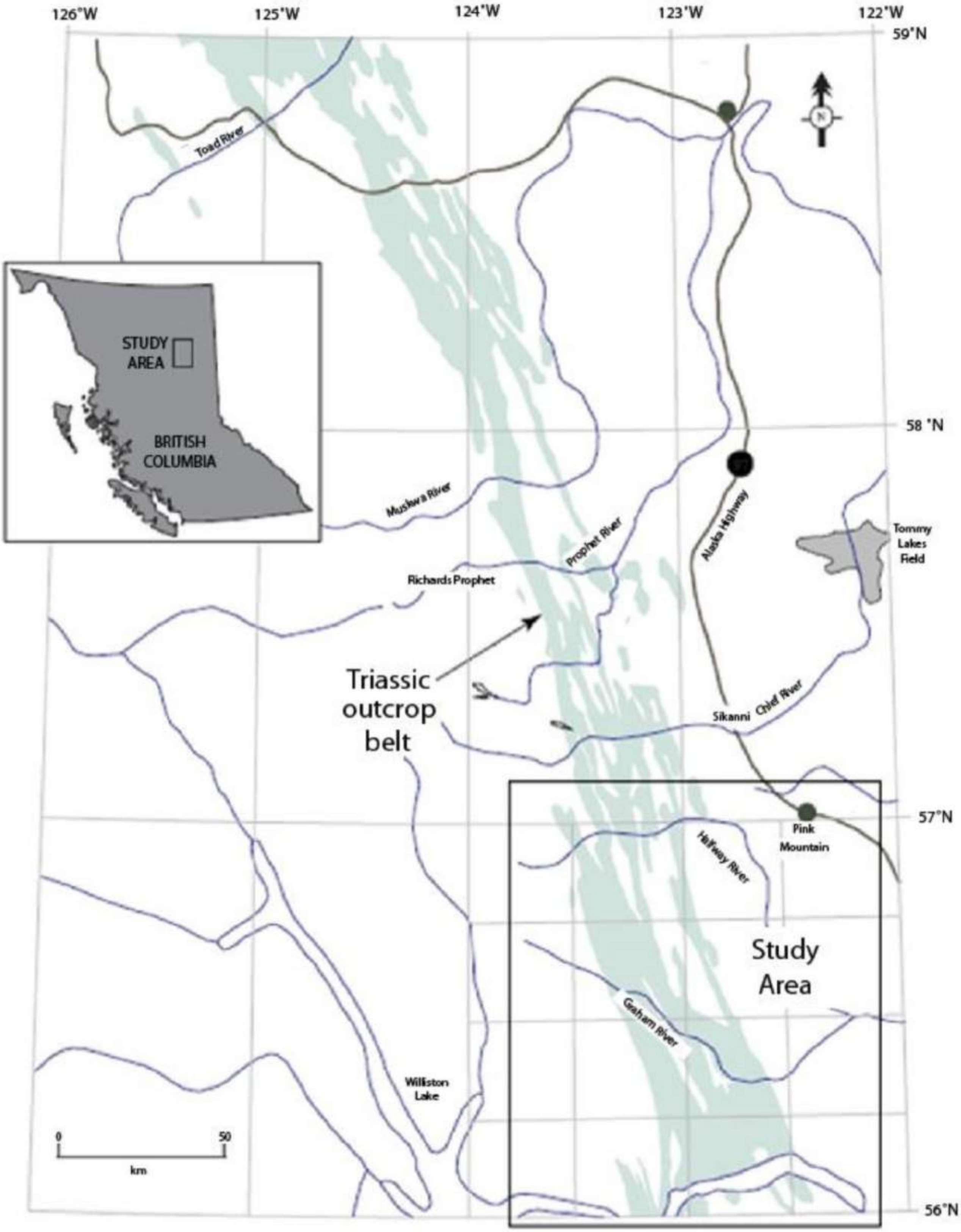

Figure 1. Location of the Halfway River study area and the distribution of economically important, potentially gas-bearing Triassic strata (pale blue) in part of northeastern British Columbia.

provenance of clastic sources. This report summarizes the progress of that investigation.

Regional Patterns of Tectonism and Sedimentation in the Triassic in the Northern Canadian Cordillera

Triassic strata in the western part of the WCSB have been shown to represent easterly derived, off-shelf sediments that were deposited along the western margin of ancestral North America (ANA; e.g., Gibson and Barclay 1989; Gordey et al., 1991; Gibson, 1993). Recent and ongoing work along the westernmost margin of ANA (representing the outer fringes of the WCSB) in northern BC and Yukon document mid to late Paleozoic extension of the margin associated with arc and back-arc development (Figure 2; Colpron et al., 2006, 2007). Geological evidence from the Yukon portion of the Cordilleran margin indicates that the Slide Mountain Ocean formed between latest Devonian and Middle Permian time as a back-arc basin east of a west-facing Yukon-Tanana Japanese-type magmatic arc (Figure 2). Pre-Late Devonian links between Yukon-Tanana and ANA have been demonstrated (Mortensen et al., 2006; Piercey and Colpron, 2009). A reversal of subduction polarity under the Yukon-Tanana arc led to the consumption of the Slide Mountain Ocean and construction of a short-lived, mainly Late Permian arc sequence that was built on the Yukon-Tanana Terrane. Final closure of the Slide Mountain Ocean in the northern Cordillera occurred in latest Permian time, at which time the pericratonic Yukon-Tanana Terrane, together with fragments of the oceanic Slide Mountain Terrane, collided with and overrode the western edge of ANA (e.g., Colpron et al., 2006; Nelson et al., 2006; Mortensen et al., 2007). Recent dating and sediment provenance studies of Triassic clastic strata in the western edge of the WCSB in the Yukon by Beranek (2009) have shown that Early to early Middle Triassic strata in this region are mainly derived from the west. These units yield detrital zircon and mica age signatures, which together with lithogeochemical and isotopic signatures, that indicate they were derived largely from erosion of the uplifted composite Yukon-Tanana/Slide Mountain block that formed the hinterland of a latest Permian to earliest Triassic collisional orogen. The Early and early Middle Triassic clastic units are interpreted to have been deposited within a foreland basin that was built on attenuated continental crust along the western edge of ANA, and were sourced dominantly from the west. By late Middle Triassic time the highland that had existed in the hinterland of this collisional orogen had largely disappeared, and Late Triassic strata were deposited as an overlap sequence that extended across both the earlier foreland and hinterland components of the collisional orogen (Mortensen et al., 2007; Beranek, 2009).

This interpretation for the Yukon portion of the WCSB is fundamentally different from previous models for the Triassic in the northern Cordillera. The Triassic sequence is now considered to consist of two very distinct components: 1) an Early to early Middle Triassic foreland basin deposit with sediments shed mainly from a hinterland block to the west; and 2) a late Middle to Late Triassic overlap sequence

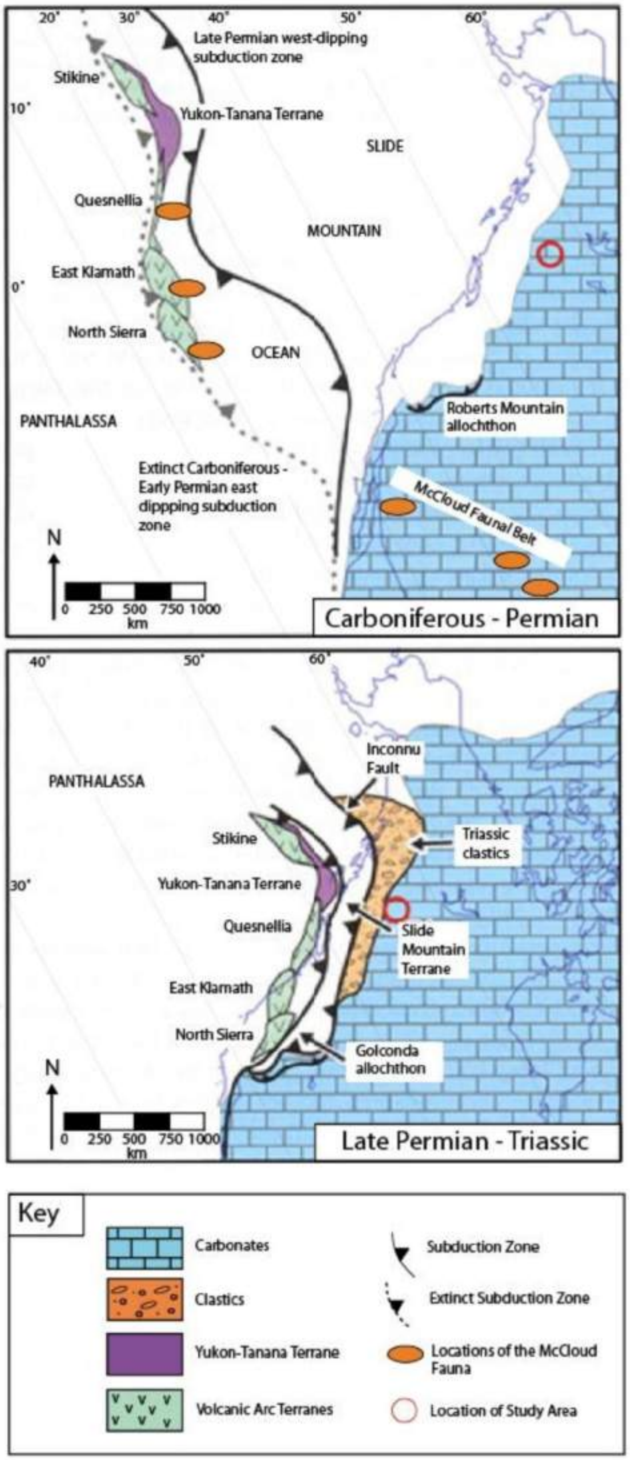

Figure 2. Tectonic interpretation of the Carboniferous to Triassic evolution of the northwestern margin of Laurentia (now northeastern British Columbia; modified from Colpron et al., 2007). Location of the Halfway River study area shown by the red circle.

that reflects a return to a west-facing, off-shelf setting, with sediments shed mainly from the east.

The Triassic sequence in northeastern BC, which is the main focus of the current project, has received somewhat less study thus far from a paleotectonic standpoint, and it is not yet clear that the tectonic model presented above for this package also applies farther to the south. The total thickness of Triassic strata in northeastern BC is in excess of 1.5 km (e.g., Gordey et al., 1991). Paleocurrent information for the Triassic in the WCSB is limited; however, data from the eastern part indicates dominantly westerly paleoflow in at least some of the units (Gordey et al., 1991). Pelletier (1960, 1961, 1963) has recorded paleocurrents from the north and northwest within the Foothills of northeastern BC. In northeastern BC, the Triassic sequence is currently interpreted as a westward, prograding clastic-carbonate succession that was deposited, in part, on a Carboniferous to Permian rift sequence represented by the Fort St. John graben system. Sedimentological and stratigraphic studies by Zonneveld and coworkers (Zonneveld et al., 1997a, b, 2003, 2004; Zonneveld and Orchard, 2002; Zonneveld and Gingras, 2003) show anomalous thicknesses and facies distributions within Early and parts of the Middle Triassic in this region that appear to indicate that a highland lay to the west of the main depocentre and was likely the source for at least some of the sediments. Early Mississippian detrital zircon grains from early Middle Triassic strata in this area is also supportive of a western source as no igneous activity of this age is found in underlying WCSB sedimentary rocks to the east (Ferri, 2009). It is therefore considered likely that the Triassic sequence in northeastern BC reflects the same two-stage depositional history as has been documented farther north, with a change from mainly westerly derived foreland basin sedimentation to mainly easterly derived off-shelf deposition occurring somewhere in Middle Triassic time. If correct, this interpretation would be fundamentally important for assessing the regional Triassic stratigraphic framework in northeastern BC and would have implications for the ultimate gas potential of Triassic rocks in this area.

Stratigraphic and Sedimentological Relationships in the Triassic in Northeastern BC

Obduction of a composite Yukon-Tanana/Slide Mountain terrane hinterland block onto the western edge of ANA would have depressed the continental crust and led to foredeep development. Restoration of Cretaceous–Tertiary strike-slip faults in the Cordillera would place late Paleozoic ophiolite complexes and arc rocks of the Sylvester allochthon (Nelson, 1993) orthogonal to the embayment defined by Triassic rocks of the WCSB in northeastern BC, suggesting that this depositional feature may be an expression of this crustal loading. Evidence for a concurrent forebulge may be found in the Peace River area of the western Foothills, where temporally significant disconformities in outboard settings and anomalous sediment thickness trends occur. In this area, Lower and Middle Triassic strata consist of organic-rich shale and siltstone deposited in a distal offshore depositional setting. Conodont data indicate that sedimentation rates were relatively consistent through the Early and early Middle (Anisian) Triassic.

However, there is an abrupt and profound change during the Ladinian (late Middle Triassic) when sedimentation rates drop dramatically, followed by a temporally extensive disconformity. Ladinian successions immediately to the east are significantly overthickened and comprise some of the thickest Middle Triassic successions in North America. The Middle–Upper Triassic boundary is characterized by an erosional unconformity, a switch to carbonate-dominated deposition and a dramatic increase in sedimentation rates (by at least an order of magnitude above Lower–Middle Triassic rates). Upper Triassic sedimentary rocks demonstrate an inverse relationship to that exhibited by Middle Triassic successions (i.e., grossly overthickened in the west and dramatically thinner towards the east).

The Ladinian decrease in sedimentation rates and subsequent disconformity in western Peace River localities are interpreted to reflect deposition on an early forebulge. During the Late Triassic, this forebulge is interpreted to have migrated eastwards, resulting in a thick deepwater succession of carbonate strata deposited in the west and a thin shallow-water succession of carbonate strata deposited in a proximal carbonate ramp setting farther to the east.

The dark, basinal shale, represented by the Triassic Montney, Toad and lower Sulphur Mountain formations, is interpreted to represent initial foredeep deposition prior to onset of coarser clastic sedimentation. Sedimentological constraints suggest that only eastern-sourced, continentally derived clastic rocks are preserved within the Triassic succession in northeastern BC. Indications of westerly derived clastic rocks are rare and are a reflection of poor preservation in the west. Chert granules and pebbles in coarse, Halfway Formation-equivalent sandstone within the western Foothills of the Peace River area suggest a local source. The fact that these coarse clasts are larger and more abundant towards the west may support the hypothesis that these sediments were derived from a western source.

Sediment Provenance Studies

A growing number of recent studies focus on the provenance of various sedimentary rock units within the WCSB (e.g., Garzione et al., 1997; Ross et al., 1997; Gehrels and Ross, 1998; Mortensen et al., 2007; Beranek, 2009). Most of these studies utilize U-Pb dating of detrital zircon grains and, to a lesser extent, Ar-Ar dating of detrital mica grains (Beranek, 2009). The U-Pb age information for detrital zircon and monazite grains provides direct information on the age(s) of igneous rock units from which the clastic detritus was eroded, or in the case of polycyclic sediments, the ages of provenance for earlier sedimentary units that were themselves eroded and reworked. In addition, the whole rock geochemistry and Nd isotopic compositions of some rock units have been determined, and these data constrain the composition and to some extent the tectonic setting of the source rocks (e.g., magmatic arc versus rift versus ophiolite). The resulting data help constrain the general provenance of the sedimentary sequences being studied, and also provide key evidence for the regional tectonic controls on sedimentation, including nature and timing of tectonic uplift within the source area(s) as well as the nature of continent-scale drainage patterns. Results from Mesozoic and younger rock units within the Cordillera also yield important constraints on the nature and timing of terrane accretion that affected the western margin of Laurentia.

The study of Triassic clastic sedimentary units in the Yukon and adjacent parts of northern BC and eastern Alaska by Beranek (2009) also used extensive U-Pb dating of detrital zircon grains and Ar-Ar dating of detrital mica grains together with whole rock geochemical and Nd isotopic studies. In addition, conodont biochronology was used to provide biostratigraphic depositional ages. Results from this multidisciplinary study provide clear evidence for initial accretion of the inboard pericratonic terranes in this part of the Cordilleran margin in earliest Triassic time, some 60 m.y. earlier than had previously been thought (Monger and Price, 2002). These results support the earlier hypotheses of Nelson et al. (2006) and Colpron et al. (2006). A western source is evidenced by the abundance of Late Devonian to Early Mississippian and Late Permian detrital zircon grains, which can only have been derived from the middle and late Paleozoic arc assemblages in the Yukon-Tanana Terrane, as well as by the presence of a geochemical component in the fine-grained clastic units that must have come from a mafic source terrane (most probably the Slide Mountain Terrane). In the absence of definitive paleocurrent evidence, which is only rarely preserved within the Triassic clastic units, provenance information such as described above is the only way to demonstrate the source(s) from which a sedimentary unit was derived. Initial detrital zircon dating studies for the lower part of the Triassic succession by Ferri (2009) also appear to suggest a partial source from accreted terranes to the west.

Current Study

A detailed provenance study of Triassic clastic strata in the Halfway River map area in northeastern BC is being undertaken with the goal of evaluating the two-stage depositional model described above for Triassic units in this region. This study includes detailed conodont biostratigraphic work that will build on previous research by M. Orchard and coworkers (e.g., Orchard et al., 2001, 2002; Orchard, 2006). The biochronology component is critical in order to provide the required temporal framework for the rock units being investigated. A total of 15 samples for conodont dating were collected from the section that was examined in 2009. The study will also include U-Pb dating of detrital zircon grains from biochronologically well dated units throughout the Triassic section in the Halfway River study area, with particular attention being paid to units for which paleocurrent information is available. Five samples were collected for this U-Pb dating of detrital zircon grains. The detrital zircon age patterns that are obtained, together with careful petrographic analysis of the samples, will provide critical information concerning the provenance of the Lower and Middle Triassic section in the Halfway River area. This will allow the comparison and contrasting of the provenance and paleotectonic setting of Triassic units of the WCSB in northeastern BC with age-equivalent rock units that have been studied by Beranek (2009) farther to the north. It is anticipated that results of this study will provide valuable stratigraphic information for industry concerning the regional depositional environment of the various parts of the economically important Triassic section (particularly the lower portion, which is presently considered to have the best gas potential). An improved understanding of the Triassic stratigraphy will be critical for assessing the nature and extent of possible source and reservoir units within the section.

Triassic Stratigraphy of the Halfway River Map Area

This study will focus on the Lower and lower Middle Triassic, which in the Halfway River map area is represented by the Grayling, Toad and Liard formations (Figure 3). Stratigraphic nomenclature is somewhat complicated in this area because different formation names are applied to some units in subsurface studies than are applied in surficial geology maps. The stratigraphy will be discussed in terms of surficial geology map units, but will include correlations with the subsurface rock units.

The Grayling Formation is the lowermost formation of the Triassic in northeastern BC, where it unconformably overlies the Permian Fantasque Formation (Gibson, 1971). It consists of a succession of dolomitic siltstone, silty shale and minor amounts of calcareous siltstone, silty limestone, dolomite and fine-grained sandstone (Thompson, 1989). The maximum thickness reached in the Halfway River map area is 35 m. It is the surface equivalent of the lower Montney Formation and contains ammonites indicative of a Griesbachian–Smithian age (Zonneveld and Gingras, 2000).

In many parts of the foreland, it is difficult to differentiate the Grayling Formation from the overlying Toad Forma-

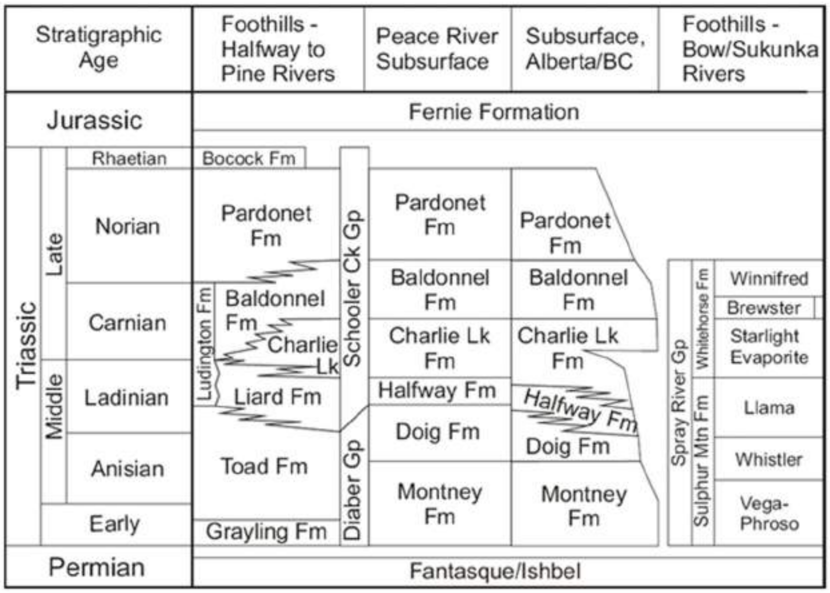

Figure 3. The formations of the Halfway River map area, northeastern British Columbia, and their correlations with other formations both in the subsurface and in southern Alberta. Modified from Ferri (2009). Abbreviations: Ck, creek; Fm, formation; Gp, group; Lk, Lake; Mtn, Mountain.

tion. In some cases the two units are therefore mapped as the Toad-Grayling Formation (Gibson, 1971). The Toad Formation itself conformably overlies the Grayling Formation, and comprises a thick sequence of argillaceous to calcareous siltstone, silty shale, silty limestone and dolomite, as well as very fine grained sandstone (Thompson, 1989). The formation achieves a maximum thickness of approximately 825 m in the Halfway River area. Its equivalents in the subsurface are the upper Montney and lower Doig formations, and pelecypods and ammonites suggest an age from Smithian to Ladinian (Zonneveld and Gingras, 2000).

The Liard Formation unconformably overlies and interfingers with the Toad Formation. It consists primarily of fine to coarse sandstone, calcareous and dolomitic siltstone and sandy to silty dolomite and limestone (Thompson, 1989). The formation shows a wide variation in thickness, from approximately 30 m in the Halfway River area, up to 300 m to the north and over 500 m in the south. The upper contact with the Charlie Lake Formation is conformable and in some areas hard to place, further complicating the measurement of unit thicknesses. The Liard Formation is the surface equivalent of the upper Doig and Halfway formations in the subsurface. A wide range of fossils suggest deposition of the formation during the Ladinian (Zonneveld and Gingras 2000).

Stratigraphy of the Lower and Middle Triassic South Halfway River Section

The stratigraphic section logged in the summer of 2009 is located to the south of the Halfway River in northeastern BC, with the base of the section at 473870E 6311694N (Zone 10, NAD 83). The oldest unit present is the Toad Formation, located on the western side of a steep ridge. The Liard Formation is present higher up the ridge (Figure 4a). The section continues over the top of the ridge and down the eastern flank, where the Charlie Lake, Baldonnel and Pardonet formations are present, together with outcrops of the Jurassic Fernie Formation and the Jurassic–Cretaceous Minnes Group. The section appears to correspond with section GK-68-5 of Gibson (1971).

The total thickness of the measured section is 643 m. The Grayling Formation was not observed and the base of the measured section lies within the Toad Formation. The measured thickness of 604 m for the Toad Formation is therefore a minimum for this area. A structural section in this area suggests between 150 and 200 m of unexposed rocks of the Toad and Grayling formations below the base of the measured section. The Liard Formation overlies the Toad Formation and only 39 m of its lower part was measured. Outcrops of the Liard Formation continue above the measured section, but are inaccessible.

Fourteen conodont samples were collected from the Toad Formation and one from the Liard Formation. Three detrital zircon samples were collected from the Toad Formation and two from the Liard Formation. Macrofossils, primarily ammonoids and pelecypods, were collected throughout the section. Seven ammonites were recovered, along with 18 samples of pelecypods. Macrofossils that could not be extracted were photographed in situ.

A schematic graphic log of the section, along with the positions where samples were collected, is shown in Figure 5.

The Toad Formation at this section consists primarily of flaggy-weathering, calcareous siltstone, interbedded with lesser amounts of recessive, carbonaceous, silty shale (Figures 4b, c). Higher in the section, the amount of argillaceous material is reduced and very fine grained sand begins to appear (Figure 4c). This change is also exhibited by the relative decrease in gamma-ray values in the upper part of the section's geophysical log. The amount of carbonate present in the rock remains high throughout the section.

The lower part of the Toad Formation appears to have been deposited in relatively quiet, offshore conditions. It shows similarities to lithofacies A2 of Zonneveld and Gingras (2000), although the proportion of silt is higher than that of

Figure 4: a) View south to the measured section containing exposures of Toad and Liard formations, south of Halfway River, northeastern British Columbia. **b)** Recessive and fissile, dark grey calcareous siltstone within the lower part of the Toad Formation (approximately 145 m from the base of the section). This grades upwards into more resistive and cleaner, buff-weathering siltstone. **c)** Ribbed, buff-weathering, calcareous to dolomitic siltstone and recessive, calcareous siltstone from approximately the 160 m level of the section. **d)** Thin-bedded, graded turbidites (some with ball and pillow structures) at the 510 m level of the section. e) Bedding-parallel bioturbation within the basal Liard Formation at approximately the 611 m level of the section. Large burrows are approximately 3–5 cm in width.

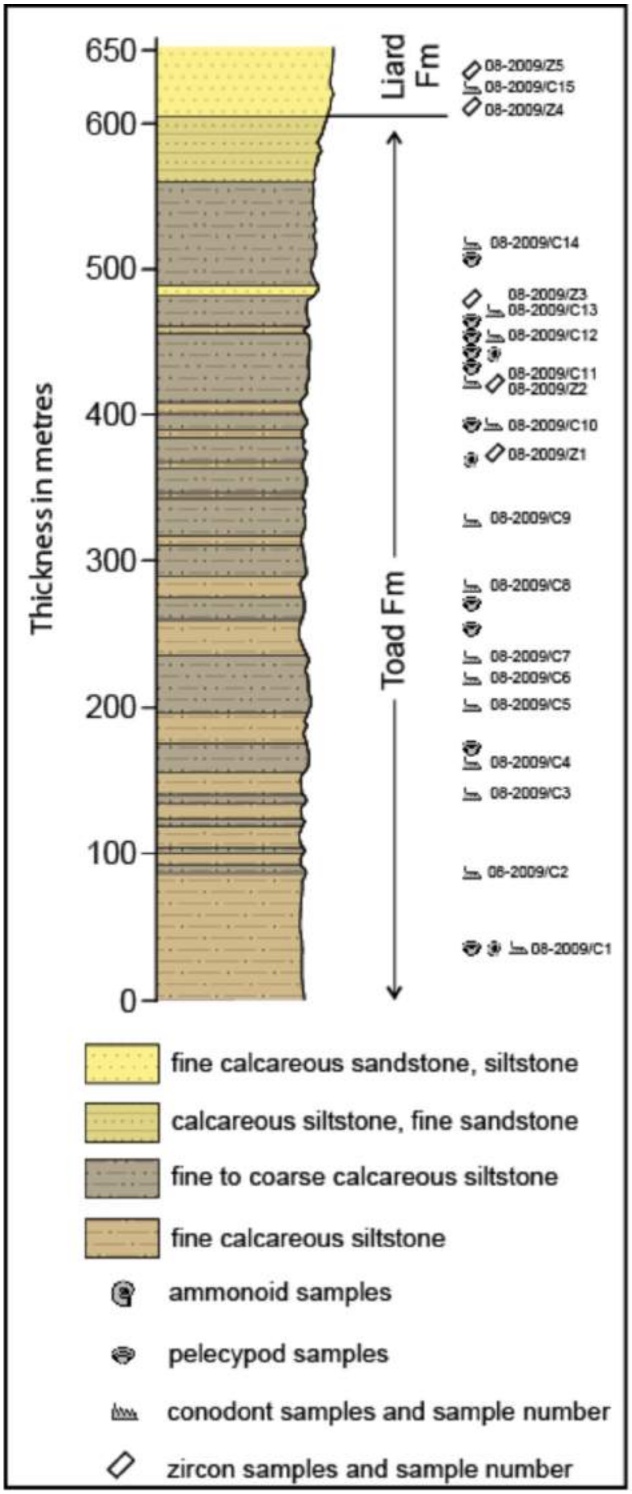

Figure 5. Schematic graphic log of the south Halfway River section, northeastern British Columbia, showing locations of samples collected. Abbreviation: Fm, formation.

shale. Higher up in the sequence, there is a greater proportion of very fine grained sandstone. There are also sedimentary structures, such as ripple and parallel lamination, convoluted bedding and possible tool marks, on the base of some beds that suggest turbiditic deposition (Figure 4d).

The upper part of the Toad Formation shows distinct similarities to lithofacies C of Zonneveld and Gingras (2000), indicating deposition on the continental shelf or slope. Fossils are rare, and consist mainly of ammonoids and pelecypods, although a crinoid and a belemnite were also found. No trace fossils were observed in this formation.

The lower boundary of the Liard Formation is drawn at the transition from dark siltstone to uniform, beige, very fine grained sandstone. Siltstone beds persist for a few metres above this horizon, before giving way to a more uniform succession of calcareous, very fine grained sandstone and siltstone. The Liard Formation is much cleaner than the underlying Toad Formation and consists entirely of calcareous sandstone and lesser siltstone at this section. The presence of limestone boulders in the talus suggests that this rock type is present higher in the sequence, above the measured section.

The coarser clastic material that comprises the Liard Formation indicates deposition in a relatively shallow-water setting compared to the Toad Formation. Similarities exist between rocks of the Liard Formation and those assigned to lithofacies E by Zonneveld and Gingras (2000), but, unlike lithofacies E, sedimentary structures in the rocks at this section are rare. The lowest part of the Liard Formation in this area likely formed in the offshore transition zone. Fossils are relatively common, although rarely found in situ. Terebratulid brachiopods are by far the most dominant body fossils present, although pelecypods were recovered as well. An ammonite and an ophiuroid were found in boulders that appear to be from the Liard Formation. Trace fossils are abundant and show a variety of forms (Figure 4e).

The section as a whole records an overall shallowing trend, from deposition on the distal shelf or slope to proximal deposition close to or above the storm wave base.

Further Work

The focus of current work is the processing and analysis of the zircon and conodont samples that were collected from the measured section. It is hoped that these will constrain the age and provenance of the sediments at this section, while helping to further refine the correlation between the conodont and ammonoid time scales for the Early and Middle Triassic. In future field seasons, other sections in the Halfway River map area will be logged and sampled. Future work will also include collection of samples for whole rock geochemistry and Nd isotopic analysis. Combining this data with that obtained from the detrital zircon grains will help to further constrain the provenance of Triassic sediments in the WCSB. In addition to work in the Halfway River map area, the project may be expanded in subsequent years to encompass other areas depending on the suitability of sections for study. This will also provide the opportunity to correlate between these sections, as well as those previously studied, to obtain an improved understanding of regional facies change and sediment transport. This in turn will allow better characterization of the Triassic gas reservoirs of northeastern BC and lead to continued production from the subsurface.

Acknowledgments

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