Energy, Mines and Resources • *Yukon Geological Survey*

# YGS Open File 2017-2

## WHITEHORSE TROUGH: PAST, PRESENT AND FUTURE PETROLEUM RESEARCH - with a focus on reservoir characterization of the northern Laberge Group

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Field assistant training in the Jackson Lake area, Whitehorse trough
Photo courtesy of M. Hindemith

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# ABSTRACT

Recent reassessment of Whitehorse trough stratigraphy and its petroleum prospectivity has resulted in a new basin outline and enhanced resource distribution maps that can be used to guide systematic petroleum research. Two areas are identified as being of sufficient data density to warrant further exploration for conventional targets by industry: Tantalus Butte and Division Mountain. Unconventional shale potential is expected to be restricted to fine-grained facies in the southeast part of the trough.

Laberge Group petroleum system characteristics and play risks have also been updated for these two areas in the northern basin, with geological success estimated at 4% for the Laberge play in Tantalus Butte and 29% for Division Mountain. Reanalyzed RockEval-TOC and vitrinite reflectance surface and shallow subsurface data highlight that source rock quality increases to the south in association with decreasing maturity. Only 17% of samples analyzed in the Tantalus Butte area exhibit source rock potential (relative to 57% at Division Mountain), inferring significant exploration risk of this system component in the northern basin. Coarse-grained, proximal facies in both areas unexpectedly exhibit characteristics of ‘tight’, low permeability gas plays. Average porosity and maximum horizontal permeability are very low (4.0% and 0.36 mD respectively) with pore space typically occluded by authigenic carbonate and kaolinite cements. Overall, there is no control on porosity by grain size, and poroperm data are highest in the distal, younger rocks at Division Mountain where increasing Kv/Kh ratios suggest permeability anisotropy and potential reservoir compartmentalization.

Integrated petrography, mineralogy and geochemistry suggest an evolution from mafic to felsic provenance, and from marine to non-marine depositional environments over time in the Laberge Group suggesting 3D facies architecture is more complex than resolved by current surface maps. The Laberge Group should therefore be viewed as one depositional system, and the Tanglefoot and Richthofen formation ‘buckets’ be abandoned. Exploration and production of hydrocarbons from the Laberge Group in the northern Whitehorse trough are likely to be both geologically and technologically challenging. Future research in the basin is therefore essential to glean as much information from surface and shallow subsurface rocks as possible in the absence of planned industry activity in the basin.

## INTRODUCTION

The Whitehorse trough is an Early to Middle Jurassic synorogenic marine sedimentary basin that overlaps the Intermontane terranes of Stikinia, Quesnellia and Cache Creek in the northern Cordillera (Fig. 1). This elongate, northwest trending basin straddles the Yukon-British Columbia border, where it tapers 650 km from Dease Lake in the south to its northernmost tip in the Carmacks area. It is the northernmost basin in a suite of Jurassic piggy-back depocenters that extend south into BC, and which includes the Bowser Basin (Colpron *et al.*, 2015).

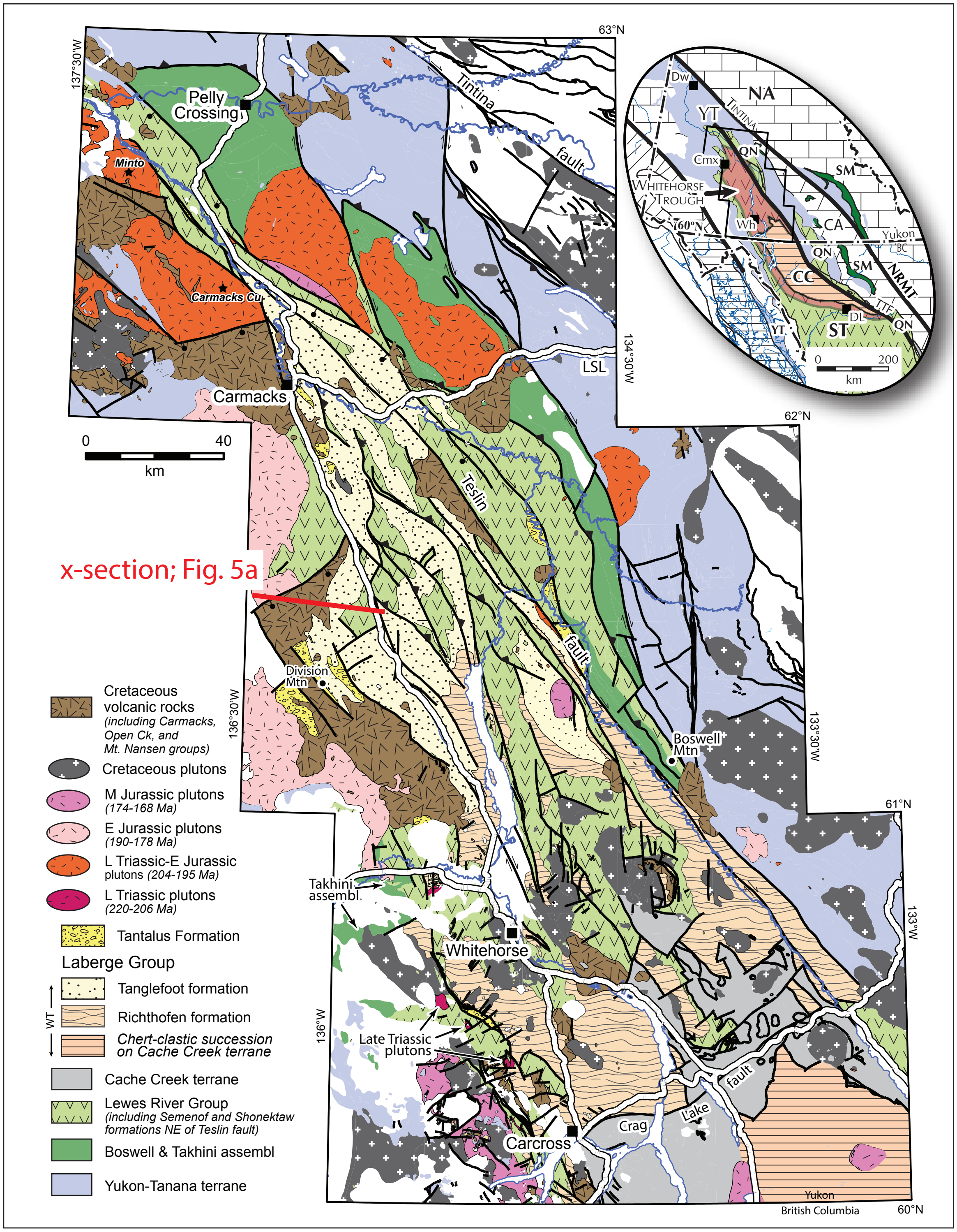


***Figure 1.*** *Regional geology of the Whitehorse trough and surrounding south-central Yukon (from Colpron et al., 2015). The location line for Figure 5a is shown on this map.*

The basin is prospective for both conventional and unconventional hydrocarbons, predominantly gas (Hayes, 2012; Hayes and Archibald, 2012), but lacks systematic petroleum studies (except source rock potential; Lowey *et al.*, 2009) due to an absence of industry activity and limited survey fieldwork. Current conventional resource assessments estimate mean, risked in-place volumes of 17.48 MMbls oil and 379.3 Bcf gas for the basin (Hayes, 2012). Speculative unconventional targets in the trough include coal bed methane and tight/shale gas (Hayes, 2012). A qualitative assessment of unconventional prospectivity in the trough suggests that evidence for shale gas is compelling (Hayes and Archibald, 2012). No reconnaissance or systematic unconventional petroleum studies have been undertaken in the Whitehorse trough to date.

The basin-fill and its enveloping terrane hinterland has been subject to various research approaches and analytical techniques over the last 30 years to understand both its stratigraphic and structural evolution and its resources, including bedrock mapping and associated sedimentological studies (*e.g.*, Bordet, 2016; Colpron and Friedman, 2008; Colpron *et al.*, 2007; 2015, 2016b; Dickie, 1989; Dickie and Hein, 1988, 1992, 1995; Gordey and Makepeace, 2003; Hart, 1997; Tempelman-Kluit, 1984, 2009); seismic surveying and geomodeling (MIRA Geoscience 2014; White *et al.*, 2006; 2012); coal exploration (Allen, 2000; Becker and Stubblefield, 2008) and petroleum potential (Hayes, 2012; Hayes and Archibald, 2012; Long, 2015; Lowey, 2004, 2005, 2008a,b; Lowey and Long, 2006; Lowey *et al.*, 2009; NEB, 2001).

This report presents the results of a new project, initiated in 2014, to assess the conventional petroleum potential of the northern Whitehorse trough. It also presents a synthesis of ideas on trough evolution and depositional controls during the Early-Middle Jurassic (with respect to petroleum potential) that was gleaned from the above referenced studies, suitable modern and ancient analogues, reconnaissance field observations in 2014, and ongoing discussions with colleagues in and outside of the Yukon Geological Survey. This report constitutes the formal publication of data and concepts presented at the 2015 Whitehorse Geoscience Forum (Hutchison *et al.*, 2015) and for the Geological Association of Canada's 2016 conference and 'transect' fieldtrip (Hutchison, 2016 and Colpron *et al.*, 2016a, respectively). The final objective of this report is to provide a series of potential research directions for future studies in the Whitehorse trough.

## EXPLORATION HISTORY

The fossil fuel prospectivity of the Whitehorse trough was established during the early 1900s, when McConnell (1901) and Cairnes (1908, 1910) documented the coal geology of the region during field expeditions. Petroleum exploration began in the 1950s, with permits covering 18 grid blocks (437 101 ha) held mainly by Yukon Exploration and Development Ltd. Surface work consisted of regional geological analysis for prospectivity, however all permits were surrendered in 1960. Between 1961 and 1970, 26 exploration permits covering 48 grid blocks (1 146 170 ha) were active and held by a suite of agents for unknown companies and by a consortium of Ensign Oil Ltd, Gyer Oil Ltd and Reliance Exploration and Mines (NEB reports 683-2-1-1, 798-1-1-1 and 5-1-1-17). By 1971, only two permits held by the consortium and an agent for an unknown company remained active in the region, and by 1980 all permits had expired. The last industrial surface exploration was conducted by Petro Canada in 1985 in the Whitehorse area, where several zones of prospectivity were defined on the basis of sample organic geochemistry and reservoir analytical results (NEB report 9137-P28-1E, parts 1 and 2).

No exploration wells have been drilled in the basin to date, and no discovered resources exist aside from coal within the Tanglefoot and Tantalus formations. The Whitehorse trough has been a key, but intermittent, focus for the Yukon Geological Survey's oil and gas group since 2003.

# GEOLOGICAL BACKGROUND

## *BASIN EVOLUTION AND ALLOGENIC CONTROLS*

The following basin overview is exerted from Colpron *et al.* (2016a) and modified here for report completeness. For further detail on the birth of the northern Cordillera and regional tectonic evolution of the Whitehorse trough, the reader is referred to Colpron *et al.* (2015).

The Whitehorse trough was originally interpreted as a forearc basin that formed during convergence of Stikinia with North America after subduction of the Anvil Ocean (now known as the Slide Mountain terrane; Tempelman-Kluit, 1979). Subsequent mapping in the area highlighted that the middle Paleozoic to early Mesozoic Yukon-Tanana and Quesnellia arc terranes separated the trough from the Slide Mountain terrane, which is now known to have closed during the Permo-Triassic (Mortensen, 1992; Nelson *et al.*, 2006; Beranek and Mortensen, 2011). Current tectonic models interpret the Whitehorse trough as a forearc basin that progressively evolved to become a synorogenic piggy-back basin during development of the Cache Creek accretionary complex and subduction of part of the Panthalassa ocean beneath the contiguous arc terranes of Stikinia and Quesnellia sometime after the end of the Pliensbachian (Mihalynuk *et al.*, 1994; English and Johnston, 2005; Nelson *et al.*, 2013; Colpron *et al.*, 2015).

The basin geology is characterized by an approximately 3 km thick deformed Lower-Middle Jurassic (late Hettangian-Bajocian) sedimentary succession (the Laberge Group), which is underlain by a depositional basement of Triassic Stikinia (the Lewes River Group) and capped by Upper Jurassic to Lower Cretaceous fluvio-lacustrine and coal deposits of the Tantalus Formation (Long, 2005, 2015), and Cretaceous to Neogene volcanic rocks (Fig. 2). Laberge Group sandstone detrital zircons all display a major Late Triassic-Early Jurassic peak (220-180 Ma) and a minor peak in the middle Paleozoic (340-330 Ma) that correspond exactly with known igneous ages from areas surrounding the trough (Colpron *et al.*, 2015). Source regions typically have Early Jurassic (*ca.* 200-180 Ma) mica cooling ages and the petrology of metamorphic rocks and Early Jurassic granitoid plutons flanking the trough suggests exhumation during emplacement that was coeval with the onset of orogenic activity in the southern Canadian Cordilleran hinterland.

In addition to basin shoulder uplift, other probable allogenic controls acting on Laberge Group deposition include volcanism, eustatically-driven sea level fluctuations (*e.g.*, Haq and Schutter, 2008) and climatic cycles (*e.g.*, Dera *et al.*, 2011) controlled in part by paleogeography and paleolatitude (Fig. 3). Coastal morphology, paleogeography and wind direction modeling (Fig. 4) suggests that proximal Laberge Group sandstone was deposited primarily by tidal-dominated and fluvially-influenced coastal processes. The Sinemurian and younger sediment, historically assigned to the Tanglefoot formation in the northern part of the trough, comprise shallow marine, deltaic, fluvial and coal deposits. Richthofen (mass flow, delta-fan conglomerate and turbiditic fine-grained clastics) and Tanglefoot formation strata are coeval in part (Lowey, 2008b), and intercalated Nordenskiöld unit dacitic tuff dated to *ca.* 188-184 Ma (Colpron and Friedman, 2008) have been recognized at several distinct horizons within both formations (*see* Fig. 2).

## *PETROLEUM SYSTEMS*

Laberge Group petroleum system components are summarized by Lowey (2008a,b), however only conclusions regarding organic carbon quantity, quality and maturity (source rock potential) are based on quantitative field and laboratory analytical data (detailed in Lowey and Long, 2006 and Lowey *et al.*, 2009). These existing, typically observation-based data (summarized below) were utilized by Hayes (2012) to build the parameter database upon which the Laberge Group petroleum play resource of the Whitehorse trough was assessed.

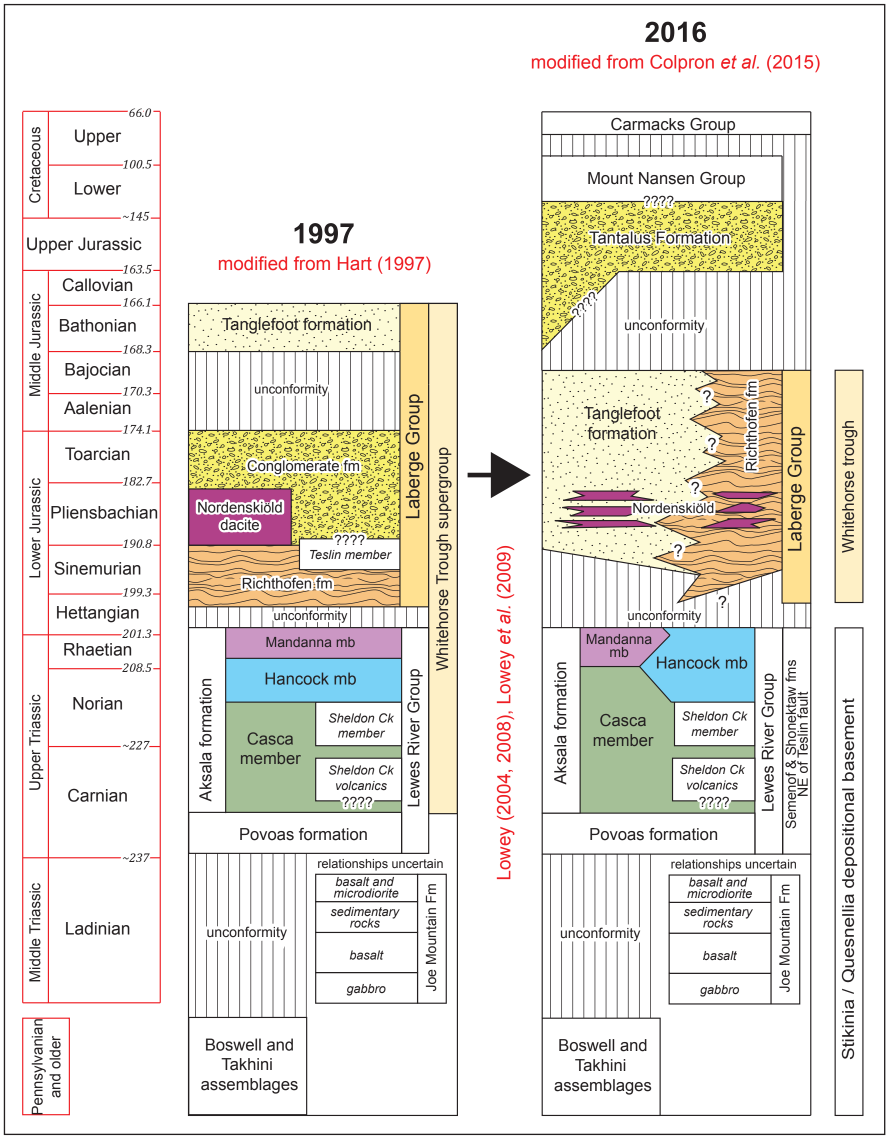


***Figure 2.*** *Basin stratigraphic nomenclature and age revisions.*

## *Source rock*

Based on a compilation of more than 600 samples taken from the Lewes River Group, Laberge Group and Tantalus Formation analyzed for RockEval-TOC, thermal alteration indices of palynomorphs (TAI) and conodonts (CAI), and vitrinite reflectance, the petroleum source rock potential of Laberge Group strata in the basin is as listed below (Appendix 1):

- Richthofen fm – a poor to fair source rock in terms of total organic carbon (TOC) quantity (Lowey *et al.*, 2009), however kerogen quality suggests minor gas potential only, and both Tmax and vitrinite reflectance suggest the rocks are postmature with respect to oil generation.
- Tanglefoot fm – a good source rock that is immature to early mature with respect to oil generation (Lowey et al., 2009), but which is typically gas prone as indicated by kerogen quality data. However, the unit also contains rare, self-sourced oil fluid inclusions that indicate minimum trapping temperatures of 75°-100°C (Lowey, 2008b; Lowey *et al.*, 2009) and which have API gravities likely reflective of varying burial depths and maturation levels in the northern basin.

Lowey (2008b) concluded that the most prospective areas for petroleum exploration based on these data are the Carmacks area (Five Finger Rapids and Tantalus Butte) and Division Mountain in the northern, proximal portion of Whitehorse trough.

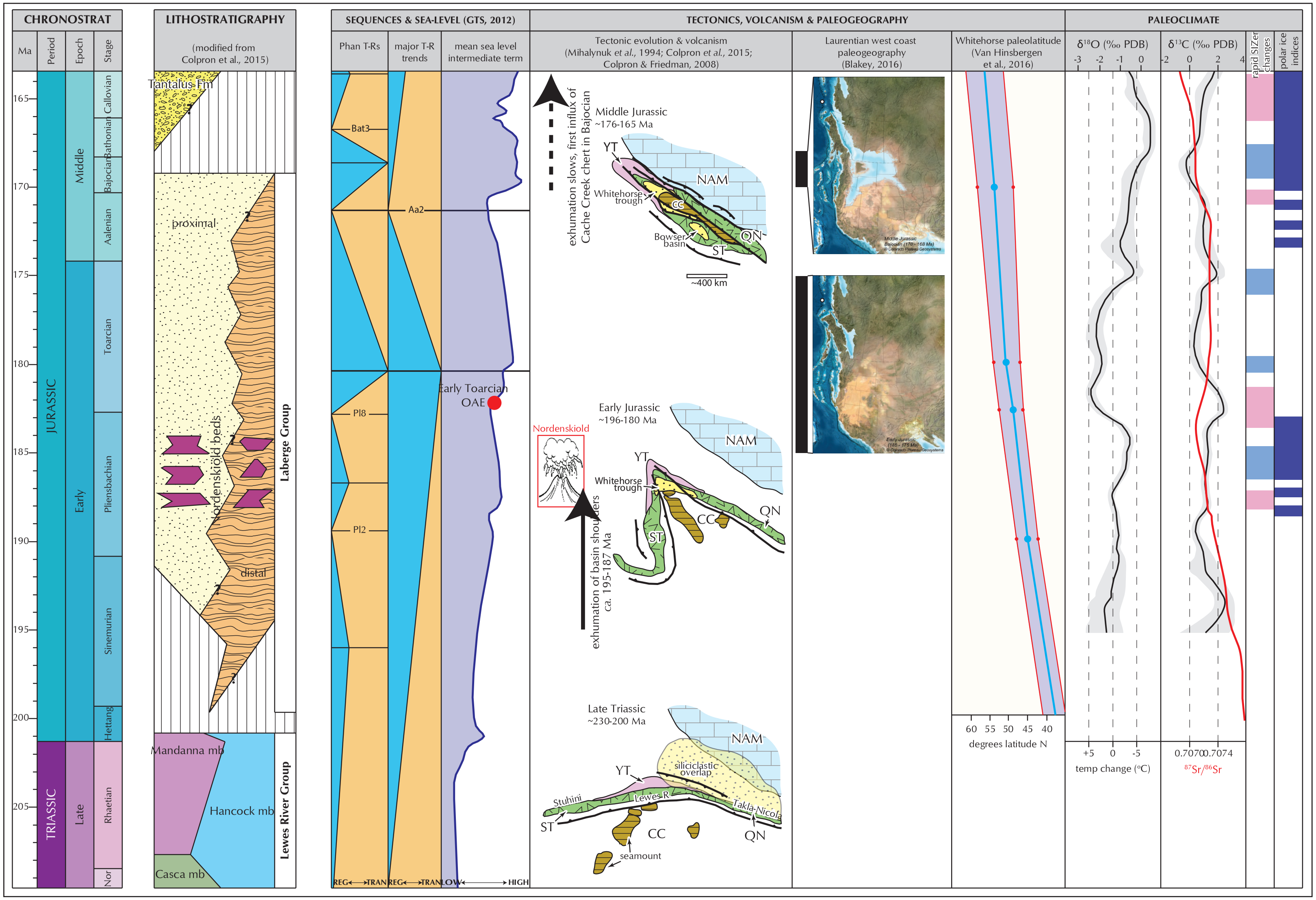


***Figure 3.*** *Summary of potential allogenic (sea-level, tectonics/volcanism, geography and climate) controls acting on Lewes River and Laberge Group deposition during the Late Triassic to Middle Jurassic. Timescale from Cohen et al. (2013), paleoclimate data from Dera et al. (2011), paleogeographic maps used with permission from Colorado Plateau Geosystems. Phan T-Rs = Phanerozoic transgressive-regressive cycles; OAE = Early Toarcian ocean anoxic event; thick grey lines surrounding paleoclimate proxy curves = 95% confidence envelopes; SiZer = significant zero crossings of the derivatives, where pink is rapid warming and blue is rapid cooling (see Dera et al., 2011).*

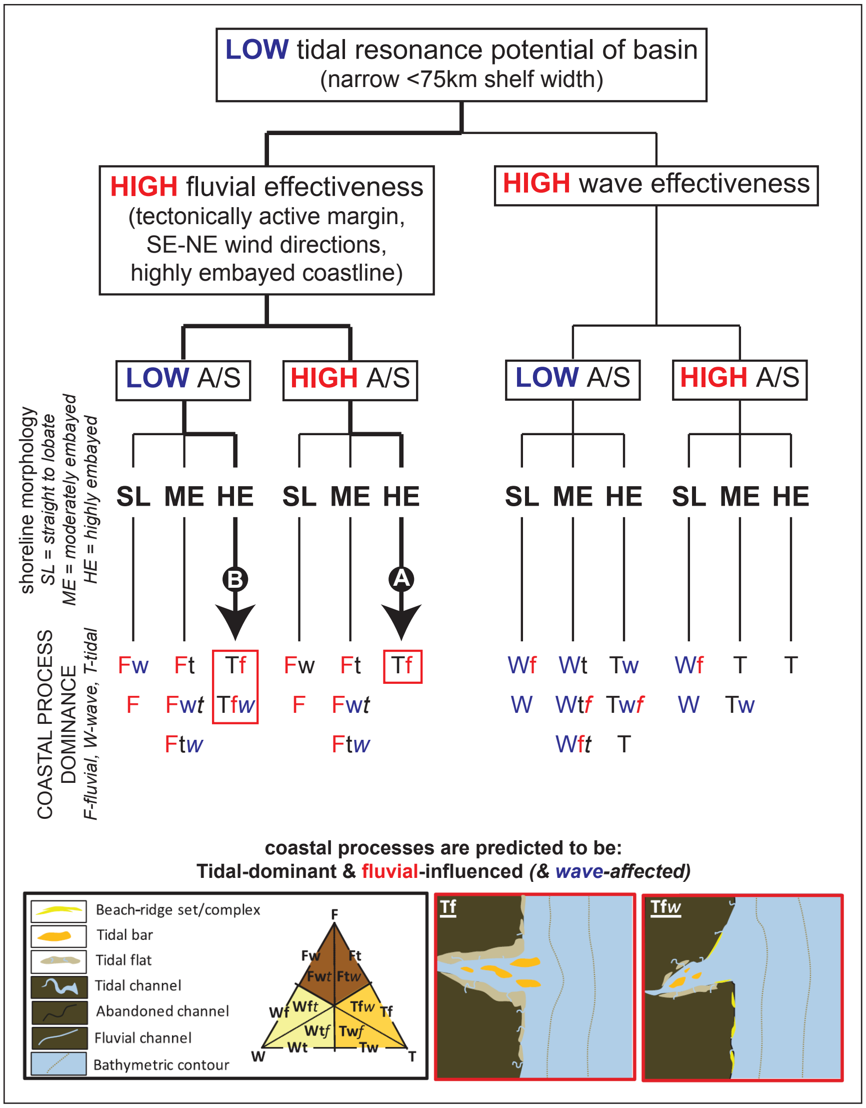


***Figure 4.*** *Coastal morphology and depositional process prediction for both basin margin configurations detailed in Figure 13. Matrices after Ainsworth et al. (2011), interpreted paleogeography from Colpron et al. (2015) and wind directions from Moore et al. (1992). Tf and Tfw morphology graphics from Ainsworth et al. (2011), used with Special Fair Use Permission from the American Association of Petroleum Geologists Publications.*

### *Reservoir and seal rocks*

Lowey (2008a) concluded that medium to thickly bedded feldspathic sandstone of the Tanglefoot formation is of low to high risk for reservoir quality based on their varying porosity characteristics which included abundant secondary porosity of 'uncertain origin'. Regional seal rocks were recognized by Lowey (2008a) in the form of interbedded conglomerate, sandstone and mudstone of the Richthofen formation to the south and overlying Cretaceous Carmacks Group (Fig. 5a) and Mount Nansen Formation volcanic rocks to the north. Mudstone mapped within the Tanglefoot formation also represents local seals, and these are required for the self-sourcing, self-sealing systems of the Tanglefoot stratigraphic play as proposed by NEB (2001) and Hayes (2012).

### *Traps*

Potential stratigraphic traps in the Laberge Group (Tanglefoot formation; Lowey, 2008a) include unconformities and facies pinch-outs. Structural traps in the basin include anticlines and high-angle faults formed during later basin-shortening. In 2004, two 2D seismic lines were acquired in the northern part of the basin which provided approximate stratigraphic thicknesses and subsurface visualization of the southwest-verging fold-and-thrust belt that shortened the basin (White *et al.*, 2006, 2012). A recent 3D geologically constrained inversion of magnetic and gravity data (MIRA Geoscience, 2014) has subsequently provided higher-resolution evidence for dome structures and 'crested anticlines' in the northern trough around Carmacks (Fig. 5b) that may act as structural traps.

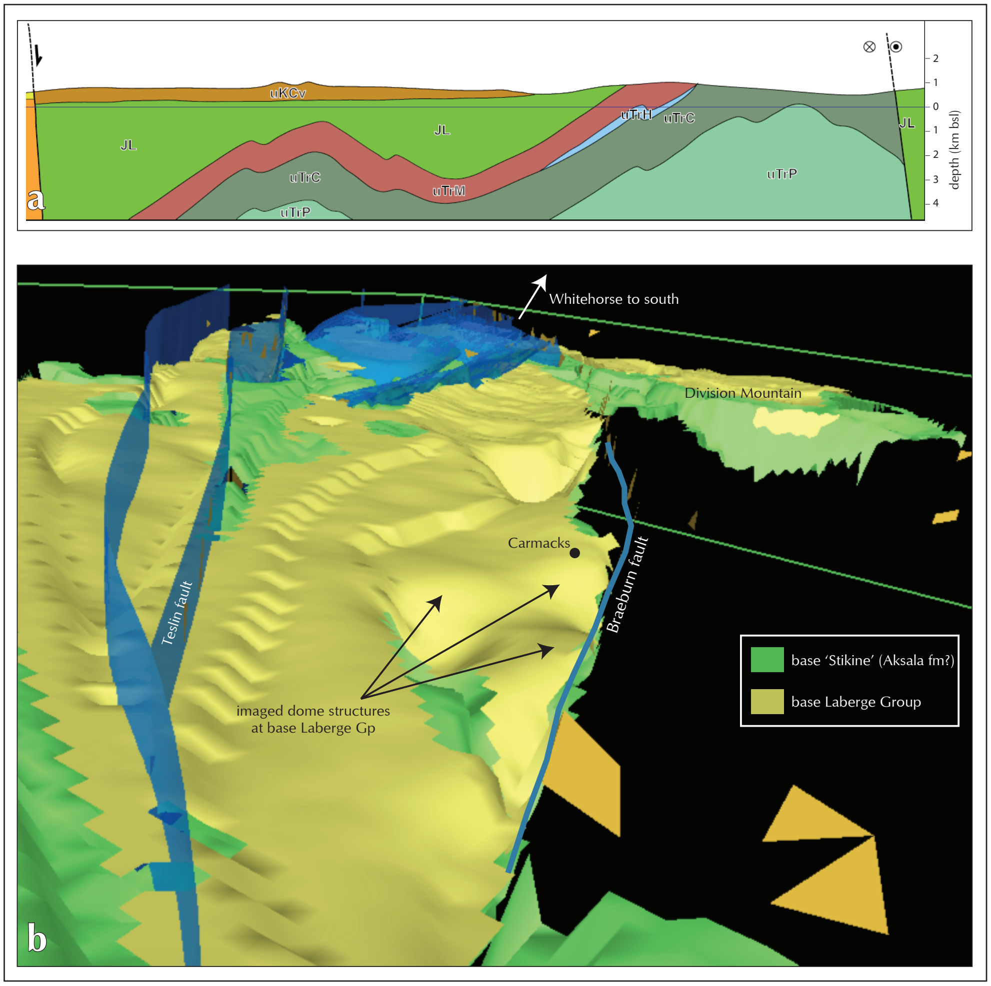


***Figure 5. (a)** WNW-ESE cross section across the north of the Division Mountain area showing folded Laberge Group (JL) underlying the Carmacks Group volcanics (uKCv). Triassic Lewes River Group symbols: uTrM – Mandanna member, uTrH – Hancock member, UTrC – Casca member, UTrP – Povoas formation. See Figure 1 for line location. Figure from MIRA Geoscience (2014); and **(b)** Extract from the 3D inversion model of the Whitehorse trough produced by MIRA Geoscience (2014). Dome structures imaged in the base Laberge Group horizon near Carmacks are highlighted.*

### *Migration and critical moment*

Burial of potential source rocks started during the Late Jurassic, with the critical moment estimated to have occurred during the Early Cretaceous (Fig. 6; Lowey 2008a,b). Minor oil charging of the Tanglefoot formation in the Tantalus Butte area was abruptly halted during regional folding and faulting in the Early Cretaceous (Tempelman-Kluit, 1979). Laberge Group outcrop and shallow drill hole sections in the Whitehorse trough identified to date are of insufficient thickness and rarely preserve key stratal surfaces with the under and overlying stratigraphy in continuous sections to yield meaningful systematic data (e.g., vitrinite reflectance) that could constrain quantitative basin modeling attempts at this time. Tanglefoot formation burial depths are estimated by Lowey *et al.* (2009) to decrease from 3.3 to 4 km at Five Finger Rapids to 3 to 3.8 km at Tantalus Butte based on fluid inclusion homogenization temperature ranges. There are insufficient data from Division Mountain to assess burial depths using this method.

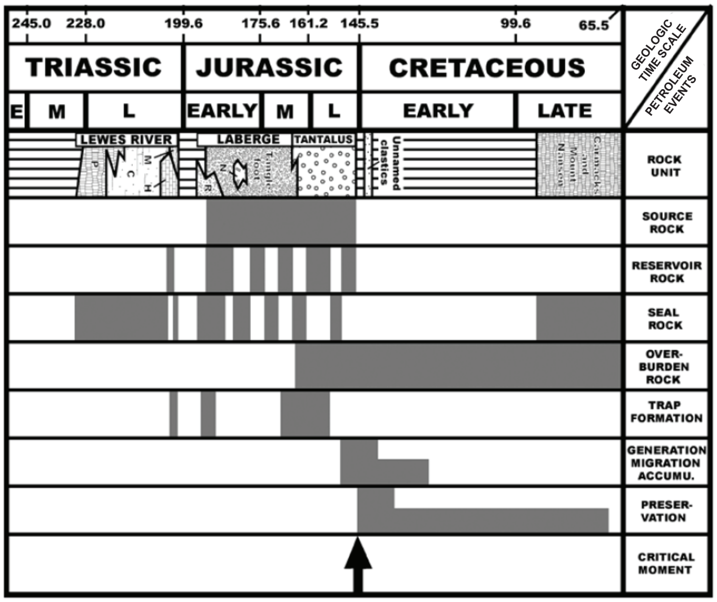


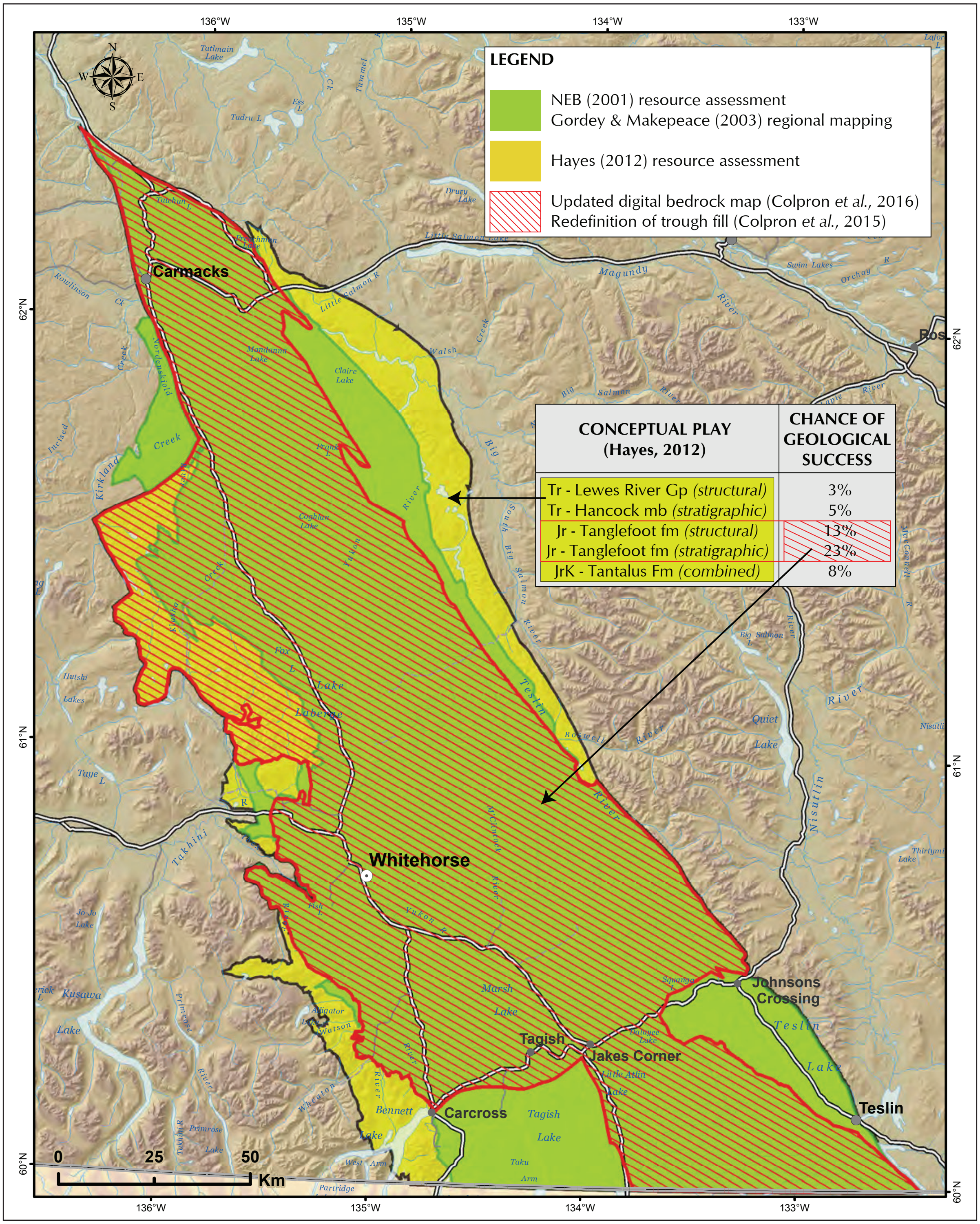
***Figure 6.*** *Petroleum events chart for the Whitehorse trough (from Lowey, 2008b; Fig. 2).*

## *REVISED BASIN RESOURCE DISTRIBUTION AND TYPE*

The Whitehorse trough sedimentary basin outline and spatial distribution of its petroleum resource have evolved in response to updated bedrock geological mapping (*e.g.*, Gordey and Makepeace, 2003; Colpron *et al.*, 2007, 2016b; Colpron, 2011) and resource assessments (*e.g.*, NEB, 2001; Hayes, 2012; Fig. 7). The basin was originally defined as including the upper sedimentary rocks of the Aksala formation of the Upper Triassic Lewes River Group (Wheeler, 1961). However, recent redefinition of the trough as strictly an Early-Middle Jurassic piggyback basin that preserves only Laberge Group (volcani)clastic rocks and coeval chert-clastic strata that overlap the Cache Creek terrane (Colpron *et al.*, 2015) has necessitated further revisions to the basin outline (Plate 1).

This new basin outline is drawn from a petroleum prospectivity perspective. It therefore includes Laberge Group strata that are likely buried beneath the Upper Jurassic Tantalus Formation and Upper Cretaceous Carmacks Group volcanic rocks in the northwest. It also recognizes that patchy, isolated outcrops of Laberge Group that occur south of Carcross or east of Whitehorse along the Takhini and Ibex valleys are not likely to be prospective, and therefore the outline is drawn at the westerly extent of coherent Richthofen formation outcrop in these areas (Plate 1). The eastern margin follows the Teslin fault south to Johnson's Crossing, and the Crag Lake fault forms the southern boundary of Laberge Group basin-fill. Cache Creek terrane overlap chert-clastic strata comprise the southernmost portion of the trough where they outcrop to the south of the Crag Lake fault.

The conventional resource assessment by Hayes (2012) lists five conceptual plays, only two of which can now be considered as Whitehorse trough basin-fill and which have chances of geological success greater than 10% (*see* Fig. 7). This recent work to redefine both the basin outline and its plays (*see* Plate 1) has therefore resulted in prospectivity polygons that are a more accurate representation of resource distribution (Fig. 8) and allow for a systematic, area-by-area approach when researching Laberge Group petroleum systems. The Tanglefoot play in the north exploration area (the main subject of this report) is the most prospective, although typically immature at surface, with conventional hydrocarbon expected to occur in both structural and stratigraphic traps (Hayes, 2012). Recent play redefinition now considers unconventional shale potential to be restricted to only the far southeast of the basin in the south exploration area.



| CONCEPTUAL PLAY (Hayes, 2012) | CHANCE OF GEOLOGICAL SUCCESS |
|---|---|
| Tr - Lewes River Gp *(structural)* | 3% |
| Tr - Hancock mb *(stratigraphic)* | 5% |
| Jr - Tanglefoot fm *(structural)* | 13% |
| Jr - Tanglefoot fm *(stratigraphic)* | 23% |
| JrK - Tantalus Fm *(combined)* | 8% |

***Figure 7.*** *Evolution of basin outline and associated resource distribution. Conceptual play data from Hayes (2012).*

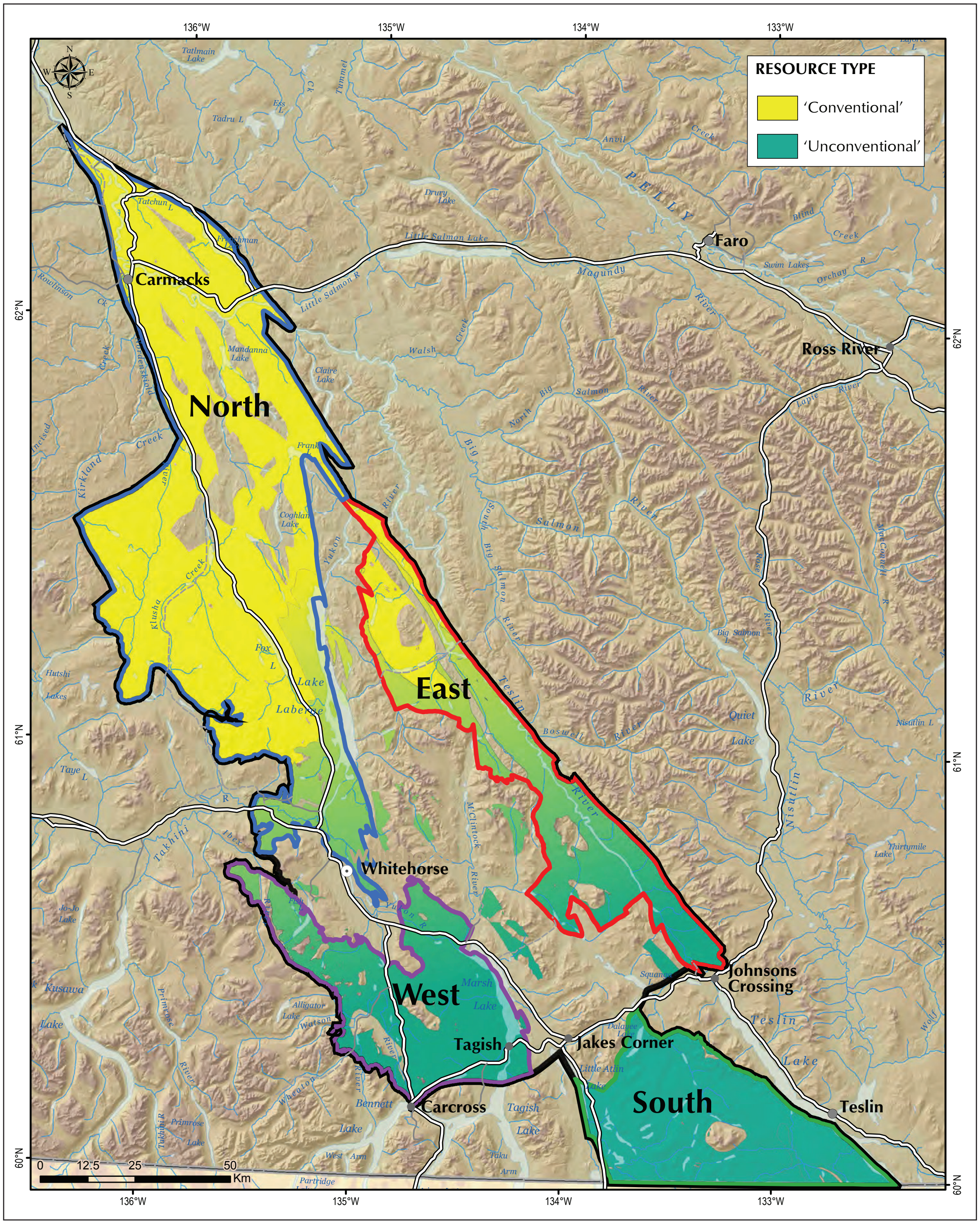


*Figure 8.* New petroleum exploration and research areas for the basin together with their expected resource play types.

# METHODS

## *RESEARCH RATIONALE*

The utility of the current (informal) stratigraphic division of the Laberge Group for understanding both the basin's evolution and its petroleum potential is still problematic (Hutchison *et al.*, 2015). Recent lithostratigraphic revisions to the group (*see* Fig. 2) have resulted in assigning rocks into formation and broad depositional environment 'buckets' rather than focusing on facies and process definition at reservoir-scale resolution. Tanglefoot and Richthofen conglomeratic facies are compositionally similar (Fig. 9) and mappable, yet their 'bucketed' assignment to different formations, together with the abandonment of the Conglomerate formation, has resulted in the obscuration of a significant influx event of coarse-grained material into the basin and this event's controlling mechanism.

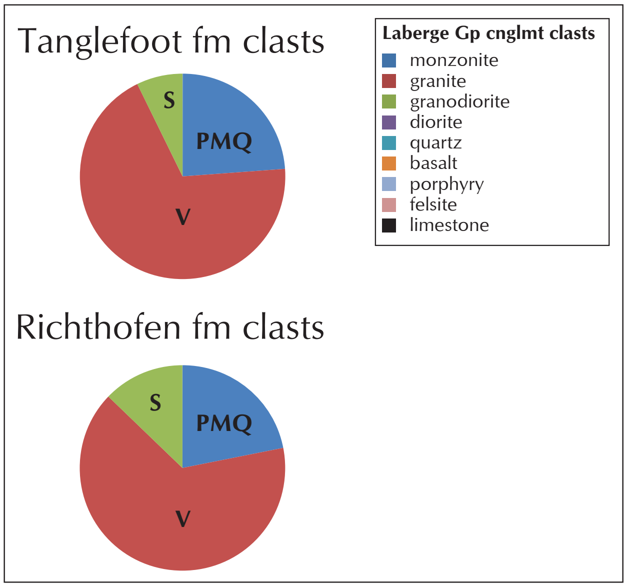


***Figure 9.*** *Laberge Group conglomerate clast proportions. Data from Lowey (2008b).*

Reference to appropriate modern (Fig. 10) and ancient delta (*e.g.*, Garrison and van den Bergh, 2004) and submarine fan system (*e.g.*, Beaubouef *et al.*, 1999) analogues has highlighted the potential complexity of Laberge Group reservoirs, and existing sedimentological data are insufficient to capture these facies relationships at local or regional scale. Furthermore, research that aims to reconstruct ancient marginal marine/delta to offshore depositional systems requires recognition and correlation of key sequence stratigraphic surfaces (*see* studies of the Cretaceous of the Western Interior Seaway by Bhattacharya and Walker, 1991; Garrison and van den Bergh, 2004; and Olariu *et al.*, 2010), with the ultimate goal of erecting an allostratigraphic framework for the Laberge Group.

Ongoing research in the basin is therefore directed towards achieving these goals, and is initially focused on the 'proximal', coarse-grained Laberge Group facies in the north exploration area (*see* Fig. 8) as the most prospective for hydrocarbon using the research strategy in Figure 11. Planned future research will then proceed systematically southeastwards, with the eventual aim of assessing any unconventional shale reservoir potential of 'distal', fine-grained Laberge Group facies in the basin.

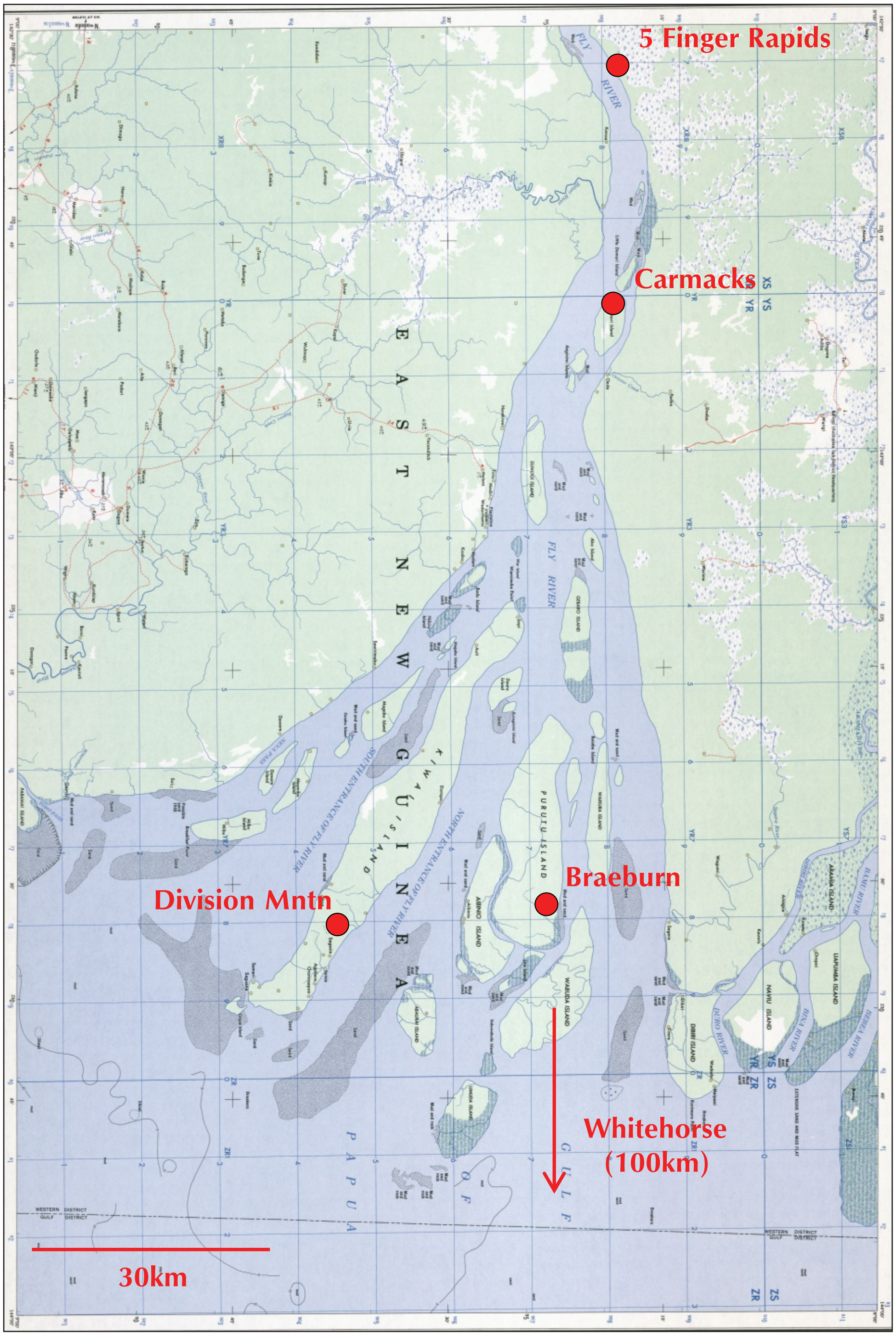


*Figure 10.* Modern analogue example of a tidal delta – the Fly River delta in New Guinea. The delta is of the same geographic scale and depositional environment as that anticipated for the northern Whitehorse trough, enabling key Yukon locations in the basin to be superimposed to facilitate understanding of the complex 3D reservoir architecture likely to exist. Map from <http://www.lib.utexas.edu/maps/ams/new_guinea/txu-oclc-6552576-sc54-4.jpg> [accessed May 20, 2016].

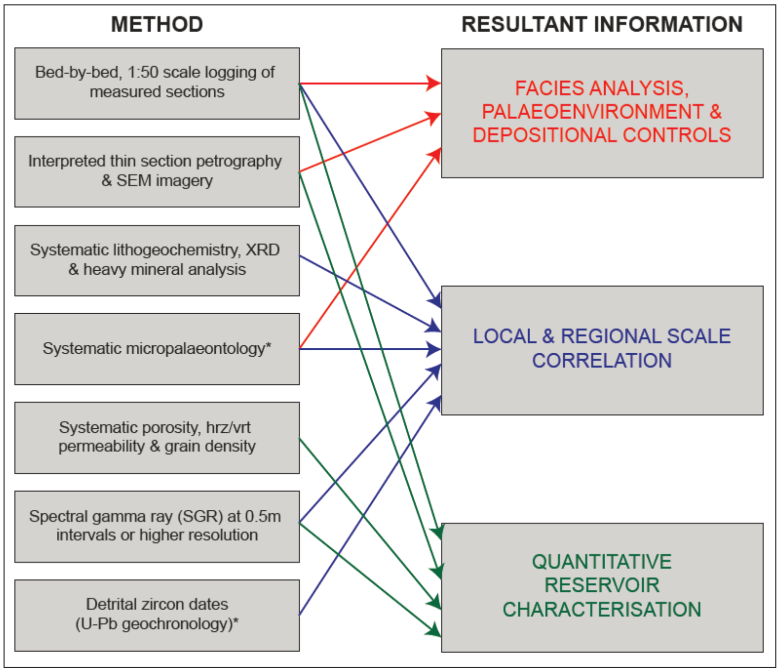


***Figure 11.** Proposed integrated methodology for current and future research studies in the Whitehorse trough.*

## *DATA COLLATION, COLLECTION AND ANALYSIS*

Analytical data from research in the Whitehorse trough conducted by the Yukon Geological Survey from approximately 1999 to 2011 were collated during 2013-14, and are presented in Appendix 2. In addition to measured section spreadsheets, sample data with associated coordinates include: fluid inclusions, palynology, body fossils, whole rock geochemistry, RockEval-TOC and vitrinite reflectance. Measured section information was captured in the form of hand-written notes and predominantly as Adobe Illustrator format sedimentary logs. However, the paucity of sedimentological data captured in the latter renders them unusable for future, high-resolution petroleum research in the trough.

Sedimentary logs presented in this current work were drafted from hand-written field notes of T.L. Allen (*see* also Allen, 2000), and redrafted from Long (2015) to ensure a consistent log format in this and future studies (Appendix 3). As these logs are not those of this author, and logs of Laberge Group outcrops on the Robert Campbell and North Klondike highways were not measured during 2015 fieldwork, no systematic facies analysis has been completed to date. Key locality descriptions and interpretation (*see* Table 1 and Fig. 8), in part modified from Colpron *et al.* (2016a), presented in the results section below are a synthesis of detailed field observations and field/analytical data collected during 2014-15 fieldwork that included:

- Outcrop spectral gamma ray from 14-MH-010, 013 and 16 at 0.5 m intervals using a hand-held spectrometer (Radiation Solution's RS-230 BGO Super-SPEC spectrometer with a 0.103 litre BGO crystal). Individual concentrations of potassium (K), uranium (U) and thorium (Th) were then proportionally summed using the following equation from Rider (2002) to give a gamma ray (GR) log in API units:

  $$GR\ (API) = 16.32*K\ (\%) + 8.09*U\ (ppm) + 3.93*Th\ (ppm)$$

- Mean grain size at 0.1 m intervals direct from outcrop (14-MH-010, 013 and 016) and at 0.5 m intervals extracted from drafted sedimentary logs of outcrop (Carmacks Pits, Mount Vowles and Teslin Creek; Long, 2015) and diamond drill core at Division Mountain (15-MH-97/63, 94/37, 94/40 and 95/54; Allen, 2000).
- Whole rock inorganic geochemistry, with samples taken at approximately 10 m intervals (14-MH-013 and 016), 2 m intervals (14-MH-010) and 5-10 m intervals (15-MH-97/63 and 94/37).

***Table 1.*** *Measured section and key locality coordinate information for this report. Note that Division Mountain core samples (labelled 15-MH-XX/YY) refer to actual coal exploration drill hole numbers of the format DDH-XX/YY, where XX is the abbreviated year drilled and YY is the assigned hole number for that year.*

| **Section ID** | **X** | **Y** | **UTM - NAD83** |
|---|---|---|---|
| 14-MH-001: Takhini Fire Hall | 483116 | 6742250 | 8V |
| 14-MH-010: Lone Pine Mountain | 439316 | 6865680 | 8V |
| 14-MH-013: Eagles Nest Bluff | 456959 | 6877113 | 8V |
| 14-MH-016: Robert Campbell Highway | 441715 | 6885880 | 8V |
| 15-MH-94/37 (DDH-94/37): Division Mountain | 444239 | 6798553 | 8V |
| 15-MH-97/63 (DDH-97/63): Division Mountain | 445251 | 6796832 | 8V |

Samples were run at Bureau Veritas Laboratories Ltd in Vancouver using analytical package code LF202. Samples were pulverized so that 85% of material passed through a 200 grade mesh sieve and washed using an extra silica wash with glass between each sample. Pulps were then subject to aqua regia acid digestion and analyzed for 21 standard major oxides via ICP-ES and 45 standard trace elements via ICP-MS. Leco carbon and sulphur concentrations were also obtained as part of the major oxide analytical package.

- X-ray powder diffraction (XRD) analysis of 17 representative sandstone samples from 14-MH-010, 013 and 016 was carried out at the Geological Survey of Canada in Ottawa. X-ray patterns of micronized bulk samples with a grain size of 5-10 µm and clay-size separates were recorded on a Bruker D8 Advance Powder Diffractometer equipped with a Lynx-Eye Detector, Co Kα radiation set at 40 kV and 40 mA. Initial identification of minerals was made using EVA (Bruker AXS Inc.) software with comparison to reference mineral patterns using Powder Diffraction Files (PDF) of the International Centre for Diffraction Data (ICDD) and other available databases. Quantitative analysis was carried out using TOPAS (Bruker AXS Inc.), a PC-based program that performs Rietveld refinement (RR) of XRD spectra based on a whole pattern fitting algorithm.
- Porosity, multidirectional permeability and grain density analyses were performed by Core Laboratories Ltd in Calgary on samples from the Mandanna member (two samples) and proximal Laberge Group (78 samples). Due to sample quality and quantity submitted (*i.e.*, a mixture of diamond drill core: 15-MH-97/63, 94/37; and outcrop: 14-MH-001, 010, 013 and 016), analytical methods to obtain the various parameters varied (*see* legend in Appendix 4c for further details).
- Thin section petrography was carried out on 20 samples submitted to Core Laboratories Ltd in Calgary from the Mandanna member (one sample) and proximal Laberge Group (19 samples from 14-MH-010, 013, 016 and 15-MH-97/63, 94/37). Thirty micron thin sections were prepared using blue dye (to highlight pore space), Alizarin Red-S (to differentiate calcite from dolomite), potassium ferrocyanide (to distinguish ferroan carbonate varieties) and sodium cobaltnitrite (to stain potassium feldspar). The thin sections were analyzed using standard petrographic techniques prior to being point counted (250 points) to determine semi-quantitative mineral and porosity percentages.
- SEM analysis was performed on a subset of the 20 thin-sectioned samples by Core Laboratories Ltd in Calgary. Small samples measuring 5x10 mm were coated with gold before being analyzed by backscatter scanning electron microscopy.

The sampling program was designed to achieve a full spectrum of analytical results (compiled data and original contractor reports presented in Appendix 4) for as many samples as quantity and quality allowed for. A primary objective in adopting this approach was to understand more fully the mineralogical (provenance and diagenetic) controls on porosity and permeability.

# RESULTS

## *KEY LOCALITIES VISITED*

### *Takhini Fire Hall (14-MH-001)*

Although this distinctive maroon outcrop is characteristic of the Upper Triassic Mandanna member (Aksala formation) of the Lewes River Group, a description is included here due to its lithological and mineralogical similarity with rocks of the basal Laberge Group exposed at Eagles Nest Bluff (*see* below). The outcrop comprises bioturbated red to maroon mudstone, siltstone and sandstone (Fig. 12a). The sandstone is fine to coarse grained and composed of angular plagioclase, hornblende, volcanic lithic grains and quartz. Maroon, pebble to cobble-sized siltstone rip-up clasts are locally abundant. Sandstone beds are typically normally graded, exhibit planar and cross-lamination, and are locally massive (Fig. 12b). Scoured bed bases and mud draped bed tops are common, and beds exhibit lensoid geometries in the upper part of the outcrop that are interpreted by Long (2005) to characterize a broad, stepped bank channel-fill succession. Detrital zircons from a nearby outcrop have a bimodal distribution, with peaks at *ca.* 338 and 205 Ma (Colpron *et al.,* 2015). The latter peak and the weighted mean age of 201.5 ± 1.5 Ma (Colpron *et al.,* 2015) are consistent with the 201.5 ± 0.6 Ma date from a tuff near the top of the Mandanna member ~15 km to the south (Lowey, 2008b, p. 183; Colpron *et al.,* 2015) and suggest a Rhaetian maximum depositional age for the Mandanna.

Bioturbation, although abundant in this section, is of very low diversity and interpreted here as *Planolites*. Burrows are subvertical cylindrical tubes that are unlined and un-branched. They are filled with a darker red, slightly finer grained matrix (Fig. 12c), or locally by coarse-grained sandstone; both cases indicate downward transport of fill-material from above. Burrow abundance decreases vertically towards the bed base suggesting downward burrowing towards higher moisture content substrate and that sediment influx was too rapid to allow for syndepositional colonization.

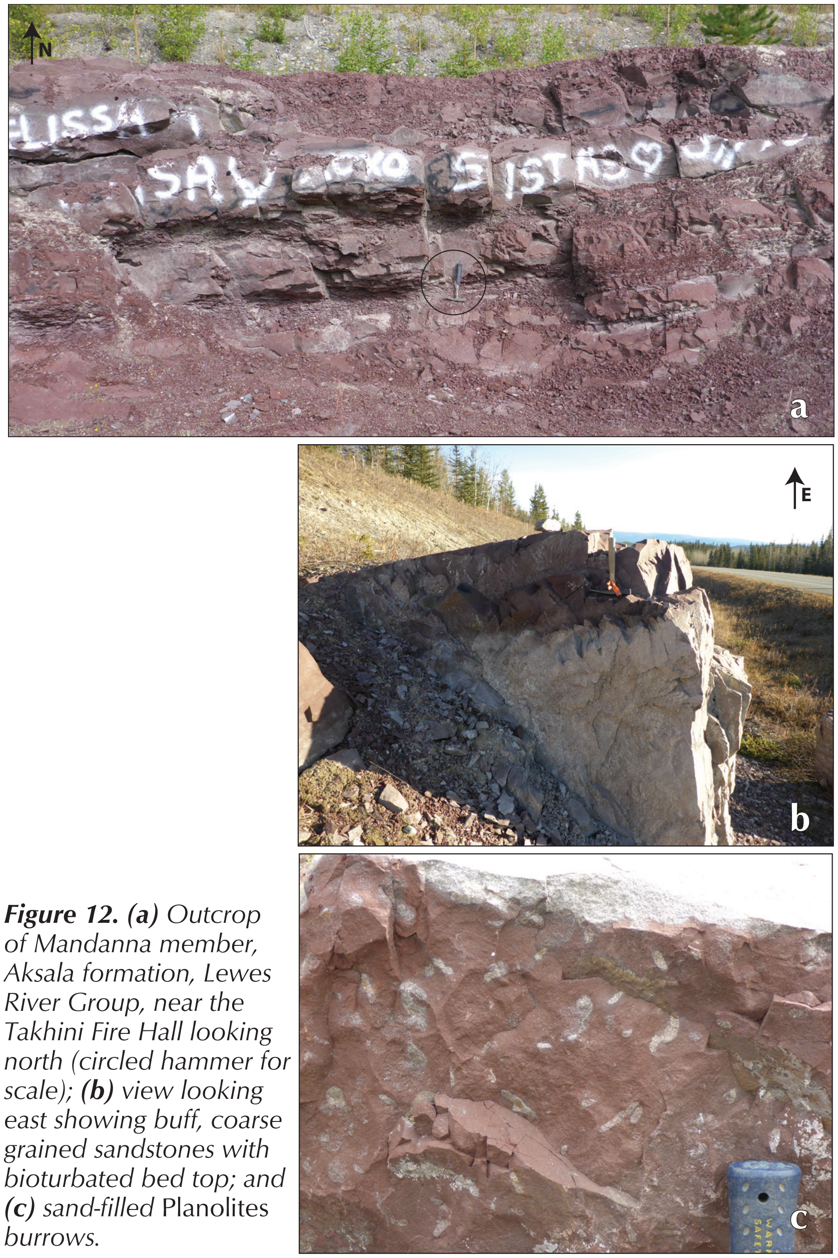


***Figure 12. (a)*** *Outcrop of Mandanna member, Aksala formation, Lewes River Group, near the Takhini Fire Hall looking north (circled hammer for scale);* ***(b)*** *view looking east showing buff, coarse grained sandstones with bioturbated bed top; and* ***(c)*** *sand-filled* Planolites *burrows.*

*Planolites* represent active backfilling of sediment in an ephemeral burrow constructed by a mobile deposit feeder (*e.g.*, Pemberton and Frey, 1982), but contrary to Long's (2005) interpretation for this outcrop, the ichnogenus cannot be used to specifically infer an intertidal environment. Local observations of caliche and desiccation cracks in this member (Dickie and Hein, 1995; Lowey, *unpbl.*) also support ephemerality and a semi-arid to arid climate. Rapid deposition resulting in massive sandstone beds, scoured to welded bed bases and mud rip-up lags also support an ephemeral, flood-dominated alluvial system interpretation. Proximity to coastline or a marine (tidal?) influence has yet to be demonstrated at this outcrop.

### *Eagles Nest Bluff (14-MH-013)*

The maroon-weathering, medium to coarse-grained sandstone and poorly sorted conglomerate exposed at Eagles Nest Bluff (Fig. 13a) are the oldest Laberge Group rocks known in the Whitehorse trough. Clasts of the conglomerate are dominated by volcanic and subvolcanic rocks, but also include lesser limestone and red mudstone. Long (2005) originally interpreted these strata as deposits of a gravel-bed meandering fluvial system, with channel-fill sequences dominated by lateral accretion surfaces and interbedded mudstone representing overbank deposits. Red mudstone interbeds (<10 cm) locally display sand-filled desiccation crack casts and raindrop impressions (Fig. 13b). Sandstone grain composition and sorting appears similar to the maroon-weathering Rhaetian (Upper Triassic) Mandanna member sandstone of the Lewes River Group farther south in the trough (*see* above), and in view of this outcrop's structural and stratigraphical position above Hancock member exposures immediately to the west, Long (2005) assigned these rocks to the Mandanna. Recently, however, detrital zircon analysis of a single coarse-grained sandstone sample yielded a weighted mean age for a cluster of young zircons of 193.8 ± 1.8 Ma (Colpron *et al.*, 2015), suggesting a Sinemurian depositional age and re-assignment of this section to the base of the Laberge Group.

***Figure 13.*** ***(a)*** *Outcrop 14-MH-013 immediately east of Eagle's Nest Bluff on the Robert Campbell Highway of the oldest Laberge Group rocks known in the Whitehorse trough to date, looking north; and* ***(b)*** *sand-filled desiccation crack casts in the lower maroon fine-grained unit.*

The section can be broadly divided into upper and lower maroon, fine-grained facies that encase a middle section of grey/red weathered, poorly sorted conglomerate and sandstone. The maroon hematitic weathering and desiccation of fine-grained clastic rocks in the Lower Jurassic basal Laberge Group and Upper Triassic Mandanna member (*c.f.*, Hart, 1997; Long, 2005) suggest the prevalence of Late Triassic depositional processes and semi-arid climate across the Hettangian-Pliensbachian sub-Laberge unconformity (Colpron *et al.*, 2015) in this area.

In addition to stratigraphic assignment, way-up direction has also been of debate at this outcrop. Long (2005) interprets scoured fluvial channel-fill deposits with an east to west way-up (*see* his Fig. 6). However, desiccation crack casts in both the lower and upper fine-grained facies and scoured channels with conglomerate lags in the middle unit at this outcrop indicate a west to east way-up direction. In addition to the absence of any structural fabric to indicate such a tight fold in the section, the latter direction is supported by the presence of Hancock member limestone unconformably capped by Laberge Group conglomerate 500 m west of this section.

### *Robert Campbell Highway (14-MH-016 and others)*

Outcrops of proximal Laberge Group along the Robert Campbell highway east of Carmacks comprise (pebbly) sandstone, conglomerate, carbonaceous mudstone, 'seat earths' and tuff. A detrital zircon date from a sandstone immediately west of this section yielded a weighted mean age of early Toarcian, 181.9 ± 3.0 Ma (Colpron *et al.*, 2015). Benthic macrofossils from Robert Campbell highway outcrops include pelecypods, brachiopods, corals, gastropods and crinoids indicative of shoreline to marginal marine environments (*e.g.*, Poulton, 1979), and fossilized plant and wood fragments (Lowey, 2004) and charcoal(?) are abundant. Fossil assemblages indicate a Sinemurian to Bajocian age for the strata (Lowey, 2004). Spore and pollen assemblages suggest a well-drained (semi-arid) alluvial and coastal plain environment (Sweet, 2007). Coral wackestone, floatstone and oyster rudstone in the formation suggest either bioclastic bar development in a shallow marine setting or supratidal storm deposits (Lowey, 2008b).

The 14-MH-016 outcrop of proximal Laberge Group consists of thick to very thickly bedded coarse sandstone and granule to pebble conglomerate intercalated with finer-grained heterolithic beds (Fig. 14a). Thick-bedded sandstone is typically internally structureless, but is often interbedded with thin mudstone beds that become reworked as angular rip-up clasts in bed bases (Fig. 14b). A rare cluster of subvertical, sparsely branched unlined burrows (*Psilonichnus*; E. Nesbitt, *pers. comm.*, 2016) was observed in the central coarse-grained interval (Fig. 14c), suggesting an estuarine or tidal delta bar depositional environment for this sandstone.

Heterolithic interval sandstone beds are finer grained (but still medium to coarse), internally structureless and locally exhibit wave-rippled bed tops. Circular patches of red-brown mottling in this sandstone are tentatively interpreted as burrows, and very rare rootlets suggest that these horizons (which are overlain by carbonaceous, mottled mudstone) represent 'seat earths'. The outcrop also displays evidence of the trough's compressional history, with shortening accommodated primarily within the mudstone of the heterolithic, fine-grained facies. Intense sigmoidal folding occurs within the more competent thin sandstone beds.

### *Lone Pine Mountain (14-MH-010) and Division Mountain*

The Lone Pine Mountain roadside outcrop forms a key link between good exposure of proximal Laberge Group gravel and sandstone in the north and the tightly-drilled, mud-prone coal deposits to the south at Division Mountain. The abrupt transition between interbedded grey-brown sandstone and mudstone to coarse-grained, white sandstone and gravel up-section is also recognized in core from Division Mountain (*see* below), where it is used to locally divide the Tanglefoot formation into a 'lower' and 'upper' member (Allen, 2000). It is a key regional surface, although likely diachronous, and shows evidence of loading along its lateral extent in outcrop (Fig. 15a). Coal deposits only occur above this horizon in the Laberge Group.

***Figure 14.*** ***(a)*** *Outcrop 14-MH-106 on the Robert Campbell Highway east of Carmacks, comprising intercalated coarse sandstone to pebble conglomerates and heterolithic fine-grained sediments;* ***(b)*** *mudstone rip-up clasts; and* ***(c)*** Psilonichnus *burrows in the central coarse-grained sandstone unit.*

A pronounced coarsening-up signature is recorded in both grain size and gamma ray logs in the lower 5 m of this section, and in equivalent strata at Division Mountain (Plate 2). Sandstone beds are typically internally structureless, although there are hints of storm-wave processes and thin, current-rippled beds. Thicker, planar beds towards the top of this interval exhibit sharp, erosive bases (Fig. 15b). Interbedded mudstone is generally too weathered and fractured to reveal structure, however its bed thickness and frequency decreases up-section. A marine environment is indicated by local Trigoniid and coral recoveries from outcrops at Division Mountain (Allen, 2000), and by glauconite observed in sandstone thin section from the base of the Lone Pine Mountain outcrop. The lack of bioturbation at this location suggests a more stressed environment than to the south at Division Mountain, with repeated sediment/freshwater(?) influx combined with possible storm activity in a prograding offshore to lower shoreface transition.

The coarse-grained sequence that forms the bulk of the outcrop exhibits abundant current-generated structures draped by mudstone and carbonized plant material (Fig. 15c). Cross-stratification is shallowly inclined, with local preservation of topsets and common muddy toesets (Fig. 15d). Reactivation surfaces, carbon/mud-rich flaser beds and current ripple-lamination are also observed. Soft sediment deformation (loading) is observed in Division Mountain cores (Fig. 15e), together with normal grading in sandstone beds (Fig. 15f). These strata are tentatively interpreted as a sequence of stacked tidal bars of estuarine or tidal-delta origin. Its presence is consistent with the progradational character of the shoreface deposits below, and the sharp contact at its base is evidence for abrupt (regional) base level fall resulting in the reworking of older swamps and low-lying coastal plains farther up depositional dip. Low-sulphur contents of the coals in the upper Laberge Group suggest a depositional environment outside of the influence of marine water (Allen, 2000), such as plains landward of the bayline, and vitrinite varieties of this unit from Division Mountain indicate an environment dominated by reeds of a low-lying wetland flora (Beaton *et al.*, 1992).

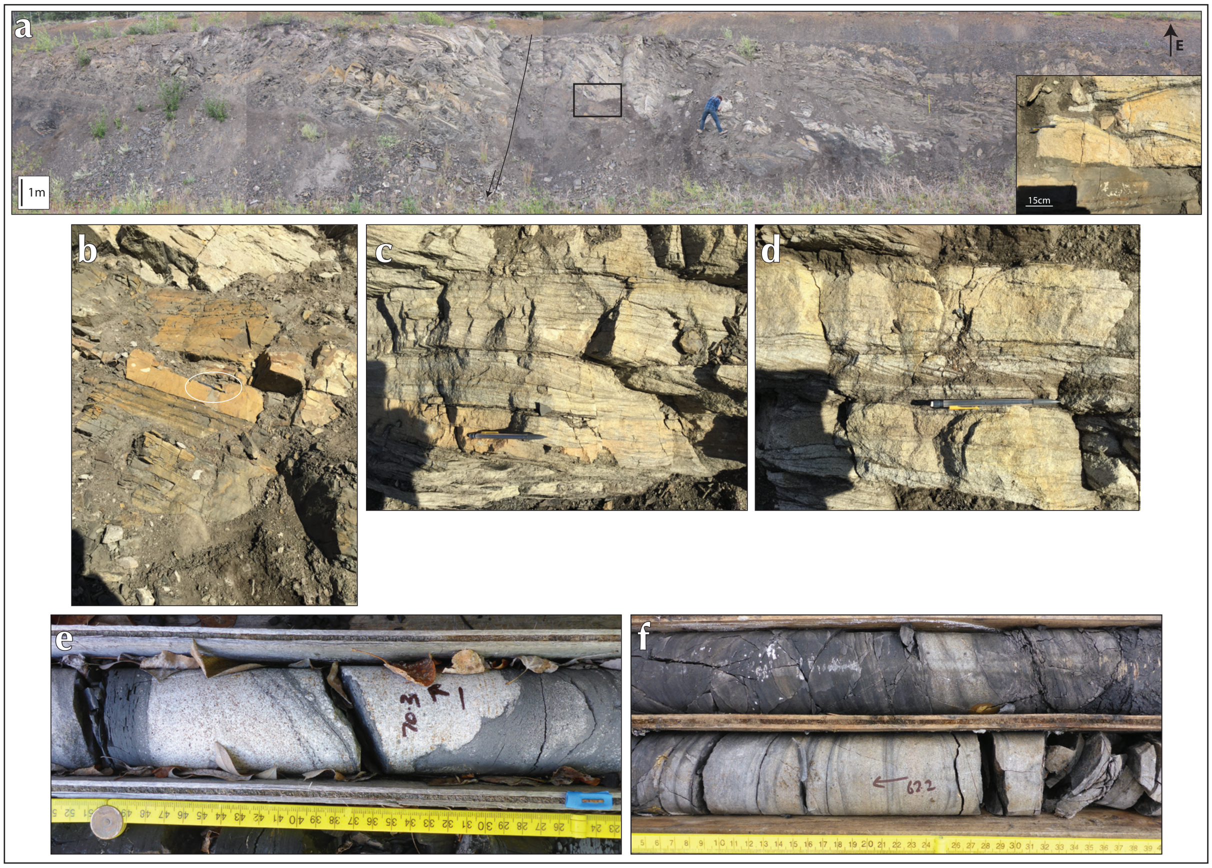


***Figure 15.*** ***(a)*** *Lone Pine Mountain outcrop photopanel and inset detail of the abrupt transition between the lower and upper sequences in this section;* ***(b)*** *orange-weathered, erosive-based planar sandstone beds at the top of the section's lower sequence (pencil circled in centre of photo for scale);* ***(c)*** *abundant current-generated structures draped by mudstone and carbonized plant material in tidal deposits of the upper sequence;* ***(d)*** *muddy toeset and foreset drapes in a thin, cross-stratified sandstone bed in the section's upper sequence;* ***(e)*** *soft sediment deformation (loading) in the upper part of Division Mountain core 15-MH-93/67; and* ***(f)*** *normally graded sandstone beds in 15-MH-93/67.*

### *Lake Laberge Campground and Deep Creek*

Distal Laberge Group exposures along the shoreline of Lake Laberge near the boat launch consist of thin-bedded (<10 cm) siltstone-sandstone and mudstone couplets. The sediment retains characteristics of deposition from turbidity currents (e.g., Bouma Tcde subdivisions, normal grading and asymmetric ripple cross-lamination; Lowey, 2004, 2005), however it also shows evidence of significant post-depositional modification by storm wave processes and biological activity.

Sandstone bed bases range from sharp and erosive to loaded with occasional flame structures (Fig. 16a), suggesting that mud substrate conditions varied between being continually waterlogged during rapid, repeated flood events or having time to dewater and indurate. Sandstone displays pinch-and-swell lenticular bedding (suggesting tractive, oscillatory transport and deposition above storm wave-base), and bed tops exhibit long wavelength, low amplitude swales (Fig. 16b) together with isolated, preserved mudstone laminae. Sandstone is also locally abundantly bioturbated with unlined, mudstone filled horizontal to sub-horizontal burrows (Fig. 16c) interpreted as *Cruziana* ichnofacies (Lowey, 2005), indicating bottom waters were oxygenated. Stacked thicknesses of unbioturbated, normally graded mudstone-sandstone couplets (Fig. 16d) suggest a storm and river-influenced shelf environment where repeated sediment influx and storm-wave reworking prevented post-depositional colonization by bottom-dwellers.

Exposures to the south, between the campground and Deep Creek (~250 m) are of thick-bedded (<1 m) lithic sandstone. This sandstone is immature and poorly-sorted, and typically comprises medium grained, angular to subrounded feldspar and quartz, lithic clasts of volcanic (and plutonic?) origin, and grains of augite and epidote. Graded siltstone-sandstone beds, up to 10 cm thick, occur between the thick sandstone, and mudstone rip-up clasts up to 10 cm in length form sandstone bed basal lags. Lenses of reworked crystal-lithic tuff similar to the Nordenskiöld occur on top of the southernmost exposure. A sample of this lithic sandstone was analyzed for detrital zircons, with the majority of grains yielding ages between 180-220 Ma, and a subordinate population of Mississippian grains with ages between 320 and 350 Ma (Colpron *et al.,* 2015). These authors calculated a weighted mean age of 190.5 ± 1.5 Ma (Sinemurian to Pliensbachian) for this sample.

***Figure 16.*** ***(a)*** *Localized loading and flame structures in the base of distal Laberge Group sandstone beds along the shoreline of Lake Laberge adjacent to the campground;* ***(b)*** *pinch-and-swell bedding in normally graded sandstone beds;* ***(c)*** *abundant sub-horizontal bioturbation in distal turbidite sandstone; and* ***(d)*** *stacked, unbioturbated sandstone-mudstone couplets displaying wavy, lenticular bedding and starved sand ripples with internal asymmetric cross-lamination.*

Overall, distal Laberge Group strata at this locality represent the products of a variety of primary and secondary depositional processes acting in an oxygenated, neritic shelf environment. Thin-bedded, storm wave-reworked turbidite was deposited in the distal outer or mid-fan lobes of a submarine fan, with the thicker-bedded, erosive sandstone closer to Deep Creek representing more proximal, channeled mid-fan or inner-fan channel-fill deposits. Variability in bioturbation abundance and substrate induration suggests fluctuations in sediment influx (flood events) over time, and this may have ultimately been controlled by staccato rift shoulder uplift and/or high-frequency climatic cycles.

### ***Horse Creek***

Laberge Group exposure in the far southwest of the northern exploration area of the Whitehorse trough (*see* Fig. 8) is dominated by polymict cobble and boulder conglomerate, together with lesser sandstone-mudstone rocks similar to those observed at Lake Laberge campground. The Horse Creek section was originally interpreted to contain the contact between the lower fine-grained Richthofen formation and the massive pebble conglomerate of the Conglomerate formation (*see* Fig. 2; Hart, 1997; Dickie, 1989; Dickie and Hein, 1995), however more recent work by Lowey (2004, 2005) resulted in the abandonment of the Conglomerate formation, and incorporation of the Horse Creek conglomerate into the Richthofen formation.

The finer-grained facies at the base of the section are dominated by interbedded thin to medium-bedded sandstone and massive to laminated mudstone (Fig. 17a). Sandstone beds have scoured bases, are normally graded and exhibit planar lamination characteristic of high-energy, upper flow regime Bouma Tab turbidite deposits (Fig. 17b). Massive to laminated mudstone was deposited during waning flow from low density turbidity currents. Sandstone beds are laterally continuous, and appear stacked in parasequences defined by sets of increasing bed thickness up-section (*see* Fig. 17a). Ammonite assemblages from these facies yielded fossils that confirm a Sinemurian age, and which locally are as young as lowermost Pliensbachian (Hart, 1997).

Sharply overlying these facies is 300 m (Dickie, 1989) of massive, cliff-forming conglomerate (Fig. 17c) consisting of both matrix-supported boulder conglomerate with mudstone rafts and clast-supported cobble conglomerate with heavily oxidized granitic clasts. Mudstone rafts, up to 3 m in length, are a feature of some of the basal conglomerate in this area (Hart, 1997). The very large average clast size, and exceptionally large individual clasts, required an extreme topographic gradient typical of an uplifted source terrain. Common unidirectional palaeocurrent structures indicate easterly, transverse mass-flow transport of debris from the trough's western shoulder (Hart, 1997; Dickie, 1989) onto submarine fan-deltas prograding into an under-filled basin. The abrupt shift in facies and energy conditions at this locality further suggests a rapid, tectonically-controlled reorganization of the western trough's drainage system. Intense soft sediment deformation observed in sandstone-mudstone turbidite deposits of the distal Laberge Group to the north around Little Fox Lake (Fig. 18) provide evidence that the deeper trough experienced seismically-triggered tsunami and seiche waves at this time (*e.g.*, Alsop and Marco, 2012).

Sinemurian-age conglomerate in the Whitehorse trough typically has a high proportion of sedimentary and volcanic clasts, with limestone characteristically representing up to 10-20% of the clast mode (Dickie and Hein, 1995; Johannson *et al.*, 1997; Shirmohammad *et al.*, 2011). By early Pliensbachian, volcanic clasts were dominant, suggesting the progressive exhumation of the arc terranes (Upper Triassic Povoas formation volcanic rocks and Mandanna and Hancock member sediments; *see* Fig. 2) that flanked the trough (*e.g.*, Colpron *et al.*, 2015).

*Figure 17.* ***(a)*** *Distal Laberge Group turbidite deposits in the lower part of the Horse Creek section. Note the stacking arrangement of parasequences defined by increasing bed thickness up-section (left to right in photo);* ***(b)*** *graded, planar-laminated turbidite sandstone; and* ***(c)*** *mass-flow, clast-supported conglomerate of the upper Horse Creek section.*

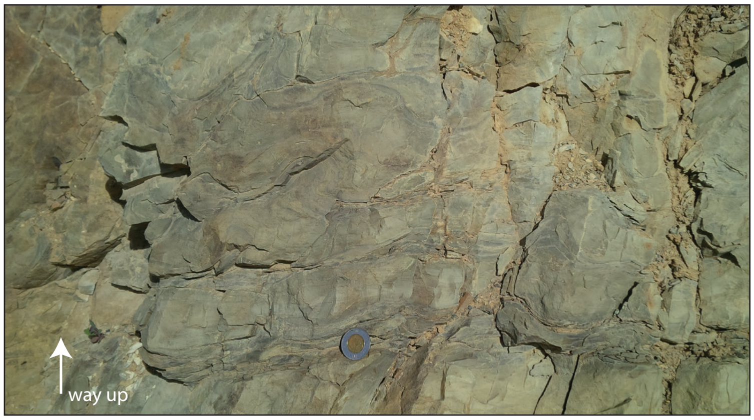


***Figure 18.*** *Seiche or tsunami-triggered contorted bedding in distal Laberge Group turbidites on the North Klondike Highway north of Fox Lake (toonie for scale).*

## *PROXIMAL LABERGE GROUP RESERVOIR CHARACTERIZATION*

### *Grade (grain size) and net pay*

Proximal strata of the Laberge Group observed in outcrop (Tantalus Butte area) or diamond drill core (Division Mountain area) are dominated by fine to very coarse grained sandstone and conglomerate, with lesser intercalated carbonaceous mudstone and coal (Plate 2). In order to more accurately define net-pay potential in heterogeneous reservoirs, and to move away from simple industry pay/non-pay models or very detailed individual grain size calculations, Sheng (2012) adopted four grain size ‘cut-off’ bins (grades) through which pay potential is assumed to progressively increase not accounting for diagenesis: clay, silt, dirty sand and clean sand (Fig. 19a).

Other rocks can be added (e.g., conglomerate, and coal and volcanic rocks in the Division Mountain play), with the ultimate goal of estimating variable pay thicknesses of the reservoir interval or section under study. In the Laberge Group, an $R^2$ value of 0.99 highlights that grade thicknesses can be accurately calculated from sections where only point-sampled grain size data were recorded (Fig. 19b).

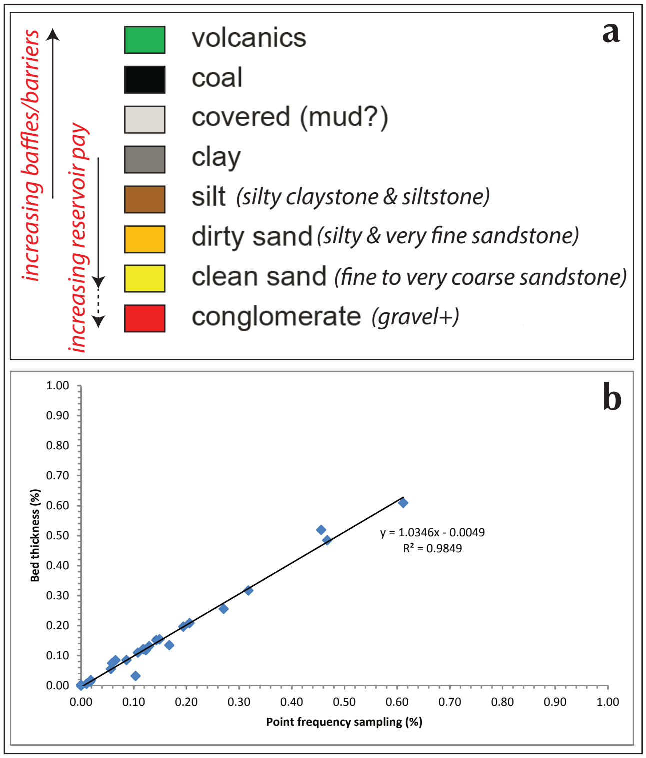


***Figure 19. (a)*** *Grades and associated rocks in which reservoir pay potential is assumed to progressively increase assuming no diagenesis (modified from Sheng, 2012); and* ***(b)*** *in the Laberge Group, an R2 value of 0.99 highlights that grade thicknesses can be accurately calculated from sections where only point-sampled data was recorded.*

Laberge Group grade proportions in Figure 20 are representative of a 'composite' section through known Laberge stratigraphy, exclusive of temporal or geographical variability (although these are easily visible in the pie-chart). From more than 2 km of measured section incorporated into this study, key conclusions include:

- The proximal Laberge Group is lithologically heterogeneous. The extensive proportion of covered section at Teslin Creek (485 m, presumed mudstone due to their poor resistance to weathering noted from exposed drill core) suggests that the group is more shale-prone than previously recognized, especially in the Division Mountain area. If a lithostratigraphic framework is re-erected for the Laberge Group during future research, the 'Tanglefoot formation' should be abandoned in favour of a suite of more numerous, but lithologically restricted, formations. This would also facilitate the process of formally recording type sections and thicknesses due to the greater chance of observing both unit base and top in a single section (e.g., the upper, coal-prone unit in Division Mountain).
- Sandstone grade sediment constitutes 39% (approximately 800 m) of Laberge section, with clean sand (fine to very coarse) representing only 36% of the section (Fig. 20). The pay contribution of Laberge Group conglomerate is currently unclear, although much of the 'white grit' (gravel; *c.f.*, Allen, 2000) recorded from the upper unit of the Division Mountain play would likely comprise viable reservoir facies.
- At least 49% of recorded Laberge Group strata constitute non or reduced-pay reservoir rocks (clay, covered intervals – mudstone(?), coal and volcanic rocks). These intervals have the potential to stratigraphically compartmentalize reservoir intervals (*i.e.*, act as baffles and/or barriers to fluid flow), especially in the carbonaceous mudstone and coal-prone upper Laberge Group in Division Mountain. In this area, the emplacement of Cretaceous Carmacks Group volcanic sills along coal-seam or mudstone planes of weakness ensures that, to some extent, barrier rocks are grouped rather than disseminated throughout the reservoir (*see* Plate 2).

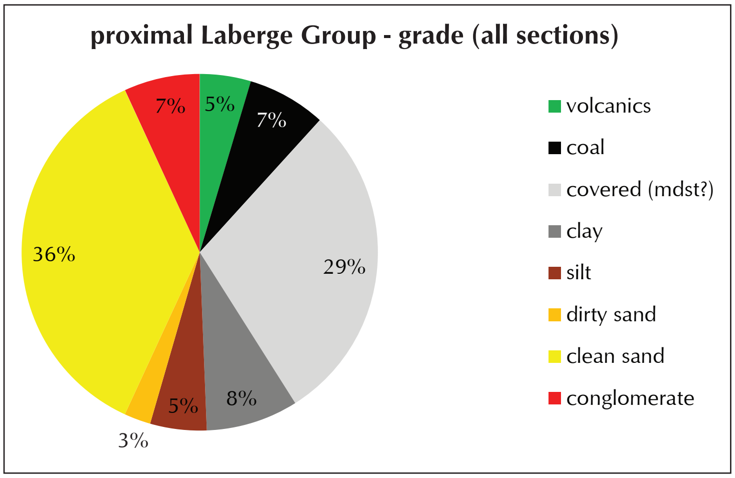


***Figure 20.*** *Laberge Group grade proportions representative of a 2 km 'composite' section through known Laberge stratigraphy, exclusive of temporal or geographical variability. Data compiled from redrafted logs presented in Appendix 3. See Appendix 3 for section line.*

### *Petrographic classification and texture*

Representative sandstone samples from the Laberge Group (and Mandanna member) sent for petrographic analysis were typically fine to medium grained, poorly to moderately sorted, and exhibited subangular to subrounded grains with point-long/concavo convex grain contacts. There was a general increase in quartz and decrease in lithic grain proportions during deposition of the Laberge Group, with oldest and most proximal (14-MH-013) to youngest and most distal (15-MH-97/63-77.10 m) samples trending from feldspathic litharenite to arkose respectively (Fig. 21). The older, Triassic Mandanna member sample from the Takhini Fire Hall section is also classified as a litharenite, and is very similar in hand specimen and thin section to the 14-MH-013 Laberge Group sample with respect to its hematitic, clay-rich matrix (Fig. 22).

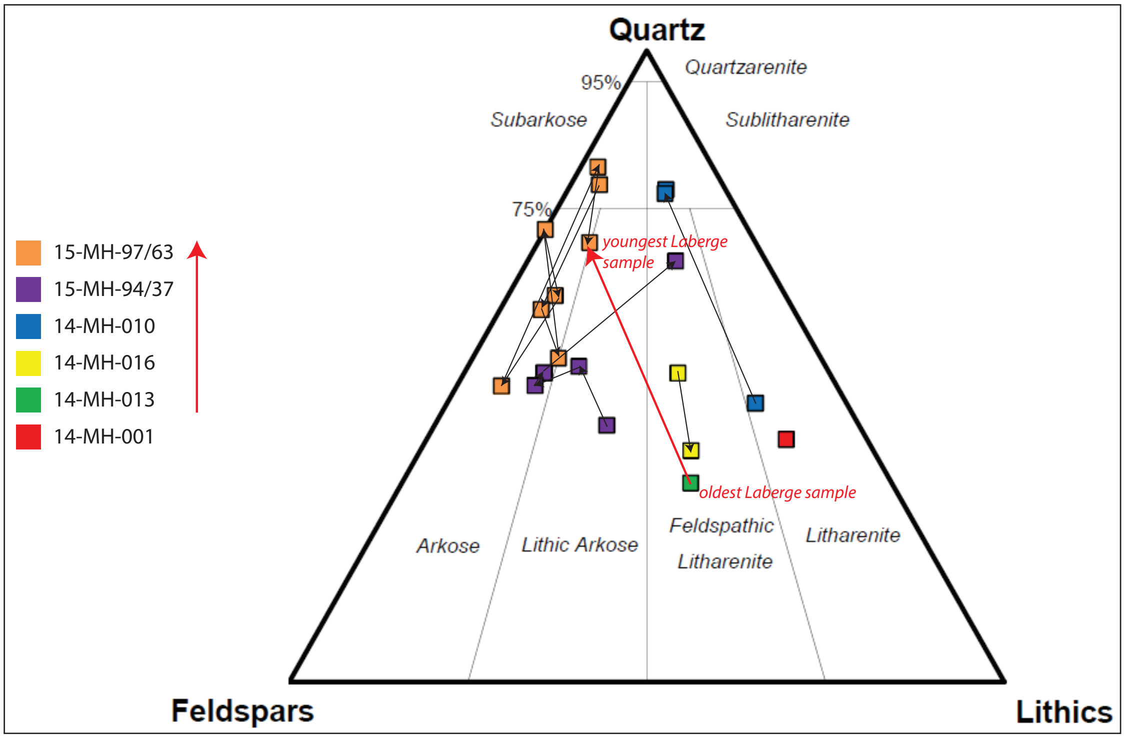


***Figure 21.*** *QFL plot for Laberge Group sandstones compiled during thin section analysis. Black arrows join together samples from the same section in a shallowing/younging direction. The red arrow illustrates the overall trend from a lithic to quartz-predominant composition over time (data from Appendix 4a).*

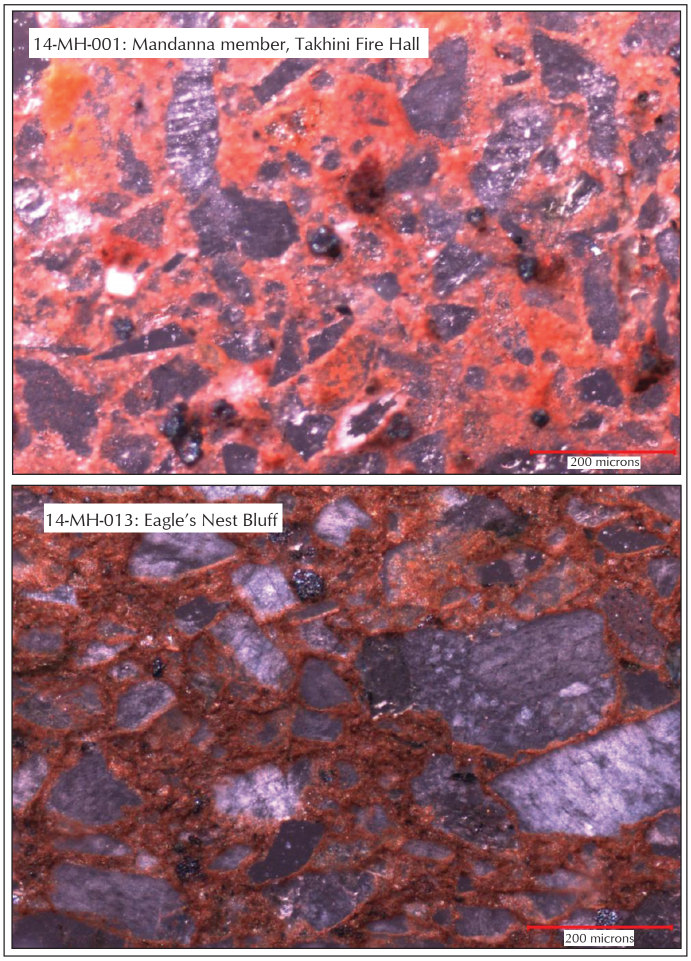


***Figure 22.*** *Reflected light thin section photographs highlighting the abundance of clay intermixed with hematite (characteristic red colouration) in sandstone samples from the Mandanna member at the Takhini Fire Hall and Laberge Group at Eagles Nest Bluff (see also Appendix 4e).*

This general trend is not, however, reflected in individual sections where sample density is relatively high (e.g., 15-MH-97/63). In the Division Mountain cores, sample composition trends from arkose to subarkose unpredictably up-section related to a combination of minor changes in provenance and a highly variable energy regime during deposition (*see* Fig. 21).

### *Petrophysical response (GR and density)*

Petrophysical data (spectral gamma ray, grain and bulk density) are available for the Laberge Group from a combination of hand-held spectrometry (outcrop), whole rock geochemistry (core) and porosity analysis (*see* Plate 2; Appendix 4). Gamma ray profiles of proximal Laberge Group sections highlight that provenance/mineralogy, rather than simple grain size difference, is the main control on gamma radioactivity in these rocks. Conglomerate and very coarse sandstone throughout the 14-MH-016 section on the Robert Campbell Highway have a high radioactivity that is comparable to the middle portion of 14-MH-013 or Laberge Group strata analyzed from Division Mountain (Fig. 23a), but which is higher than strata of equivalent grain size in the lower and upper units of 14-MH-013 (Eagles Nest Bluff). Whole rock elemental data highlight that these latter units are significantly depleted in potassium (average of 1.30%) relative to the middle unit, the entire 14-MH-016 section or samples from Division Mountain (average of 2.81%; Fig. 23b). They appear, however, to be very similar to those of the older Mandanna member around Whitehorse (averaging 1.52%), suggesting an active persistence of Triassic source areas into the Early Jurassic, and an interceding pulse of sediment from a new Jurassic source during deposition of the middle unit at Eagles Nest Bluff.

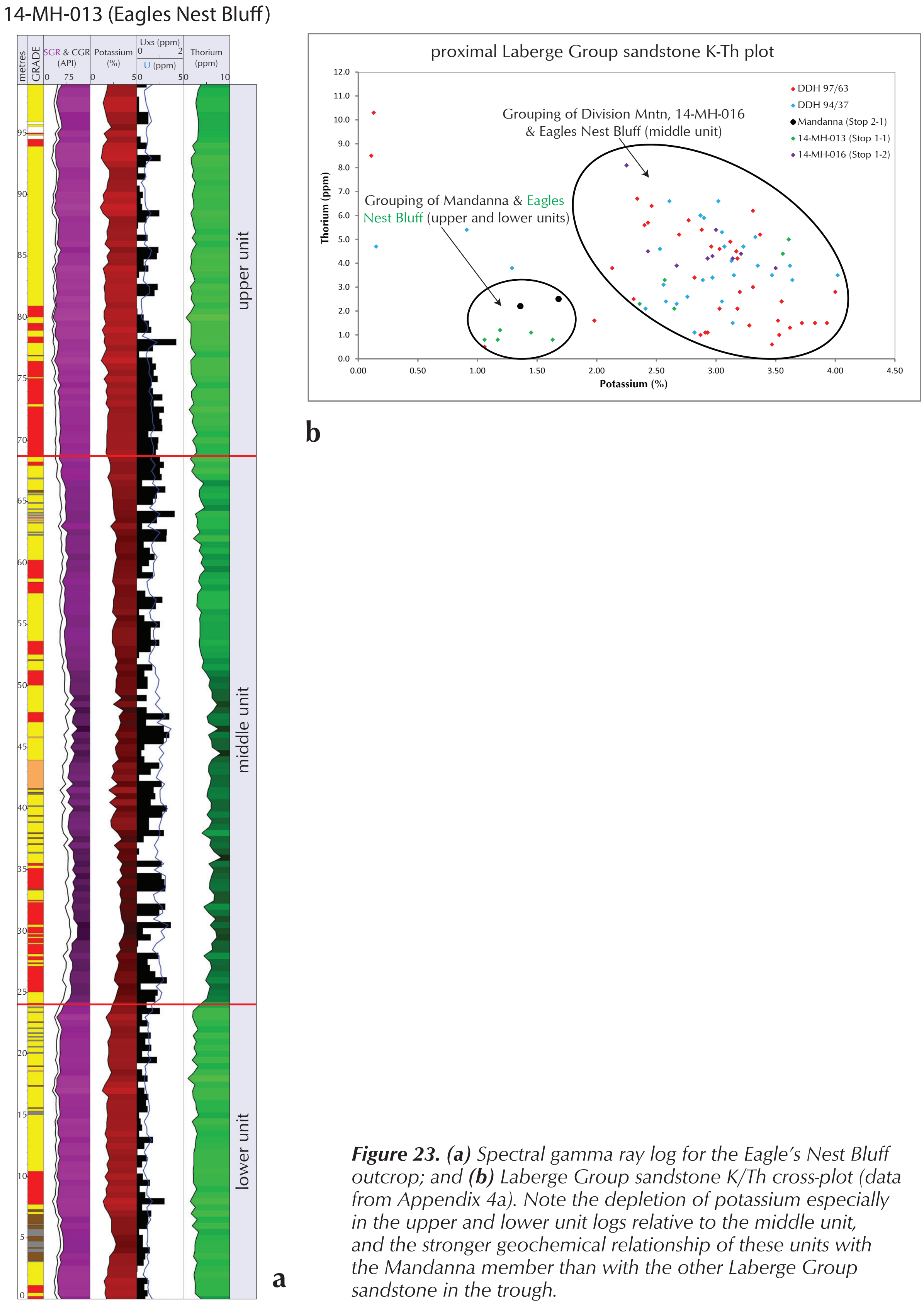


***Figure 23. (a)** Spectral gamma ray log for the Eagle's Nest Bluff outcrop; and **(b)** Laberge Group sandstone K/Th cross-plot (data from Appendix 4a). Note the depletion of potassium especially in the upper and lower unit logs relative to the middle unit, and the stronger geochemical relationship of these units with the Mandanna member than with the other Laberge Group sandstone in the trough.*

Establishing baseline density data for Laberge Group clastic rocks is useful for future exploration to: 1) initially calibrate wireline density log tools; 2) to aid in the identification of anomalous density zones (*e.g.*, coal or borehole breakout) and formation fluids (*e.g.*, gas, brine or freshwater); and 3) to estimate pressure gradients. The proximal Laberge Group samples have a mean actual dry bulk density of 2.58 g/cc (Appendix 4), with both sandstone and mudstone mean values (2.57 and 2.68 g/cc respectively) and ranges exceeding those apparent bulk densities of both fine and coarse-grained 'typical' clastic rocks (Fig. 24; mineral actual and apparent bulk densities typically vary by less than 0.1 g/cc; Glover, 2016). Sandstone grain density averages are slightly higher than their corresponding bulk density (2.67 g/cc), which together correspond to a dominantly lithic (*i.e.*, mafic mineral), immature composition with relatively low quartz and low porosity (*see* next sections). Authigenic carbonate cement, where present, also serves to increase sandstone bulk and grain densities (Glover, 2016).

### *Depositional environment and provenance*

In addition to standard sedimentological observations, chemostratigraphic characterization can also be used to differentiate previously undivided stratigraphic successions into lithofacies assemblages on the basis of their provenance and marine or non-marine/mixed geochemical signatures (*e.g.*, Pearce *et al.*, 2005; Ratcliffe *et al.*, 2007). These techniques, modified for use in this study, enabled Ratcliffe *et al.* (2007) to successfully distinguish between mafic *vs.* felsic, and marine *vs.* non-marine/deltaic lithofacies assemblages in sandstone and conglomerate of the late Middle Jurassic to Early Cretaceous Bowser and Sustut basins in British Columbia. However, to develop Ratcliffe *et al.*'s (2007) methods further, this Yukon study also benefits from complementary XRD, petrographic and SEM data for representative samples.

Profiles of selected trace element concentrations and ratios display subtle geochemical variations within the basal Laberge Group sections in the Tantalus Butte area (14-MH-013, 016). These become more distinct as sediment gets younger and more distal to the south in the Division Mountain area, promoting the identification of four chemostratigraphic zones within the upper Laberge Group in 15-MH-97/63 (*see* Plate 2). The sequence boundary that divides Allen's (2000) 'lower' and 'upper' Tanglefoot formation in Division Mountain core is also well-resolved by geochemical variation (Plate 2). It is defined by increasing quartz and felsic *vs.* mafic minerals

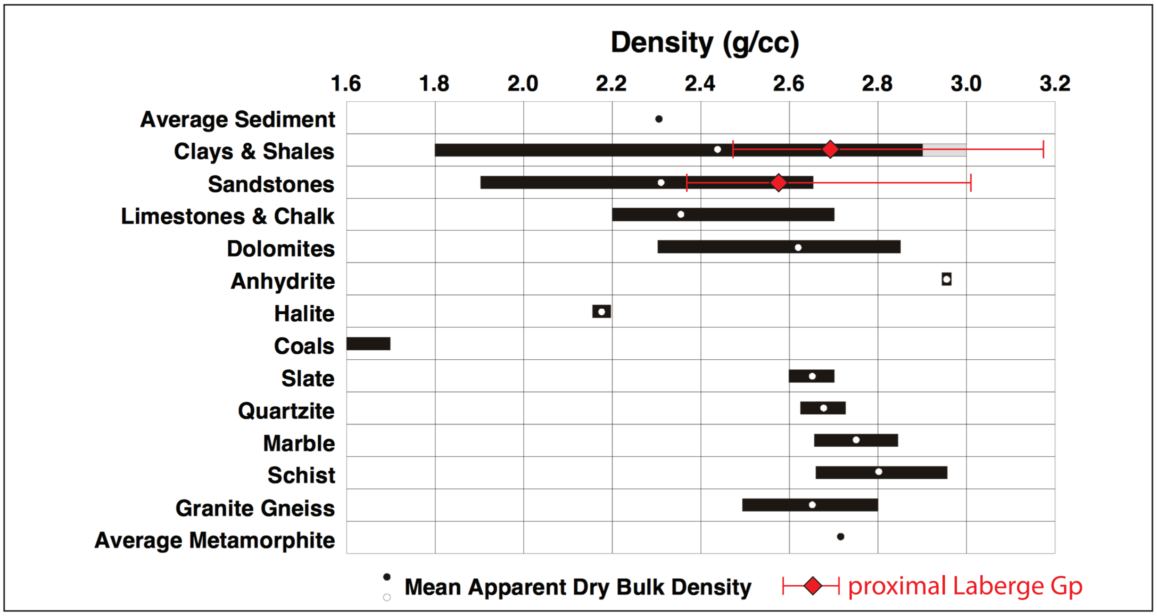


***Figure 24.*** *Apparent bulk densities for a range of units, with Laberge Group fine and coarse-grained data superimposed (modified from Glover, 2016).*

up-section (also supported by increasing $SiO_2/Al_2O_3$, Zr/Cr and Ce/C ratios; Ratcliffe *et al.*, 2007) and decreasing volcanic grain percentages. This horizon tentatively correlates to the Lone Pine Mountain section (14-MH-010), where it represents base level fall (lower shoreface to tidal delta bar) preceded in both core and outcrop by a package of coarsening-up (grain size) and 'cleaning-up' gamma ray sediment indicative of, and consistent with, a prograding depositional system (*e.g.*, Olariu *et al.*, 2010).

Ternary and binary plots using Fe, Mg and Si/Al concentration highlight variability in marine influence in sections of both areas (Fig. 25a,b). Decreasing marine influence is interpreted from an overall increase in the $SiO_2/Al_2O_3$ ratio (detrital quartz *vs.* clay) and decreasing Fe-Mg concentrations, whereby marine sediment often contains higher concentrations of siderite or ferroan dolomite cement, or clay minerals such as chlorite, mica or glauconite (Ratcliffe *et al.*, 2006, 2007). This is observed in both the transition from lower shoreface to tidal bar sediment up-section in 14-MH-010, and also in core between the lower sandstone of 15-MH-94/37 and the upper interbedded sandstone and coal of 15-MH-97/63. The sandstone from 14-MH-016 in the Tantalus Butte area is also interpreted as tidal or estuarine in origin, and its distribution in Figure 25a overlaps that of the upper, marginal marine exposed at Lone Pine Mountain. This same relationship are also evident on the binary Fe-Mg plot (Fig. 25b), where XRD and petrographic analyzes document high concentrations of authigenic (ferroan) dolomite, together with lesser chlorite and glauconite in the lower shoreface samples (*see* Appendix 4a). Caution in using these plots to infer marine affinity without this supporting XRD work is required – 'red-bed' terrestrial sandstone from the basal Laberge Group at 14-MH-013 (Fig. 25a) also has high Fe-Mg concentrations, but this is due to its immature, mafic mineralogy that includes 10% clinopyroxene, 5% chlorite and 4% amphibole (*see* Appendix 4a and 4d).

Lithogeochemistry plots can also be used to infer provenance, where the Zr/Cr ratio is a proxy for relative concentration of felsic *vs.* mafic minerals (*e.g.*, Ratcliffe *et al.*, 2007). In Figure 25c, an interpreted marine to non-marine divide (based on Fig. 25a,b) also broadly differentiates sediment with a mafic, volcanic provenance (low Zr/Cr ratio) from that with a felsic provenance. The Na/Al ratio (Fig. 25d) also decreases significantly between the basal Laberge Group at Tantalus Butte (14-MH-010, 013 and 016: average of 0.22) and Division Mountain (average of 0.07), although the basal 50 m of 15-MH-94/37 retains a Tantalus Butte area ratio signature (average of 0.17). This trend is primarily controlled by a decrease in plagioclase feldspar (*see* Plate 2) and an increase in authigenic kaolinite cement (Ratcliffe *et al.*, 2007, 2010).

In the Laberge Group, relationships of provenance and marine affinity also correspond to relative depositional age and geographic position down depositional dip (Fig. 25e). In these northern trough areas, sandstone and conglomerate become less mafic and less marine-influenced with time: a previously unreported relationship which mirrors that observed in conglomerate clast proportions in the distal Laberge Group to the south, and which reflects the progressive unroofing of the Lewes River arc (*e.g.*, Dickie and Hein, 1992; Colpron *et al.*, 2015). The relationship between marine affinity and age documented in this suite of plots also supports a progradational proximal Laberge Group depositional system operating during overall base level fall from the Early to Middle Jurassic.

### *Porosity and permeability*

Porosity and permeability results recorded from 53 sandstone and conglomerate core plug analyses are presented in Appendix 4 and summarized in Table 2. Average plug porosities (4.0%, range 0.5-10.0%) and permeabilities (Kmax: 0.36 mD, range 0.003-3.75 mD; Kv: 0.15 mD, range 0.003-3.16 mD) are unexpectedly low considering the typically coarse-grained nature of the proximal Laberge Group. Despite the decrease in pay thickness down depositional dip (*see* Fig. 20), porosity and permeability (especially Kmax) increase in the younger, more distal Laberge Group sediment at Division Mountain (Fig. 26a). However, most horizontal and vertical permeability data fall within 'tight' (*c.f.*, Law, 2002) play petrophysical parameters (Fig. 26a,b).

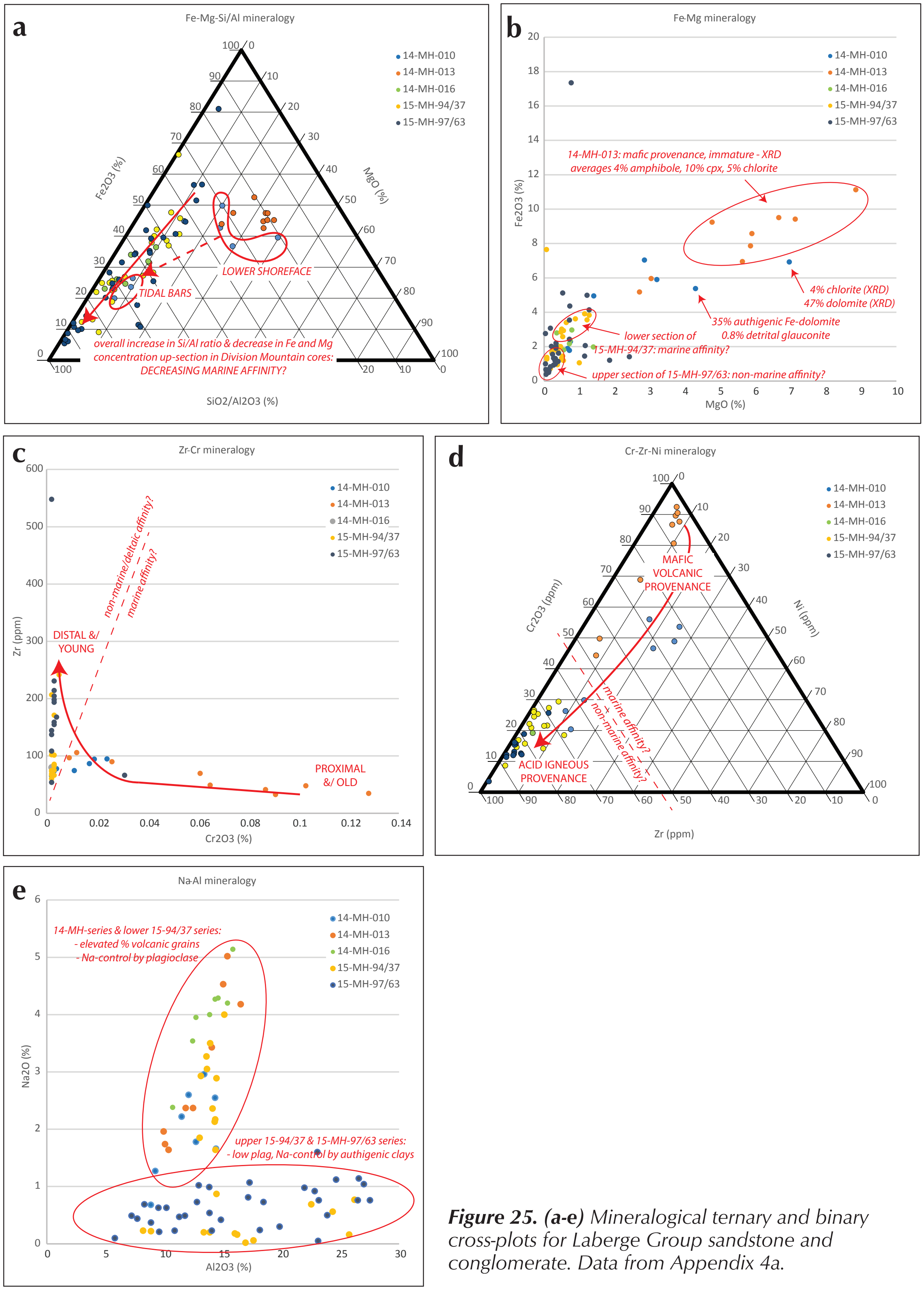


***Figure 25.*** ***(a-e)*** *Mineralogical ternary and binary cross-plots for Laberge Group sandstone and conglomerate. Data from Appendix 4a.*

Overall, there is no significant control on porosity by grain size (Fig. 26c), with pore spaces instead typically occluded by authigenic carbonate and kaolinite cement (Figs. 26d and 27a) resulting in rock 'tightness'. Two moderate correlation coefficients ($R^2>0.4$) were obtained from 14-MH-016 (Robert Campbell Highway) and 15-MH-97/63 (Division Mountain), although their opposing trends reflect the inherent spatial and temporal variability in cementation in the northern trough. Pore-lining chlorite prevented quartz overgrowth in many of the thin sections analyzed (*see* Fig. 27b), and was consistently positively correlated with porosity using both XRD mineralogy ($R^2=0.24$) and thin section petrography ($R^2=0.44$) data (Fig. 26d,e). In basal Laberge Group strata from 14-MH-013, and in the older Mandanna member sample from the Takhini Fire Hall, almost complete occlusion of pore space is provided by matrix hematite intermixed with detrital clays (*see* Fig. 22) - again suggestive of similarity in depositional environment and provenance during deposition of these Triassic and Early Jurassic sediment.

Core plug porosities were much higher than those recorded from thin section petrographic analysis where complementary data exist (Table 2). This suggests that primary macroporosity is principally derived from fracturing (Fig. 27c), and/or either grain size or cement heterogeneity at a scale larger than observable in thin section. On average, microporosity (thin section) contributes only 36% of the total core plug porosity, and is derived mainly from secondary feldspar or volcanic grain dissolution rather than from primary inter-granular pore space preservation (Table 2; Fig. 27a).

Intra-reservoir barrier/baffle thickness and frequency in the Laberge Group increases to the south (*see* Plate 2), with lithological heterogeneity present at both core plug scale (*e.g.*, from carbonaceous or detrital clay laminae drapes – *e.g.*, Allen, 2000; *see* also Appendix 4e) and at bed scale (*e.g.*, from intercalated coal, carbonaceous mudstone and volcanic beds). This heterogeneity is reflected in core plug Kv/Kmax ratios that indicate increasing permeability anisotropy down depositional dip (Fig. 26f).

## DISCUSSION

### *DEPOSITIONAL CONTROLS*

Proximal Laberge Group sedimentology and mineralogy from the 2014-15 research program suggests that deposition in the northern Whitehorse trough occurred in prograding shoreface, estuarine/tidal delta and coastal wetland environments. In addition to U-Pb detrital zircon data, stratigraphic age and correlations can also be inferred from palynology, body fossils and paleoclimatic indicators (Plate 2). True coal seam development, which occurs in the Laberge Group in the Lone Pine and Division Mountain sections, is promoted during rapid warming intervals, such as interpreted by Dera *et al.* (2011) to have occurred around the Aalenian-Bajocian boundary (*see* Fig. 3). Body fossil assemblages from the Division Mountain area broadly support this interpretation, suggesting a middle Bajocian age for the Laberge Group in 15-MH-94/37 (Tempelman-Kluit, 1984; Poulton, 1979), and a Toarcian to Bajocian age for the uppermost Laberge Group interbedded sandstone and coal in 15-MH-97/63 (Tempelman-Kluit, 1984; Allen, *unpbl.*). The intervals of carbonaceous mudstone and 'seat earth' horizons in 14-MH-016 are older (maximum depositional age of 181.9 ± 3.0 Ma: Colpron *et al.*, 2015), and this section may correlate to another rapid period of warming at the Pliensbachian-Toarcian boundary (*see* Plate 2).

Subsidence and Early Jurassic coarse clastic sedimentation in the trough occurred concurrently with exhumation of the basin shoulders (Colpron *et al.*, 2015). Based on conceptual models for submarine fan architecture and morphology in deep-water marine clastic depositional systems (*e.g.*, Hadler-Jacobsen *et al.,* 2005), deposition would have been dominated by transport from the basin shoulders in a high shelf-basin relief (SBR) margin basin with a high accommodation/sediment supply (A/S) ratio (Fig. 28). Hettangian and younger, shelf-detached submarine fan-delta conglomerate and deep-water turbidite characterize Laberge Group deposition in the Whitehorse area and southern trough at this time. During later shoaling and oroclinal closure of the entrapped

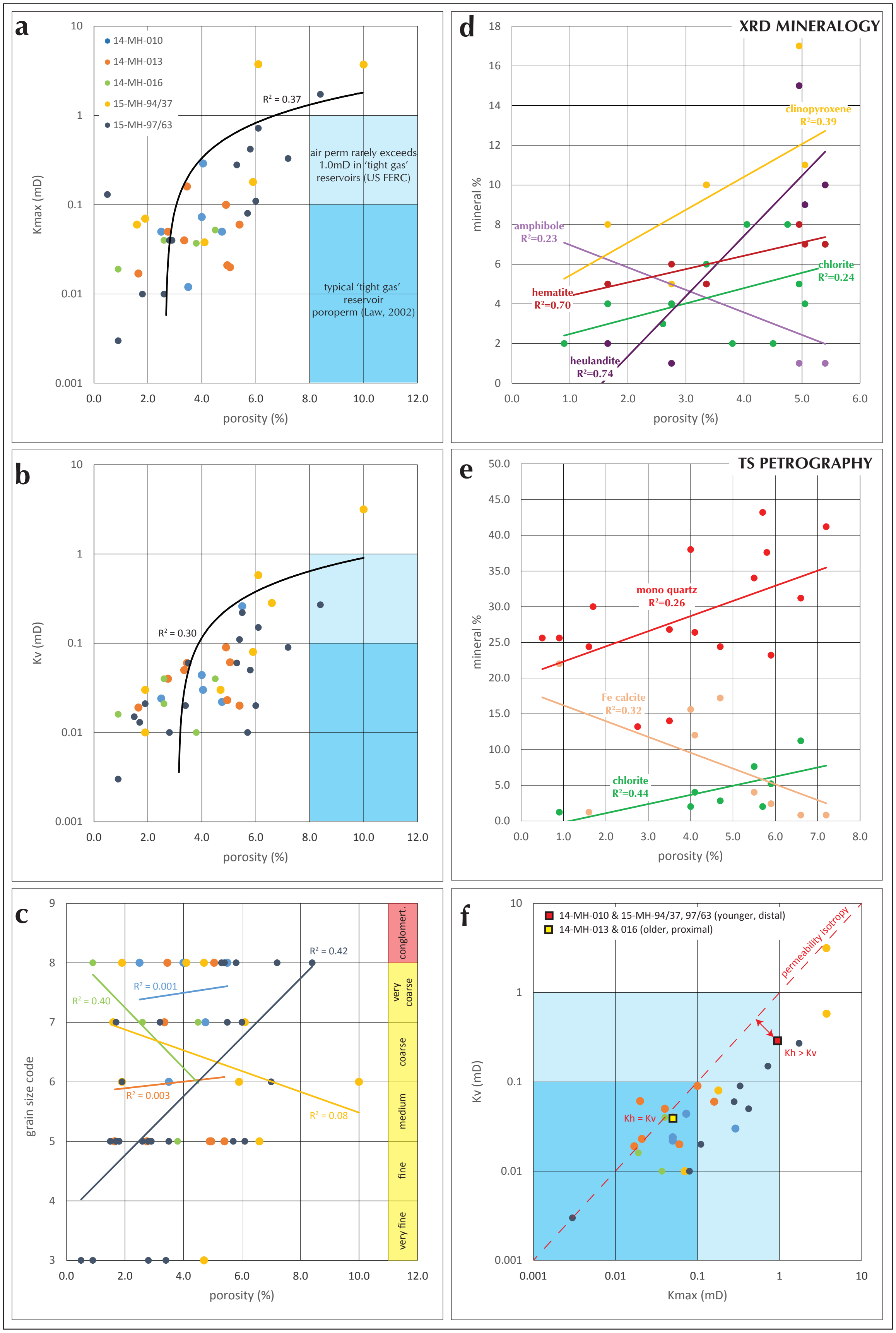


***Figure 26. (a-e)*** *Poroperm, grain size, XRD mineralogy and thin section petrology cross-plots exploring the controls on porosity and permeability in Laberge Group sandstone and conglomerate. Kmax=maximum horizontal permeability, Kv=vertical permeability of core plug sample.*

Panthalassa ocean fragment, Laberge Group deposition became progressively dominated by axial, southeasterly-directed transport as the margin's SBR and A/S ratios decreased and the basin filled with sediment of the proximal Laberge Group.

Despite the usefulness of this conceptual model to explore Laberge Group depocentre evolution from Late Triassic to Middle Jurassic, outcrop facies observations and interpretation suggests that development of the 'trough' as a bathymetric feature is considerably more complex at a local scale. The presence of limestone clasts in Laberge Group conglomerate suggests reworking of either re-exposed or paleohigh Hancock reefs (e.g., Eagles Nest Bluff or Grey Mountain) that developed outboard of the Lewes River arc during the Late Triassic, and overall Laberge Group conglomerate clast proportions highlight no significant provenance differentiation between the two units (*see* Fig. 9). Limestone (including rudstone and rare shell fragment) clasts also increase in frequency

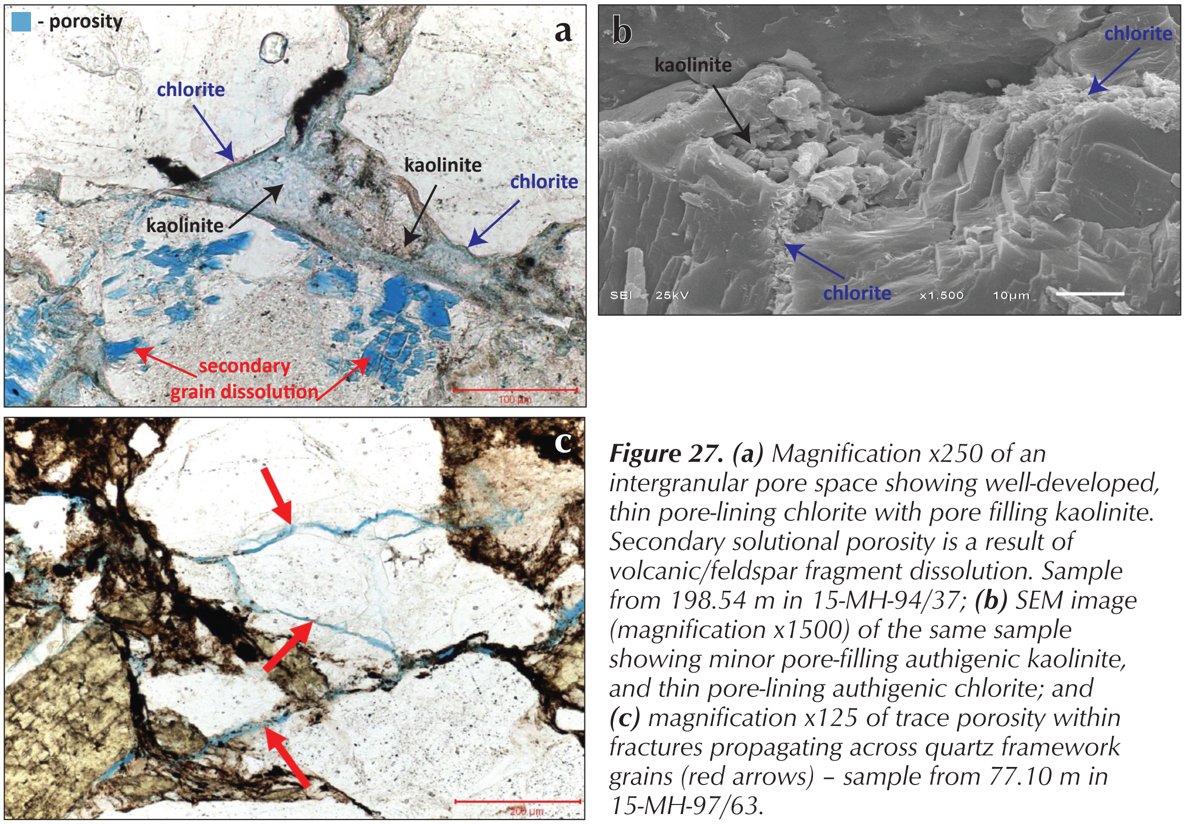


***Figure 27.*** ***(a)*** *Magnification x250 of an intergranular pore space showing well-developed, thin pore-lining chlorite with pore filling kaolinite. Secondary solutional porosity is a result of volcanic/feldspar fragment dissolution. Sample from 198.54 m in 15-MH-94/37;* ***(b)*** *SEM image (magnification x1500) of the same sample showing minor pore-filling authigenic kaolinite, and thin pore-lining authigenic chlorite; and* ***(c)*** *magnification x125 of trace porosity within fractures propagating across quartz framework grains (red arrows) – sample from 77.10 m in 15-MH-97/63.*

***Table 2.*** *Sandstone and conglomerate porosity and permeability data for key Laberge Group sections in the northern Whitehorse trough. TS=thin section (data from Appendix 4a).*

| | Kmax (mD) | Kv (mD) | Kv/ Kmax | Core Porosity (%) | TS Grain Porosity (%) | TS Sol Porosity (%) | TS/Core Ratio |
|---|---|---|---|---|---|---|---|
| ***number of samples*** | *36* | *41* | *28* | *53* | *16* | *16* | *16* |
| **15-MH-97/63** | 0.300 | 0.070 | 0.285 | 3.90 | 0.00 | 1.70 | 0.32 |
| **14-MH-010-upper** | 0.138 | 0.090 | 0.395 | 4.01 | 0.00 | 2.00 | 0.39 |
| **15-MH-94/37-lower** | 1.305 | 0.596 | 0.397 | 4.75 | 0.60 | 1.40 | 0.43 |
| **14-MH-010-low** | 0.031 | 0.022 | 0.440 | 4.13 | 0.00 | 0.00 | 0.00 |
| **14-MH-016** | 0.037 | 0.025 | 0.704 | 2.88 | 0.00 | 0.80 | 0.89 |
| **14-MH-013** | 0.059 | 0.045 | 1.115 | 3.94 | 0.00 | 0.00 | 0.00 |

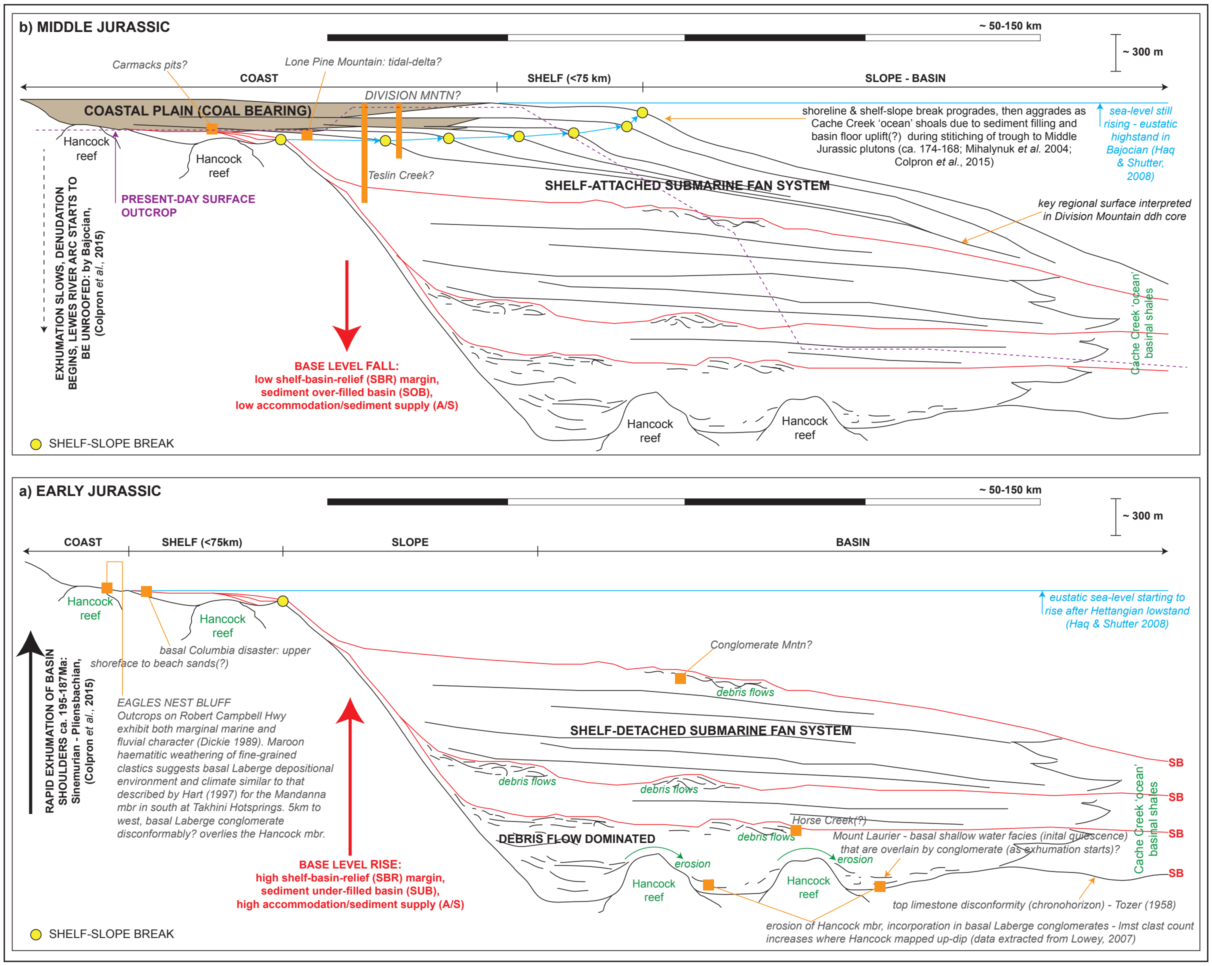
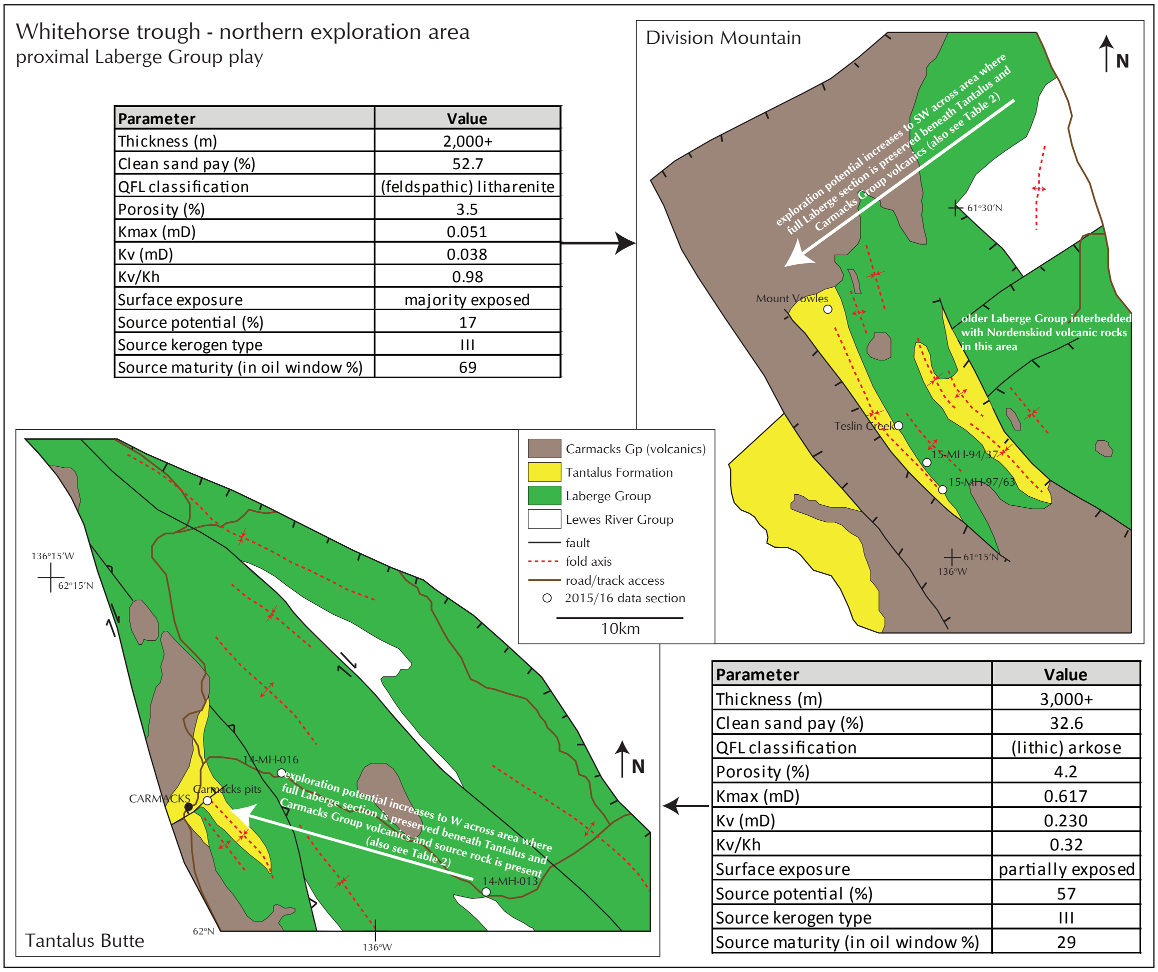


***Figure 28.*** *A conceptual model for axial deposition of the Laberge Group in the trough (modified from Hutchison, 2016 and Colpron et al., 2016b, after Hadler-Jacobsen et al., 2005).*

up-section in the oldest known Laberge Group sediment (Eagles Nest Bluff – 193.8 ± 1.8 Ma: Colpron *et al.*, 2015), and shell lags are observed in shallow marine facies at the base of proximal Laberge Group strata in the Columbia Disaster section (immediately west of Eagles Nest Bluff – L. van Drecht, *field observation*, 2016). Basal Laberge Group shallow water facies, dominated by calcareous or current to wave-rippled sandstone (e.g., Bordet, 2016; Colpron *et al.,* 2015; Lowey, 2005) are also observed unconformably overlying Hancock member limestone on Grey Mountain and Mount Laurier in the south of the basin.

## *UPDATED PETROLEUM SYSTEM CHARACTERIZATION*

Updated petroleum system parameters and risk factors that document the exploration potential of the proximal Laberge Group in the Tantalus Butte and Division Mountain areas are summarized in Figure 29 and Table 3 and discussed below. Due to limited outcrop exposure and core availability, these two areas are those for which adequate quantitative data exist to update Lowey's (2008a,b) and Lowey *et al.*'s (2009) generally qualitative characterization of Laberge petroleum system components in the northern basin, and Hayes' (2012) play risks for the 'Tanglefoot' structural and stratigraphic play (herewith combined into the proximal Laberge play). Geological factors that are likely to significantly challenge drilling activities in these two areas are also discussed.



| Parameter | Value |
|---|---|
| Thickness (m) | 2,000+ |
| Clean sand pay (%) | 52.7 |
| QFL classification | (feldspathic) litharenite |
| Porosity (%) | 3.5 |
| Kmax (mD) | 0.051 |
| Kv (mD) | 0.038 |
| Kv/Kh | 0.98 |
| Surface exposure | majority exposed |
| Source potential (%) | 17 |
| Source kerogen type | III |
| Source maturity (in oil window %) | 69 |

| Parameter | Value |
|---|---|
| Thickness (m) | 3,000+ |
| Clean sand pay (%) | 32.6 |
| QFL classification | (lithic) arkose |
| Porosity (%) | 4.2 |
| Kmax (mD) | 0.617 |
| Kv (mD) | 0.230 |
| Kv/Kh | 0.32 |
| Surface exposure | partially exposed |
| Source potential (%) | 57 |
| Source kerogen type | III |
| Source maturity (in oil window %) | 29 |

***Figure 29.*** *Summary of Laberge Group play and petroleum system data in the northern exploration area of the basin. Thickness estimates derived from White et al. (2006) for the Tantalus Butte area and MIRA Geoscience (2014) for the Division Mountain area. Basemaps modified from Colpron (2011).*

### *Source rock*

Previous interpretations of source rock potential suffer from bias introduced into the dataset by only sampling where there is available rock exposed, trenched or drilled (*i.e.*, typically the result of past coal exploration activities) and by not employing systematic point or interval sampling techniques across entire outcrop or drill core sections. Re-plotted RockEval-TOC data for the proximal Laberge Group at Tantalus Butte (including north to Five Finger Rapids and east along the Robert Campbell Highway) and Division Mountain are presented in Figure 30. Overall, 23% of northern Laberge Group data (*i.e.*, that listed as Tanglefoot formation in existing YGS project databases) can be defined as potential source rocks in the basin (after Harris, 2015). In the Tantalus Butte area to the north, only 17% of proximal Laberge Group samples were classified as source rocks (*see* Fig. 29). Down depositional dip to the south at Division Mountain, 57% of samples represent potential source rocks, suggesting that source rock presence and quality increases (and therefore risk decreases) southwards in the basin (Table 3).

The majority of Laberge Group samples plot below the generation potential threshold defined by Harris (2015), highlighting the fact that much of the organic material in this uppermost Laberge depositional system is associated with coal (*i.e.*, 'dead carbon'). Vitrinite reflectance data (Fig. 31) suggest that source rock maturity with respect to oil generation increases to the north (29 to 69%), with mature samples in both areas concentrated in the early to peak phases. Thicker Laberge

***Table 3.** Revised petroleum system risks for the Laberge Group in the northern Whitehorse trough (see also Fig. 29). Pg=overall chance of geological success. Note that this study combines Hayes' (2012) structural and stratigraphic 'Tanglefoot' plays into one Laberge Group play.*

**Laberge Group play - Tantalus Butte area**

| System component | Risk | Comments |
|---|---|---|
| SOURCE risk | 0.50 | *only partial regional seal in west, low intra-formational source potential* |
| RESERVOIR risk | 0.70 | *low poroperm reservoir rocks, although much of full section remains untested* |
| SEAL risk | 0.30 | *mostly exposed at surface, intra-formational mudstones unlikely to be sealing as intercalated with sands* |
| TRAP risk | 0.60 | *map, model and seismic show high density of potential structural traps - trap breach risk high* |
| TIMING risk | 0.68 | *no new information - charge*migration from Hayes (2012)* |
| **Pg** | **0.04** | |

**Laberge Group play - Division Mountain area**

| System component | Risk | Comment |
|---|---|---|
| SOURCE risk | 0.85 | *moderate intra-formational source potential, probable marine source at depth* |
| RESERVOIR risk | 0.85 | *low poroperm rocks but better than in north, only the upper 250+ m of Laberge section tested* |
| SEAL risk | 0.75 | *high regional seal coverage, low Laberge Gp surface exposure, intra-formational mudstones likely to be sealing* |
| TRAP risk | 0.80 | *mapping shows high density of potential structural traps - trap breach risk moderate (with regional seal in place)* |
| TIMING risk | 0.68 | *no new information - charge*migration from Hayes (2012)* |
| **Pg** | **0.29** | |

sections visited by Allen (2000) at Red Ridge Canyon, and by Long (2015) at Teslin Creek - both in the Division Mountain area, include up to 600 m of lower Laberge Group, marine(?) interbedded mudstone and sandstone that remain untested as to their source potential. However, if these buried mudstone facies in Division Mountain are marine and organic-rich (*see* Table 3), they are therefore likely to exhibit increased maturity relative to the outcrop and shallow subsurface samples presented in Figure 31 (*i.e.*, sit within the peak to late oil maturity window), and contain a greater percentage of type I or II kerogen (*i.e.*, oil generating).

### *Reservoir quality and controls*

Integrated sedimentology, whole rock geochemistry and mineralogy data suggest that the proximal Laberge Group in the northern exploration area evolved from a marine, mafic-sourced depositional system to non-marine, felsic-sourced system during the Early to Middle Jurassic. This evolution of the basin and its fill is consistent with the unroofing and exhumation of the Lewes River arc basin shoulder during the Early to Middle Jurassic (e.g., Colpron *et al.*, 2015), and is mirrored in the evolution of the younger, but contiguous, Bowser and Sustut basin depositional systems to the south in BC (Ratcliffe *et al.*, 2007). Reservoir quality is anticipated to increase up-section and down depositional dip in the Laberge Group (Figs. 29 and 32) as more mature, younger sediment with less compactable mafic and detrital clay mineral grains are expected to retain a greater percentage

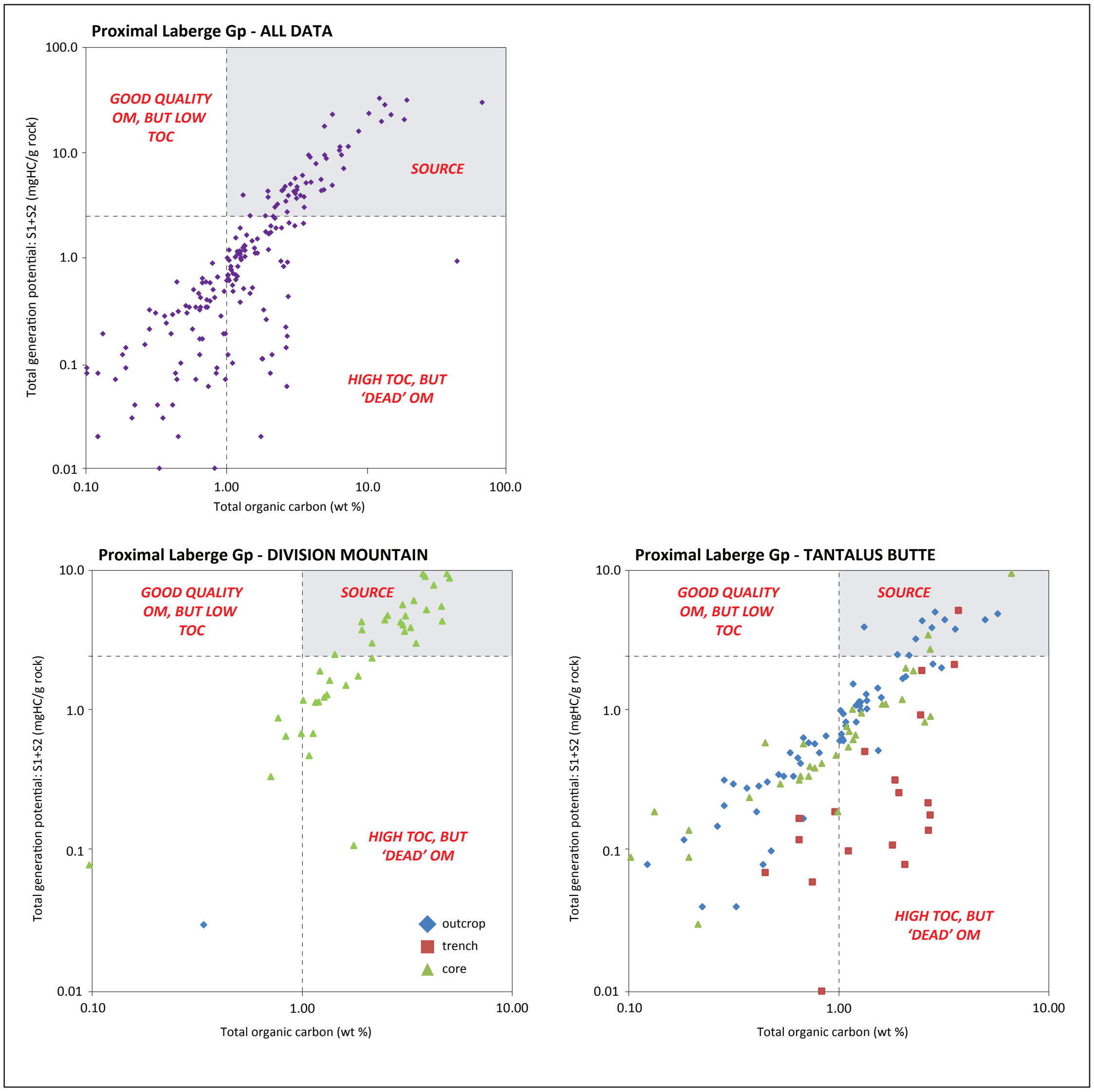


***Figure 30.*** *Replotted RockEval/TOC data showing source rock potential (after Harris, 2015) for the Tantalus Butte and Division Mountain Laberge Group (see Fig. 29 for area maps and Appendix 2 for data).*

of their primary porosity and directional permeabilities (e.g., Harris, 2015; Ratcliffe *et al.*, 2007). Higher $SiO_2/Al_2O_3$ ratios and Zr concentrations up-section (*i.e.*, increasing quartz and decreasing detrital clay) also support increasing compositional maturity and higher system energy (Ratcliffe *et al.*, 2007), and therefore increasing reservoir quality (Fig. 32).

The unexpected 'tightness' of the Laberge Group, however, attests to the significant diagenetic alteration and constriction of pore throats which counteracts the influence of primary grain mineralogy (discussed above) on anticipated fluid flow behaviour. In the more proximal, marine-influenced Laberge sediment (e.g., 14-MH series and lower 15-MH-94/37), the abundance of soft mafic lithic grains, plagioclase feldspar and detrital clay can act to both absorb some of the compaction stress (thereby promoting preservation of intergranular pore space by inhibiting pressure solution along grain contacts, e.g., Brocculeri *et al.*, 1991), and generate secondary porosity during late-stage grain dissolution. However, these effects are counteracted by the pervasive authigenic carbonate cementation that probably reflects the mafic mineralogy of the older sediment and their saturation by marine brines during deposition.

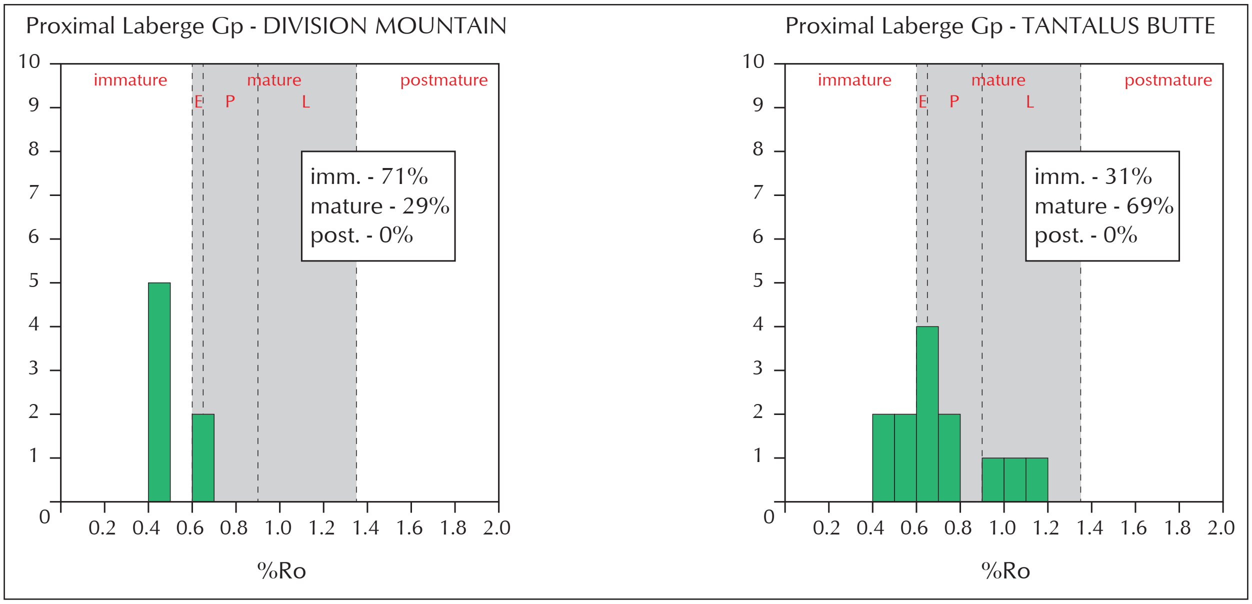
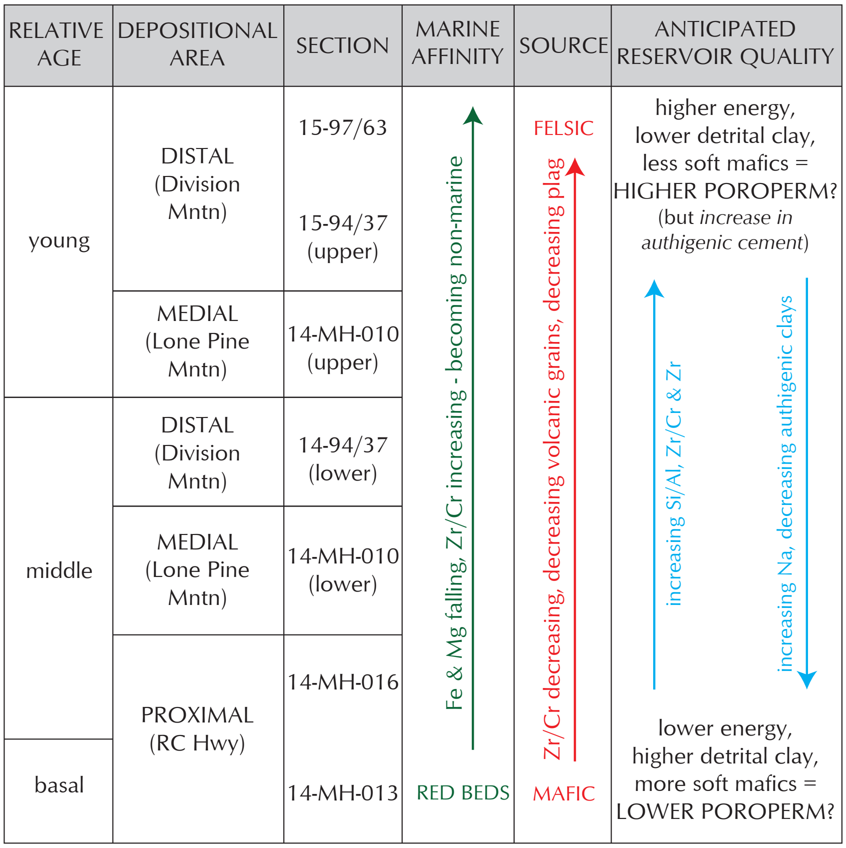


***Figure 31.*** *Replotted vitrinite reflectance data for the Laberge Group in the Tantalus Butte and Division Mountain areas.*



| RELATIVE AGE | DEPOSITIONAL AREA | SECTION | MARINE AFFINITY | SOURCE | ANTICIPATED RESERVOIR QUALITY |
|---|---|---|---|---|---|
| young | DISTAL (Division Mntn) | 15-97/63<br>15-94/37 (upper) | Fe & Mg falling, Zr/Cr increasing - becoming non-marine | FELSIC<br>Zr/Cr decreasing, decreasing volcanic grains, decreasing plag | higher energy, lower detrital clay, less soft mafics = HIGHER POROPERM? (but *increase in authigenic cement*) |
| | MEDIAL (Lone Pine Mntn) | 14-MH-010 (upper) | | | increasing Si/Al, Zr/Cr & Zr<br>increasing Na, decreasing authigenic clays |
| middle | DISTAL (Division Mntn) | 14-94/37 (lower) | | | |
| | MEDIAL (Lone Pine Mntn) | 14-MH-010 (lower) | | | |
| | PROXIMAL (RC Hwy) | 14-MH-016 | | | |
| basal | | 14-MH-013 | RED BEDS | MAFIC | lower energy, higher detrital clay, more soft mafics = LOWER POROPERM? |

***Figure 32.*** *Summary of mineralogical and geochemical controls on Laberge Group reservoir quality (porosity and permeability) in the northern exploration area of the trough.*

Of greater interest to reservoir quality in the more prospective, upper Laberge Group sandstone and gravel at Division Mountain (*e.g.*, 15-MH-97/63; Table 3) is the influence of kaolinite on permeability and water saturation. In areas where the pore throat network is better connected, kaolinite platelets also have the potential to significantly affect fluid flow on production timecales by migrating to occlude pore space in less permeable rock. The abundance and origin of authigenic kaolinite in sandstone is closely related to the abundance and alteration of alkali feldspar (Lanson *et al.*, 2002; Lunde, 2013; also *see* Appendix 4e). Based on eight thin sections in 15-MH-97/63, it represents 2-14% of the rock volume, although there is only a very weak positive correlation between the two minerals ($R^2 = 0.1$).

There are two hypotheses for kaolinite crystallization (Lanson *et al.*, 2002), both of which are initially equally applicable to arkosic Laberge Group sediment in the northern trough:

- Fluids of meteoric origin flush the formation (sometimes repeatedly) either during early diagenesis or later structural inversion: a process common in onshore basins, and which occurred in the basin during the Early Cretaceous (Tempelman-Kluit, 1979).
- Acid-rich fluids resulting from the maturation of organic material in mudstone and coal beds adjacent to the sandstone act with meteoric fluids to alter feldspar and precipitate kaolinite. Similar processes have been reported from North Sea sandstone where kaolinite is concentrated at the contacts with over/underlying shale (Garn Formation; Ehrenberg, 1991) or the contact between the Permian Rotliegend sandstone and the Carboniferous coal measures (Platt, 1993).

The kaolin stability domain is also restricted to low temperature and shallow burial depths (*e.g.*, Burley and MacQuaker, 1992), and at approximately 120°-140°C (Ehrenberg and Nadeau, 1989) it reacts with remaining K-feldspar to form illite (a clay mineral which has not been observed in trough sandstone samples to date). Minimum trapping temperatures of 75°-100°C for oil inclusions (Lowey, 2008b; Lowey *et al.*, 2009) also support the fact that Laberge Group burial depths to the north around Carmacks (inferred at 3-4 km by these authors from the inclusion data) did not exceed the kaolin stability domain.

Key unknowns in the assessment of diagenetic cementation on reservoir quality in the Laberge Group are variable with ‘field-scale’ geography and ‘well-scale’ depth (as current data are derived from limited outcrop and shallow drill holes). Kaolinite crystal habit, and therefore its effect on pore throat occlusion, ability to migrate and ultimately on fluid producibility, is affected by burial depth (Lanson *et al.*, 2002). Authigenic carbonate cementation such as that observed in those strata of marine affinity (*e.g.*, lower 14-MH-010), unlike quartz overgrowth development, is ‘patchy’ within reservoir intervals (*e.g.*, Harris, 2015) and will also result in unpredictable fluid flow behaviour. Low permeability reservoirs (*c.f.*, Law, 2002) require additional data with which to assess their petroleum exploration and production potential, and this focus is typically on characterizing *in situ* pore geometries/connectedness and reservoir pressure regimes.

Hydrocarbon production wells are likely to require reservoir intervals at depths in excess of 2000-3000 m to generate sufficient overburden pressure to produce gas without the need for artificial mechanical stimulation (J. Hogg, *pers. comm.* 2016). In the Division Mountain area, proximal Laberge Group pay thickness decreases down-section (*see* Plate 2), with the risk that as wells get deeper (*i.e.*, the depositional facies belts move farther offshore), the sand becomes more isolated, infrequent and thinner. In the Tantalus Butte area, outcrop exposure suggests that the proximal Laberge Group is coarse-grained in its entirety (making source rock presence a large risk). It is difficult to estimate group total stratigraphic thickness along the Robert Campbell Highway, but strata typically young westwards between Eagles Nest Bluff and Carmacks (at dips up to 50°; Colpron, 2011), suggesting that subvertical wells drilled close to Carmacks with an easterly inclination may penetrate a fuller Laberge Group section and reservoirs at the depths required (Fig. 29). Thrust and fold repetition of stratigraphy along the Robert Campbell Highway (*e.g.*, White *et al.*, 2006, 2012) will likely facilitate targeting the required thickness and depth of Laberge Group in this area.

### *Seals and traps*

Play risks (updated from Hayes, 2012, Tanglefoot structural and stratigraphic plays) are also presented in Table 3, with the highest risk attributed to lack of formational top seal across most of the northern trough, especially in the Tantalus Butte region. In the two areas studied, top seals may be provided by the Tantalus Formation (although its preservation is localized to the area of the old coal mine workings close to Carmacks), and by the Cretaceous Carmacks Group volcanic rocks (shoshonitic basalt – Hart and Langdon, 1998) in the Division Mountain area (*see* Fig. 5a). The Carmacks Group is modeled as approximately 600 m (2000 ft) thick by MIRA Geoscience (2014), and it forms a laterally extensive, flat-lying formational seal to the underlying deformed proximal Laberge Group. To the south of the Carmacks Group continuous outcrop at Division Mountain, top seal risk is predicted to increase (Table 3; Fig. 29), and volumes are more likely to occur in stratigraphic traps sealed by intraformational mudstone, that may or may not exhibit a structural overprint. In addition to intraformational mudstone seals, intrusive basaltic sills are also frequent and localized in the upper, coal-prone Laberge Group stratigraphy (*see* Plate 2 and Fig. 20; *e.g.*, Long, 2015; Allen, *unpbl.*). However, their cumulative thickness (and frequency) does appear to decrease southwards based on measured outcrop section data, from 55.5 m (30%) at Mount Vowles to 2 m (<1%) at Teslin Creek (Long, 2015).

Although prospective large-scale structures are documented in both areas (*e.g.*, the ‘crested anticlines’ and domes modeled by MIRA Geoscience in 2014; Fig. 5; Table 3), trap integrity is typically of high risk in the trough (due to the pervasive fault and fracture network), both for finding hydrocarbon volumes in place and for subsequent drilling activities to extract them. Small scale fault networks are likely to compartmentalize reservoirs, impeding fluid flow to the well bore, and high resolution seismic is required to understand fault density and frequency in this area prior to planning a well. Shallow coal exploration boreholes were reduced in diameter from HQ to NQ when ‘badly broken’ ground was encountered at Division Mountain, and some holes were subject to excessive caving, collapse and even total loss at relatively deep depths after drill rods were pulled back due to soft mudstone and ‘loose’ silt and sand (*e.g.*, Gish, 1997). Locally the often intense fracturing is likely to impose risk of circulation losses prior to installing surface casing in deeper hydrocarbon wells.

## *FUTURE RESEARCH DIRECTIONS*

Exploration and production of hydrocarbon from the Laberge Group in the northern Whitehorse trough is likely to be both geologically and technologically challenging. The lack of subsurface thickness information and the consequent inability to obtain the types of petrographic, mineralogical, poroperm and structural/fracture data required to assess both conventional and tight plays from *in situ* reservoirs at depth, greatly contributes to the group’s uncertainty in petroleum potential in the basin. Until further fieldwork results and a facies analysis is undertaken for the proximal Laberge strata, the lithological complexity that exists at reservoir scale in the northern trough will ensure that the prospectivity data summarized in this report (especially characterization as a tight play) remain applicable at group level only.

Ongoing research in the basin is therefore essential to glean as much information from surface and shallow subsurface rocks as possible in the absence of planned industry activity in the basin (*i.e.*, availability of well or seismic data). Future outcrop petroleum research in the Whitehorse trough is recommended to initially focus on the north exploration area (*see* Fig. 8) as the most prospective for hydrocarbon using the research strategy in Figure 11. Key concepts to guide this research will include:

- Recognition and logging, sampling or mapping rocks as Laberge Group stratigraphy only – the use of Tanglefoot and Richthofen formation ‘buckets’ should be temporarily abandoned until enough data are collected and interpreted to allow their spatial and temporal character to be defined by formal lithostratigraphic procedures (if required, *see* next point below).

- Recognition and correlation of key sequence stratigraphic surfaces, with the ultimate goal of erecting a stratigraphic framework for the Laberge Group composed of allomembers rather than lithomembers. This research approach is standard procedure in studies that aim to reconstruct ancient marginal marine/delta to offshore depositional systems, especially in the Cretaceous of the Western Interior Seaway (*e.g.*, Bhattacharya and Walker, 1991; Garrison and van den Bergh, 2004; Olariu *et al.*, 2010). The approach is very useful in reservoir characterization studies as it allows the mapping of lateral facies variation in time-equivalent rock packages, thereby enabling greater accuracy in predicting reservoir fluid-flow properties in addition to better facilitating reservoir distribution predictions away from well or outcrop control. Limitations on outcrop exposure/quality and availability of core material in the Whitehorse trough may be offset by the use of additional systematic whole rock geochemical or mineralogical analysis techniques, and by frequent high-resolution geochronological sampling.
- Investigating the age and depositional context of the basal Laberge Group contact with the underlying Lewes River Group sediment. Although not strictly related to petroleum potential, this study would provide critical information on the structural and sedimentological evolution of the basin's inception, including the distribution and quality of the high-potential shallow marine facies at the base of the Columbia Disaster section on the Robert Campbell Highway.
- Focusing on describing the facies present and interpreting processes and depositional environments systematically. Recent studies in Lower (Bluesky Formation) and Upper (Dunvegan Formation) Cretaceous marginal marine plays in the Western Interior Seaway (*e.g.*, Bhattacharya and Walker, 1991; Gingras *et al.*, 1998; Botterill *et al.*, 2015, 2016) have highlighted the importance of integrating trace fossil and sedimentological data to facilitate recognition of physico-chemical stresses to reconstruct ancient depositional environments.
- Investigating the origins and development of authigenic cement in the proximal Laberge Group, and how it varies in space and time (depth). The fact that the reduction in permeability in the proximal Laberge Group is diagenetic in origin, rather than primarily depositional (*e.g.*, fine grain sizes and/or detrital clay matrices), suggests that studying the development of authigenic cement is as equally valid a research topic as collecting data on depositional systems within the trough from a petroleum perspective.
- Studying the sealing capacity of intra-reservoir mudstone in the Laberge stratigraphic play. Field observations in 2014 highlight the potential for thick, intraformational mudstone to significantly impact hydrocarbon production from reservoirs of the Laberge stratigraphic play. In this situation, determining the seal potential of the mudstone is critical, *i.e.*, whether it will compartmentalize the reservoir by reducing vertical connectivity between adjacent sandstone bodies (and therefore act as barriers/baffles to fluid flow to the wellbore). In association, it is also important to understand the sandstone permeability regime, *i.e.*, whether horizontal reservoir permeability is sufficient to permit fluid flow if interbedded mudstones are found to be sealing.

Finally, the data presented here for the proximal Laberge Group could be used to inform a subsequent iteration of Hayes' (2012) resource assessment of the Whitehorse trough. Input parameters such as porosity and pay thicknesses exert a significant influence on calculated volumes, and the availability of actual data (rather than best estimates) will also serve to further condition risk assigned to those resources.

# CONCLUSIONS

Recent reassessment of Whitehorse trough stratigraphy and its petroleum prospectivity has resulted in a new basin outline and enhanced resource distribution maps that can be used to guide systematic petroleum research. The Laberge Group should be approached as one depositional system, with coarse-grained, proximal facies in the northern trough unexpectedly exhibiting characteristics of 'tight', low permeability gas plays. Two areas are identified as being of sufficient data density to warrant further exploration: Tantalus Butte and the western end of the Robert Campbell Highway, and Division Mountain (west of Braeburn). Unconventional shale potential is restricted to fine-grained facies in the southeast part of the trough.

Conceptually, the Whitehorse trough evolved from a high shelf-basin relief (SBR) margin with a high accommodation/sediment supply (A/S) ratio to a low SBR margin with a low A/S ratio during shoaling and oroclinal enclosure of part of Panthalassa in the Middle Jurassic. Depositional processes and environments in the northern part of the trough were predicted for both margin models using coastal morphology classification matrices, paleogeographic interpretations and Jurassic wind directions. Modeling suggests that the proximal Laberge Group sandstone was deposited primarily during the low SBR, low A/S regime by tidal-dominated and fluvially-influenced coastal processes. Outcrop and core observations support the model results, with the Laberge Group comprising prograding shoreface, marginal (estuarine/tidal) marine and coastal wetland sedimentary rocks. Deposition was controlled by dominant basin shoulder uplift during the Early Jurassic, and potentially by subordinate sea-level and climatic fluctuations in the shallower shelf of a low SBR margin basin. The most basal Laberge Group rocks at Eagles Nest Bluff reflect semi-arid, ephemeral 'mudflat' depositional conditions which persisted from the Late Triassic.

Laberge Group petroleum system characteristics and play risks have been updated for the Tantalus Butte and Division Mountain areas in the northern basin, with geological success estimated at 4% for the Laberge play in Tantalus Butte and 29% for Division Mountain. Reanalyzed RockEval-TOC and vitrinite reflectance data highlights that source rock quality increases to the south in association with decreasing maturity (at surface). Only 17% of samples analyzed in the Tantalus Butte area exhibit source rock potential (relative to 57% at Division Mountain), inferring increasing exploration risk of this system component northwards in the basin. Integrated petrography, mineralogy and geochemistry suggest an evolution from mafic to felsic provenance, and from marine to non-marine depositional environments over time in the basin. Average porosity and permeability (Kmax) are very low (4.0% and 0.36 mD respectively) with pore space typically occluded by authigenic carbonate and kaolinite cement. Overall, there is no control on porosity by grain size, and poroperm data are highest in the distal, younger rocks at Division Mountain where increasing Kv/Kh ratios suggest permeability anisotropy and potential reservoir compartmentalization.

Exploration and production of hydrocarbon from the Laberge Group in the northern Whitehorse trough are likely to be both geologically and technologically challenging. The lack of subsurface thickness information and the consequent inability to obtain the types of petrographic, mineralogical, poroperm and structural/fracture data required to assess both conventional and tight plays from *in situ* reservoirs at depth, greatly contributes to the group's uncertainty in petroleum potential in the basin. Future research in the basin is therefore essential to glean as much information from surface and shallow subsurface rocks as possible in the absence of planned industry activity in the basin.

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