An overview of shale studies in Yukon during the 2017 field season

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ABSTRACT

Summer 2017 fieldwork in Yukon's lower Paleozoic shale basins (Selwyn basin and Richardson trough) involved participants from government geological surveys (Yukon Geological Survey, Geological Survey of Canada) and several universities (Queen's, McGill, St. Francis Xavier, Stanford and Dartmouth College). Research interests include: 1) shale chemostratigraphy and biostratigraphy, and pyrite trace element geochemistry to characterize shale units and assess lower Paleozoic paleoenvironmental conditions and depositional controls; and 2) an assessment of hyper-enriched black shales, specifically the colloquial 'Nick' or 'Ni-Mo' mineralized Ni-Zn-Mo-PGE deposit, in order to develop internally consistent genetic and exploration models for these types of deposits. This paper describes individual research projects underway and summarizes fieldwork in summer 2017.

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INTRODUCTION

Recent academic interest in shale deposits in Yukon led to a busy summer of fieldwork in Yukon's Paleozoic shale basins. In late 2016, the Yukon Geological Survey (YGS) invited current shale researchers to join an informal shale working group to share research ideas and to coordinate field-related logistics. This paper summarizes the current state of shale research in Yukon and activities during the 2017 field season.

PALEOZOIC SHALE BASINS

Cambrian to Middle Devonian shale basins (Selwyn basin and Richardson trough; Fig. 1) characterized the northwestern margin of ancestral North America (Laurentia). These were sites of deposition of thick shale sequences situated outboard of an extensive carbonate platform known as the Mackenzie platform. The lower Paleozoic tectonic setting consisted of relatively quiescent passive margin sedimentation with intermittent extension and mafic volcanism in the Cambrian, Early to Middle Ordovician, Silurian and Middle to Late Devonian (Nelson *et al.*, 2013). Richardson trough was the main focus of field studies in 2017, along with minor work in Selwyn basin (Fig. 1). Figure 2 displays the generalized stratigraphy of the Paleozoic shale units in Richardson trough and Selwyn basin that are mentioned in this paper.

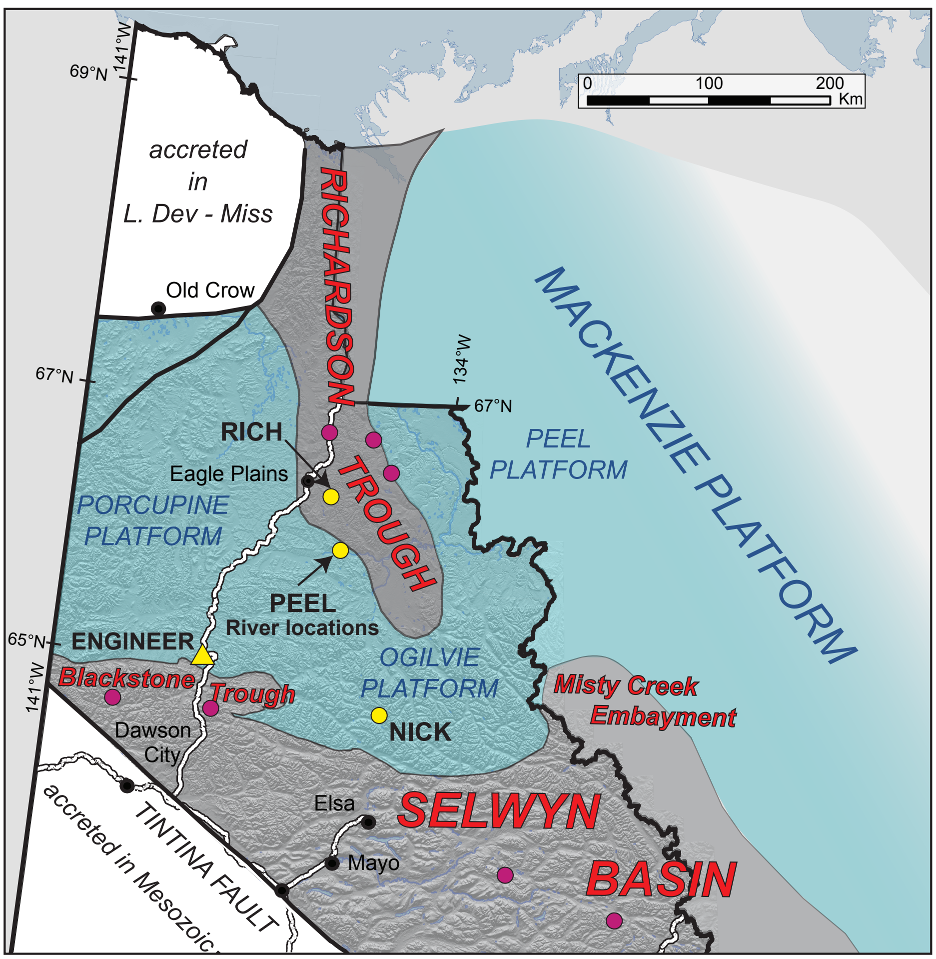

Figure 1. *Generalized map of North Yukon with location of major lower Paleozoic carbonate platforms (blue) and basins (grey). All circle markers (yellow and purple) indicate locations of Nick-style or Ni-Mo mineralization (also, hyper-enriched black shales: HEBS) with yellow denoting locations mentioned in the paper. The purple dots are Ni-Mo horizon outcrops noted from other sources (e.g., Yukon MINFILE 2017, Fraser and Hutchison, 2017). The yellow triangle marks the location of a shale outcrop of indeterminate Paleozoic age measured by YGS in summer 2017.*

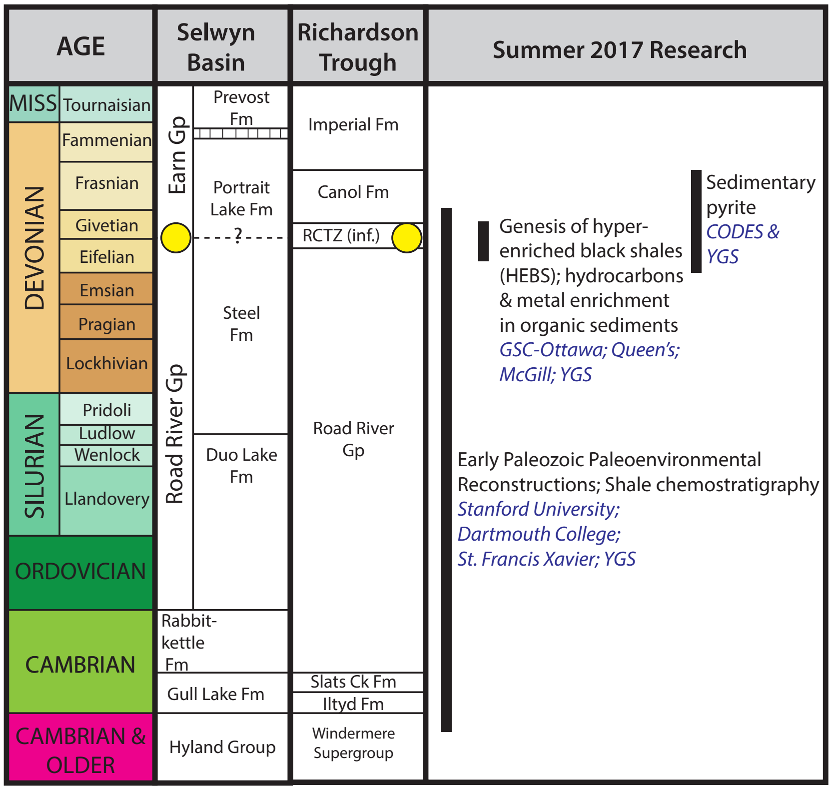

Figure 2. *Generalized stratigraphy for the lower Paleozoic sections in Selwyn basin (NTS 105 I,J,K map areas; after Gordey and Anderson, 1993; Gordey, 2013) and Richardson trough (after Fraser and Hutchison, 2017) alongside the 2017 shale research programs in Yukon. The yellow dot denotes the position of the Nick or Ni-Mo mineralized zone referred to in the text.*

SHALE CHEMOSTRATIGRAPHY

With some notable exceptions, including seminal work on lower Paleozoic stratigraphy (e.g., Lenz and Pedder, 1972; Cecile *et al.*, 1982; Pugh, 1983; Norris, 1985, 1997; Gordey and Anderson, 1993; Morrow, 1999; Gordey, 2013) and bedrock mapping (e.g., Norris 1981; 1982a,b,c,d; Cecile *et al.*, 1982), lower Paleozoic fine-grained sedimentary rocks (*i.e.*, mudstone, siltstone, shale) in north and central Yukon have been largely overlooked in the past. Detailed studies have been restricted to petroleum source rock generative potential (e.g., Feinstein *et al.*, 1988; Link *et al.*, 1989) or mineral potential (e.g., SEDEX deposits; e.g., Goodfellow, 1987; Gadd *et al.*, 2016). Missing from the Yukon dataset are systematic and comprehensive lithogeochemical analyses of these fine-grained rocks, which would facilitate the differentiation and correlation of these commonly thick, regionally distributed units that were deposited over long time periods. To fill this void, the YGS has been identifying and evaluating fine-grained sedimentary rocks in the traditional oil and gas regions of North Yukon for several years (e.g., Allen, 2010; Fraser *et al.*, 2012; Fraser, 2014; Fraser and Reinhardt, 2015; Fraser and Hutchison, 2017). As these units can be difficult to differentiate in drill core, YGS is using a combination of field studies and chemostratigraphy to provide lithofacies interpretations and a sequence stratigraphic framework for the shales. These studies not only provide detailed lithogeochemical markers that can be used for identification and correlation, but have also been useful in characterizing paleoenvironmental conditions such as redox, hydrography, eustasy, and in fossil poor sections have provided a proxy for age control (*see* Fraser and Hutchison, 2017).

In 2017, Tiffani Fraser (YGS) continued work on the Cambrian-Middle Devonian Road River Group and overlying Middle-Upper Devonian Canol Formation (Richardson trough) or Earn Group (Selwyn basin; Fig. 2), with a particular interest in determining the sequence stratigraphic framework for the mineralized contact zone between the two. This interval is known as either the "Nick" zone, after a mineral property of the same name 133 km north of Mayo (Fig. 1), or alternatively as the "Ni-Mo" horizon (herein) for its metal enrichment (percentage level concentrations of Ni and thousands of ppm of Mo). At the Nick property, the Ni-Mo horizon is a thin, stratiform, ≤3 cm thick metalliferous unit with anomalous concentrations of Ni, Zn, PGE, Se, As, Mo, Pb, Ba, U (Hulbert *et al.*, 1992) that has an extensive distribution through north and central Yukon. Two exceptional outcrop exposures of this interval occur along the Peel River, upstream of Aberdeen Canyon, in the former Richardson trough (Figs. 3 and 4). Tiffani, along with Patrick Sack (YGS), investigated the south bank exposure in July; and in August, Tiffani continued the investigation on the north bank with Leyla Weston (YGS) and a contingent from the Geological Survey of Canada (GSC; Mike Gadd and colleagues, project described below). A similar stratigraphic sequence was also visited in the eastern Richardson Mountains, along a creek exposure on the Rich property (Fig. 1). As part of a long-standing project on characterizing the extensive shale deposits of North Yukon, Tiffani and Leyla also evaluated several indeterminate shale outcrops along the Dempster Highway, in the vicinity of Engineer Creek (Fig. 1) with a goal of defining their age and stratigraphic position.

SEDIMENTARY PYRITE

The upper Road River Group from the Peel River south bank section, previously mentioned (Fig. 3), was also systematically sampled in summer 2017 by Patrick Sack for sedimentary pyrite. This work is part of an ongoing study in conjunction with the Centre for Ore Deposit Research (CODES) at the University of Tasmania. The study involves determining the trace element content of syngenetic and early diagenetic pyrite (herein sedimentary pyrite) that can be used as a proxy for paleo-ocean chemical conditions at the time of formation (e.g., pH, alkalinity and oxygenation level of coeval seawater; *see* Large *et al.*, 2017). The trace element content of sedimentary pyrite in the Road River Group samples will be determined at CODES using laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS). The study will compare results of this technique to other paleo-ocean chemistry proxies (e.g., bulk geochemical compositions) currently being conducted on the same rocks by other research teams.

EARLY PALEOZOIC PALEOENVIRONMENTAL RECONSTRUCTIONS

Summer 2017 marked a third and final field season for a research team composed of Erik Sperling (Stanford University, California), Justin Strauss (Dartmouth College, Vermont), and Michael Melchin (St. Francis Xavier University, Nova Scotia), in collaboration with Tiffani Fraser (YGS), studying the Road River Group along the Peel River (Fig. 3). The Road River Group at this locality preserves an essentially continuous deep marine record

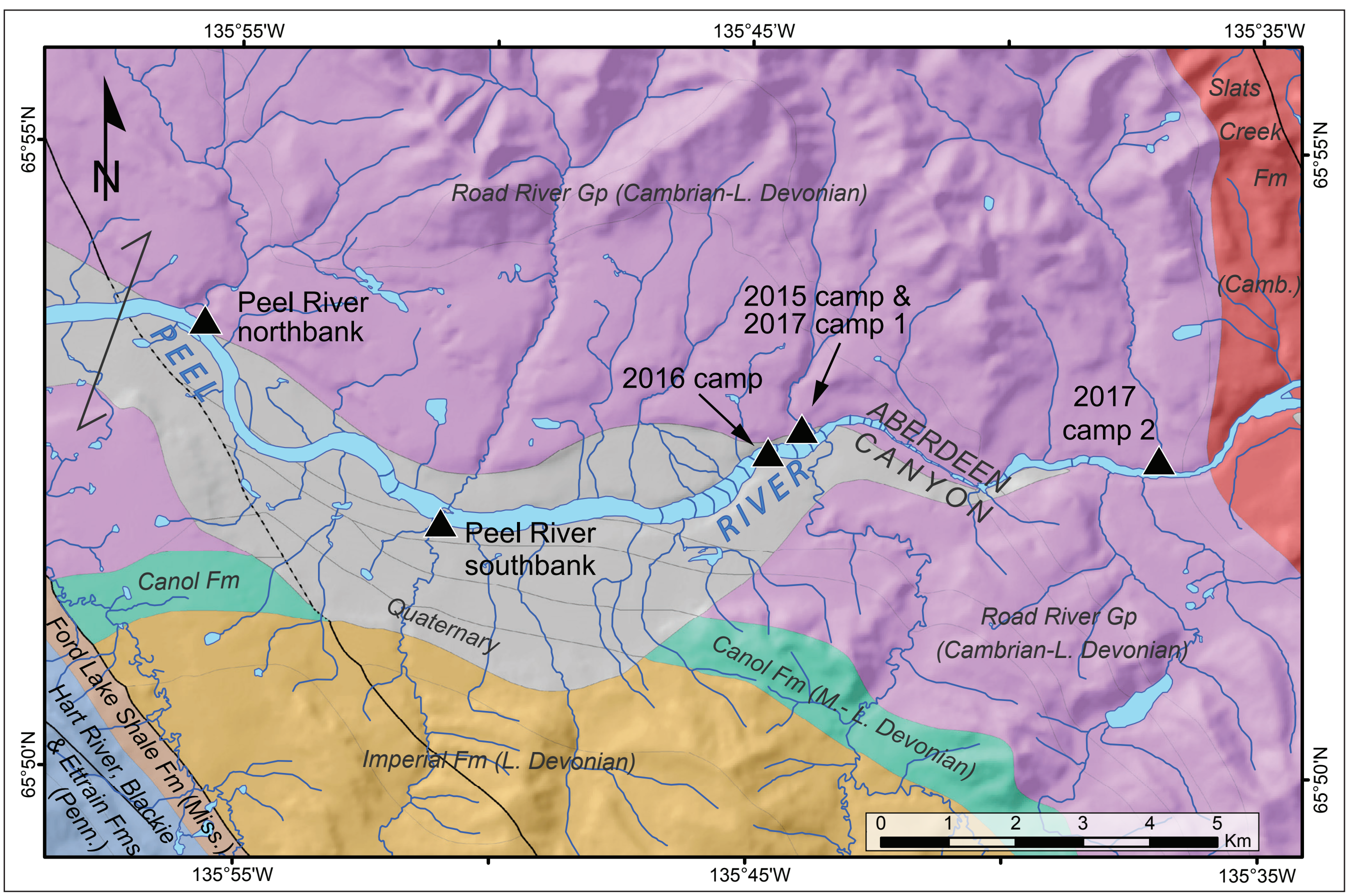

Figure 3. *Bedrock geology map of study area showing shale research stations (black triangles) along the Peel River mentioned in the text. The 2015, 2016 and 2017 sites were camping locations for the Stanford University and Dartmouth College teams in respective years. Geology after Yukon Geological Survey (2015). Black lines denote faults (solid = actual; dashed = inferred). Light grey lines are mapped formation/group subdivisions.*

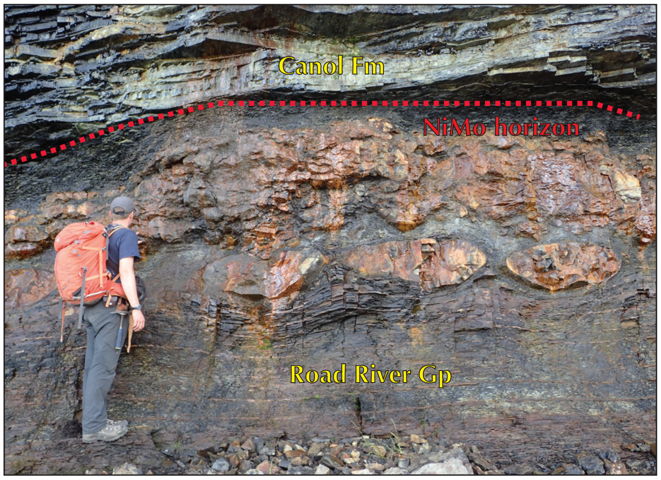

***Figure 4.** Erik Sperling (Stanford University) at the Peel River south bank section. The Ni-Mo horizon (position marked by red dashed line) sits at the contact between the Road River Group and overlying Canol Formation. At this and other locations, large carbonate concretions characterize the uppermost strata of the Road River Group (brown/orange resistant masses between Erik's head and waist region).*

of late Cambrian through Middle Devonian time in a single, unmetamorphosed and well-exposed stratigraphic section along the Peel River (Lenz and Pedder, 1972). This work has shown that the rocks do not support the premise that the stratigraphic record is "more gap than record". The detailed re-examination of this section led by Erik and Justin will provide a unique opportunity to build an ~120-million-year record of early Paleozoic Earth history. Overall, the study goals are to: 1) provide a detailed sedimentological framework for the Peel River section of the Road River Group; 2) produce a detailed age model for the section based on U-Pb geochronology and multiple lines of biostratigraphic evidence; and 3) analyze multiple geochemical proxies to determine how local and global paleoenvironmental conditions changed during this interval.

This research began in 2015 on the north side of the Peel River with systematic measuring and sampling of the Middle Ordovician through Upper Silurian part of the Road River Group (2015 camp; Fig. 3). In 2016, focus was on the south side of the river from the Upper Silurian through to the Peel River south bank section of the Ni-Mo horizon currently being studied by other research groups summarized in this paper (2016 camp; Fig. 3). Finally, in summer 2017 there were two camps (2017 camp 1 and 2; Fig. 3). The first was to re-visit the 2015 camp with the goal of completing detailed graptolite biostratigraphic and carbon isotope chemostratigraphic studies of Upper Ordovician and Lower Silurian strata. The second camp was located below (east of) Aberdeen Canyon, and work here focused on measuring and sampling Upper Cambrian through Middle Ordovician strata.

With a complete composite stratigraphic section of the Road River Group completed, the focus is now on biostratigraphic, geochronological, and geochemical analyses. With respect to age control, four Ordovician ash beds have been analyzed using high-precision chemical abrasion isotope dilution thermal ionization mass spectrometry (CA-ID-TIMS) methods on zircon (Fig. 5). In combination with two new ash beds sampled in 2017, these ages provide anchor points for the Road River Group and will help revise the global Ordovician timescale. Graptolite biostratigraphic studies (Fig. 6) in combination with organic carbon isotope chemostratigraphy have precisely located the position of key Ordovician and Silurian stratigraphic boundaries, and all of the major Silurian positive carbon isotope excursions have been identified. This is the first time these carbon cycle perturbations have been recognized in Yukon shale successions. Ongoing graptolite and conodont biostratigraphic study in the previously undated Devonian portion of the Road River Group should improve time resolution in strata preceding the Ni-Mo horizon. Finally, shale samples have been collected throughout the section at ~2 m stratigraphic intervals and are being analyzed for iron speciation, redox-sensitive trace metal abundance, organic carbon contents and isotopes, and pyrite sulphur isotopes. Ultimately, this high-resolution dataset should provide new insight into many aspects of early Paleozoic paleoenvironmental change.

***Figure 5.** Tom Boag (Stanford University) and Justin Strauss (Dartmouth College) collecting samples from Lower Ordovician ash beds (red dashed lines) in the Road River Group below (immediately east of) Aberdeen Falls, Peel River.*

Figure 6. *Graptolite impressions in Lower Ordovician (Tremadocian) strata below Aberdeen Falls, Peel River. The large impression on the left is Kiaerograptus. The larger one on the right is Clonograptus. Centimetre scale at bottom of photograph.*

HYPER-ENRICHED BLACK SHALES

Through the Targeted Geoscience Initiative (TGI) of the Geological Survey of Canada, Mike Gadd and Jan Peter (GSC-Ottawa) are researching the origin of, and processes responsible for, hyper metal-enriched black shales (HEBS), including the Ni-Mo horizon, contained within Devonian stratigraphy of North Yukon. HEBS are thin (<10 cm) and geographically widespread (10 000s of km^2), and are an important global repository for Zn, Ni, Cu, Mo, Se, U, V, ± Cr, Co, Ag, Au, platinum group elements (PGE) and rare earth elements (Jowitt and Keays, 2011). The HEBS layers consist of semi-massive to massive sulphides hosted in carbonaceous shales, that are intercalated with ‘background’ carbonaceous shales (*i.e.*, not hyper-enriched). Yukon hosts some of the best examples of HEBS globally (*e.g.*, Nick Ni-Zn-Mo-PGE deposit (Ni-Mo horizon); Hulbert *et al.*, 1992) and there is significant potential for further discovery of deposits. Indeed, several HEBS occurrences have been documented in the Richardson trough area of North Yukon (Fig. 1), and these are surmised to have been deposited at the same stratigraphic interval as at the Nick property (*i.e.*, at the Middle Devonian contact of the Road River Group and Canol Formation; Figs. 3 and 4).

Fieldwork in 2017 focused on lesser known examples of HEBS deposits along the north and south banks of the Peel River (Fig. 3) and on the west side of the Richardson Mountains at the Rich property (Fig. 1). At the Peel River localities, we documented for the first time up to three discrete HEBS layers that are not structural repetitions. We have identified abundant biogenic debris — conodont elements and petrified wood (Fig. 7) — within these metalliferous shale layers. Whereas the uppermost HEBS layer at Peel River has been constrained biostratigraphically to the Givetian stage (Gadd and Peter, 2018), the underlying HEBS layers have not yet been dated. However, the stratigraphically lower HEBS layers also contain biogenic debris, and we aim to characterize this as well. This will fulfill one of the salient research goals, to constrain the duration of HEBS mineralizing events. A critical aspect of this research is to understand the processes responsible for HEBS deposit formation. Preliminary data indicate that the metals and metalloids were scavenged from seawater, the efficiency of which was enhanced by extremely low rates of clastic sedimentation (*i.e.*, condensed sedimentation; *see* Fraser and Hutchison, 2017) and highly efficient organic matter remineralization (Gadd and Peter, in press). Ultimately, we aim to develop internally consistent genetic and exploration models for HEBS deposits in Yukon.

Affiliated with the TGI HEBS study, is research by Isobel Crawford. Her MSc graduate research at Queen’s University (Ontario) is being conducted under the supervision of Dan Layton-Matthews. Isobel is investigating the ambient paleoenvironmental redox conditions of Richardson trough during deposition of the HEBS Ni-Zn-Mo-PGE horizon (Ni-Mo horizon) and adjacent stratigraphy, using Mo, Tl and U isotopes. Fieldwork in August focused on

Figure 7. *Pyritized plant fragments on a bedding surface of the Ni-Mo horizon at the Peel River north bank section.*

systematic collection of samples collected from outcrop and short drillcores from the Peel River north and south bank sections (Fig. 3). The study aims to contribute to the greater research goal of developing genetic and exploration models for HEBS in the Ogilvie and Richardson mountains in Yukon.

HYDROCARBONS AND METAL ENRICHMENT IN ORGANIC-RICH SEDIMENTS

Complementary to the Ni-Mo work previously described, Kyle Henderson, PhD graduate student at McGill University (Quebec) under Anthony Williams-Jones' supervision, is investigating the role of organic material and related hydrocarbons in the metal enrichment processes that were responsible for this horizon. It has long been known that microbial activity in oxidizing environments and organic matter in anoxic environments play a critical role in enriching sediments in a wide variety of trace elements. As well, there is a large volume of research dedicated to the processes that affect organic matter accumulation, preservation and trace metal uptake by organic-rich sediments (Algeo and Maynard, 2004; Brumsack, 2006; Calvert and Pedersen, 1993; Pedersen and Calvert, 1990; Piper and Calvert, 2009; Tribovillard *et al*., 2006). These sediments are source beds for liquid hydrocarbons (*i.e.*, crude oil), metalliferous hydrothermal fluids, and they may host base-metal ore deposits. Based on this previous work, Kyle will be studying the relationship between the thermal maturity of the organic matter, trace metal mobility and hydrocarbon generation with the objective of understanding the role (if any) that liquid hydrocarbons may have played in metal concentration. A longer-term objective of the project is to improve understanding of atmosphere-biosphere-lithosphere interactions through time. Kyle collected bitumen samples from the Ni-Mo horizon and associated shale along the Peel River (north and south bank sections; Fig. 3), and at the Rich property in summer 2017 (Fig. 1).

WHAT'S NEXT?

All shale research teams in Yukon in 2017 anticipate several years of investigation into samples collected, with publications forthcoming. Continued fieldwork in summer 2018 is anticipated by geologists from YGS, GSC-Ottawa, and Queen's and McGill universities. These shale studies may prove useful to base metal exploration in Yukon. With renewed interest in base metal exploration, the research described here may help differentiate thick, prolonged shale intervals, facilitate correlation of shale intervals within and between basins, and ultimately refine the stratigraphic column with enhanced age, lithologic, and genetic data. The YGS plans to extend detailed shale studies into Selwyn basin in future years.

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