New geochemistry from old drill holes at the Tom property, Macmillan Pass, Yukon

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Abstract

This paper presents new data from historical drill core and outcrop specimens from Macmillan Pass, Yukon. Whole rock lithogeochemical data are presented from analyses of core from three drillholes at the Tom property. The core covers intervals ranging from the Middle Devonian Road River Group (Sapper Formation) to the Upper Devonian Earn Group (Portrait Lake Formation–Fuller Lake Member) and includes the Macmillan Pass volcanic suite that occurs at the Road River–Earn Group contact. Samples were collected to characterize the depositional history of Middle–Upper Devonian fine-grained rocks in the region to aid with paleogeographical reconstructions, depositional models, improve age control and to aid in correlation of thick shale units. Baseline geochemical profiles and sedimentology for all fine-grained units indicate turbidity current deposition in a range of shelf to basinal settings and variable oxic to anoxic conditions. Additionally, eleven existing Middle Devonian conodont collections were re-examined to provide better biozone refinements and a tighter constraint of the contact between the Road River Group (Sapper Formation) and Earn Group (Portrait Lake Formation) to the Late Eifelian *australis-ensensis* biozones.

Organic carbon isotope data from the upper Sapper Formation immediately below the Macmillan Pass volcanic suite display a negative 3.2‰ excursion. This thin (≤15 cm) interval coincides with enrichment of trace elements Mo, Ni, Zn, Se, P, As, Ag, Au, Zn and P_2O_5. Isotope data combined with the updated conodont ages indicates an anomalous shale interval age-equivalent to the 'NiMo' or hyper-enriched black shale horizon observed regionally in Selwyn basin, Richardson trough and Kechika trough at the contact between the Road River Group and Canol Formation/Portrait Lake Formation (Earn Group). This interval is also coeval with the Kačák Event, a global biocrisis that spans the Eifelian–Givetian boundary and is characterized in the marine realm by a condensed section of black shale sedimentation, sea-level instability, a negative isotopic excursion and pelagic faunal changes (*i.e.*, massive extinction followed by a radiation). Whether the strata at Macmillan Pass records this global event requires further biostratigraphic control; however, its presence would be a significant marker for the Eifelian–Givetian boundary in eastern Selwyn basin. Unlike other NiMo occurrences elsewhere in Yukon, this anomalous shale interval at Macmillan Pass is overlain by volcanic rocks. The local influence of the Macmillan Pass volcanic suite on metal concentrations and on the carbon isotopic signature in underlying shale also requires further examination.

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Introduction

Yukon Geological Survey (YGS) examined historical core at Macmillan Pass (Mac Pass) in summer 2019 as a reconnaissance study for future fieldwork in the area. The research is part of a regional study looking at the lithogeochemistry of shale sections in Selwyn basin to define the regional stratigraphic framework and evolution of the basin to facilitate paleogeographical reconstructions, depositional models, improve correlation, and provide age control of thick shale units. This paper presents lithogeochemical and organic carbon isotopic data from selected drill core on the Tom property that provide baseline information on Middle–Upper Devonian shale packages in the region. Presented are geochemical profiles that offer proxies for paleoenvironmental sediment source and proximity to carbonate banks and shorelines, redox conditions of bottom water and associated organic matter preservation, and relative sea level change. A negative organic carbon isotopic excursion and enrichments of Ni, Zn and Mo near the upper contact between the Sapper Formation (Road River Group) and the Macmillan Pass volcanic suite may correlate to the global Kačák Event, a late Eifelian–early Givetian bioevent that records a sea-level transgression, anoxic conditions in the marine realm, and a turnover in pelagic fauna (e.g., House, 1996; Walliser, 1996; Schöne, 1997; DeSantis, 2010; Elwood *et al.*, 2011). We also explore the possibility that this metal-enriched interval of the uppermost Sapper Formation is the local expression of the Middle Devonian hyper-enriched black shale (HEBS) mineralization (locally known as the NiMo horizon) observed elsewhere in Selwyn basin and Richardson trough at the Eifelian–Givetian (Middle Devonian) boundary. Eleven slides containing conodonts from a previous bedrock mapping project in the Macmillan Pass region were re-examined for further age refinement. Presented herein are biozonal ranges for Early to Middle Devonian-aged conodont collections that constrain the contact between the Road River Group (Sapper Formation) and Earn Group (Portrait Lake Formation) to the Late Eifelian *australis-ensensis* biozones.

Location

Mac Pass is in eastern Yukon near the border with the Northwest Territories, at the northeastern end of the North Canol Road, ~200 km from the community of Ross River (Fig. 1). The region north of the Canol Road lies in the Traditional Territory of the First Nation of Na-Cho Nyäk Dun, and to the south of the road, the Traditional Territory of the Ross River Dena Council and Liard First Nation (Kaska Dena Council). Macmillan Pass proper forms a broad valley at the head of the South Macmillan River that transects the Selwyn Mountains at an elevation of ~1360 m. The surrounding landscape is mountainous with surrounding peaks attaining >2000 m.

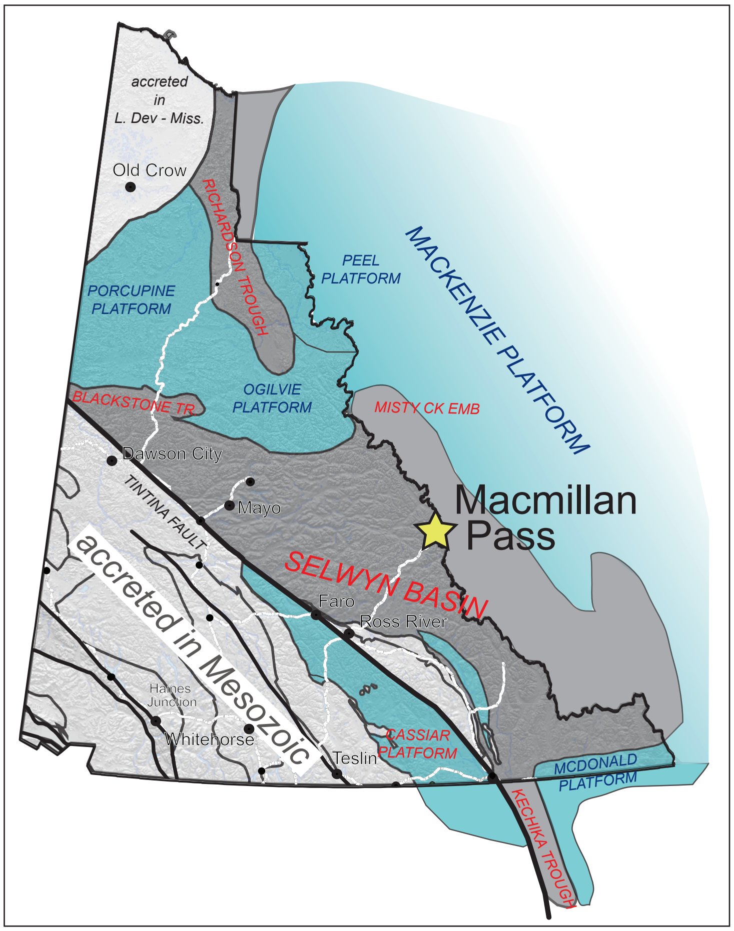

Figure 1. *Lower Paleozoic paleogeographic elements in Yukon (after Nelson and Colpron, 2007) highlighting Paleozoic carbonate platforms (blue) and basins (dark grey with red text) on the Laurentian margin. Macmillan Pass occurs in the east-central part of Selwyn basin at the border between Northwest Territories and Yukon. Younger terranes (Late Paleozoic and Mesozoic) are shown in light grey. White lines are roads.*

The Macmillan Pass region is known for the Tom and Jason Zn-Pb-Ag deposits, and the Boundary and End Zone mineralization systems (Fig. 2). Tom and Jason have a combined mineral resource of 11.2 Mt Indicated at 6.59% Zn, 2.48% Pb and 21.33 g/t Ag, in addition to 39.5 Mt Inferred at 5.84% Zn, 3.14% Pb and 38.15 g/t Ag (Arne and McGarry, 2018). Since discovery of the Tom deposit in 1951, the claims have undergone various ownership changes; in 2018 Fireweed Zinc Ltd. (Fireweed) acquired the Tom and Jason properties from Hudson Bay Mining and Smelting Company. A trailer camp and core storage facility are situated on the Tom property (63.1645°N, -130.1589°W). Fireweed has been drilling seasonally and using the camp since 2017.

Macmillan Pass Stratigraphy and Tectonic Setting

This paper uses the lithostratigraphic nomenclature of Abbott (2013), shown in Figure 3, however, it is recognized that different naming conventions occur in the literature (*e.g.*, Carne, 1976; Abbott 1983; Abbott and Turner, 1991; Goodfellow and Rhodes, 1991) and that many names originated in publications from adjacent areas (*e.g.*, Gordey and Anderson, 1993; Cecile, 1982, 2000).

Cambrian–Middle Devonian rocks of the area were deposited in Selwyn basin—a depocentre close to the NW margin of Laurentia (ancestral North America) that lay outboard of contemporaneous carbonate platforms (Gordey and Anderson, 1993; Gabrielse, 1967; Fig. 1). Neoproterozoic to lower Cambrian strata include clastic sedimentary rocks that formed during formation of the Laurentian margin, namely the Narchilla and Vampire formations (Fig. 3). These are overlain by latest early to middle Cambrian clastic and carbonate units (Sekwi, Gull Lake and Hess River formations) that record intermittent extension prior to the establishment of a more stable carbonate platform and basin configuration in the latest Cambrian to Ordovician (Dilliard *et al.*, 2010; Cecile, 1982; Gordey and Anderson, 1993; Fig. 1). At Macmillan Pass, Ordovician to Middle Devonian strata are assigned to the basinal Road River Group (Duo Lake, Steel and Sapper formations), which comprise siliceous shale, chert, variably calcareous siltstone and shale, and lesser limestone/dolostone. The Middle Devonian is marked by intermittent volcanism (Macmillan Pass volcanic suite), and black siliceous shale and chert deposition (Sapper Formation and Portrait Lake Formation–Niddery Lake Member). The Macmillan Pass volcanic suite is an informal stratigraphic term to describe carbonate-altered alkalic mafic volcaniclastic rocks that occur in at least two stratigraphic intervals: at the contact between the Earn and Road River Groups, and within the Macmillan Pass member, Portrait Lake Formation, Earn Group. During the Late Devonian, the North American margin transitioned to an active convergent margin (Nelson *et al.*, 2006) and the Mac Pass region experienced back-arc extension marked by normal faults and the deposition of the Earn Group coarse clastic sequence (chert pebble conglomerate of the Portrait Lake Formation–Macmillan Pass Member; Abbott and Turner, 1991). Sub-seafloor replacement of barite by sphalerite and galena occurred during Late Devonian time, resulting in formation of the Tom and Jason Zn-Pb-Ag ± Ba deposits (Magnall *et al.*, 2020). This mineralization event was occurring during a background of siliceous shale and chert deposition of the Fuller Lake Member (Portrait Lake Formation). Strata of the Selwyn basin region were later incorporated into the Mesozoic Cordilleran fold and thrust belt. In the study area, major Mesozoic right lateral strike slip faults (Macmillan and Hess fault zones; Fig. 2), that reflect pre-existing Devonian rift structures, divide the area into the North, Central and South blocks (Abbott, 1983; Abbott and Turner, 1991. The new data presented in this paper are from the Central Block, also the location of all Macmillan Pass Devonian Zn-Pb-Ag deposits, although some of the older conodont samples derive from the North Block (Fig. 2).

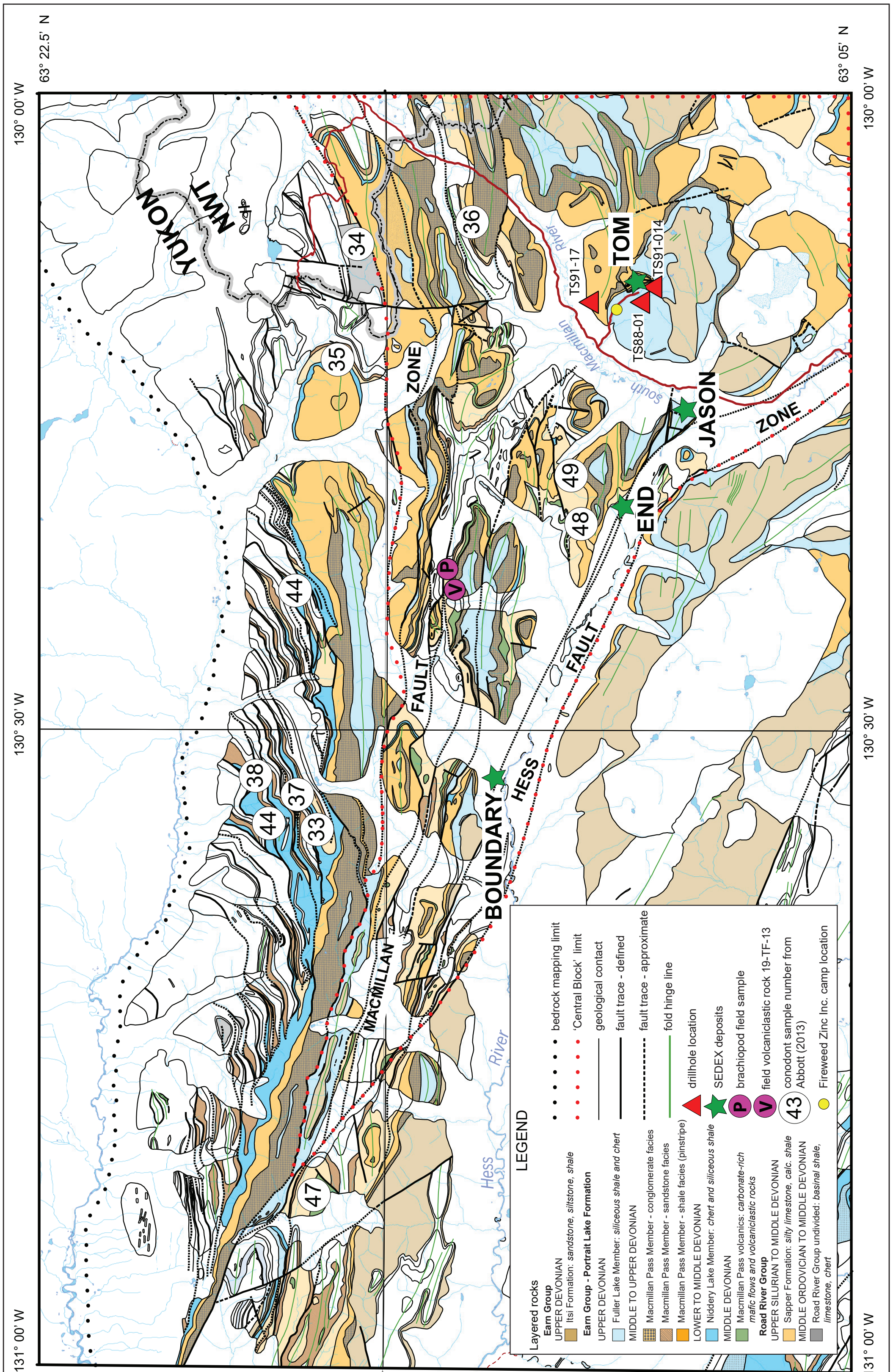

Figure 2. *Simplified geology map of Macmillan Pass area highlighting Devonian strata and the location of the 'Central Block' (after Abbott, 2013). Locations of the Zn-Pb-Ag deposits, drillholes and field data presented in this paper are included.*

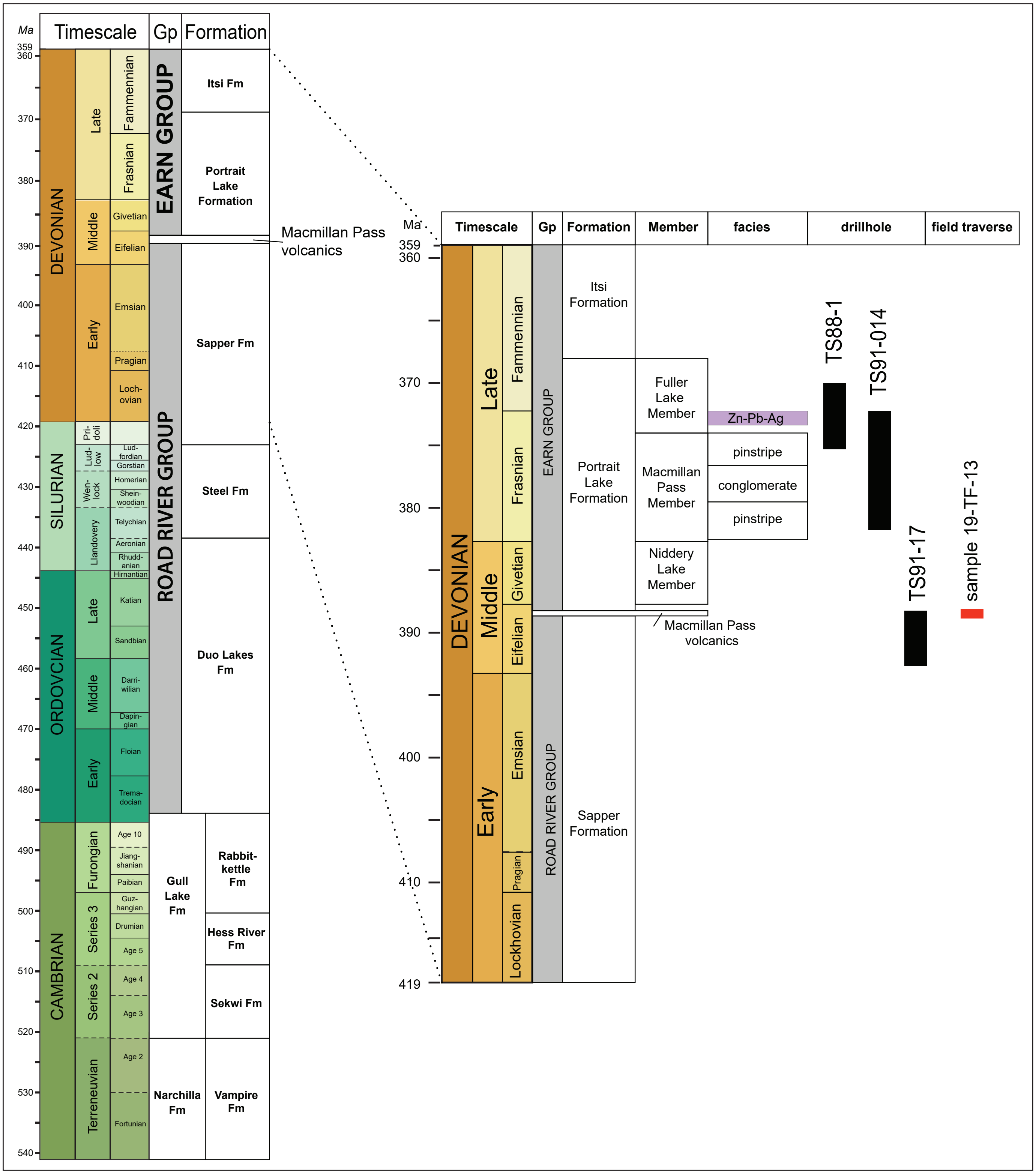

Figure 3. *Chronostratigraphy of the Devonian units at the Jason deposit, Macmillan Pass, Yukon, highlighting the Devonian section (after Abbott, 2013). Drillhole and field traverse strata examined in this study are highlighted. Geological timescale from Gradstein et al., (2012).*

Methods

Core logging and lithogeochemistry

Core looked at for this reconnaissance study are from holes drilled on the Tom property and include T88-1 (63.1553°N, -130.1535°W), TS91-17 (63.1760°N, -130.1765°W), and TS91-014 (63.1585°N, -130.1504W; Fig. 2), and were chosen because they covered extended parts of Devonian basinal rocks. Core was logged onsite; however, boxes 1–16 of TS91-014 are stored at the YGS Bostock Core Library in Whitehorse and were logged there. The focus of the study was to sample Devonian shale intervals to evaluate background shale lithogeochemistry, and therefore finer grained intervals were sampled and analyzed. Sample spacing was in 2 m increments for holes T88-1 and TS91-17 (n = 73 and 15, respectively), and 1 m for TS91-14 (n = 53). Whole rock lithogeochemistry, including total organic content for shales, was conducted at Bureau Veritas in Vancouver, BC using ICP-ES and ICP-MS instrumentation. Selected geochemical profiles that assist with paleoenvironmental interpretation such as terrestrial sediment source, proximity to carbonate platforms and continental shorelines, redox conditions and organic matter preservation, and relative sea level are presented in the results section. Geochemical results are provided in the Appendices.

Fifty-three shale samples from drillhole TS91-17 were analyzed for organic carbon isotope signatures at the Pacific Centre for Isotopic and Geochemical Research, Department of Earth Ocean and Atmospheric Sciences, The University of British Columbia, Vancouver, with a mass spectrometer. Carbon isotopic values are normalized to the Vienna PeeDee Belemnite (V-PBD).

Twenty-nine thin sections were made from the drill core, however, these were mainly limited to coarser grained intervals due to rock competency. Thin sections were prepared at Vancouver Petrographics using standard procedures.

The use of paleoenvironmental proxies

This study focuses on a subset of geochemical data used to ‘blueprint’ relatively monotonous shale intervals and to make high-level paleoenvironmental interpretations about their deposition. Proxies for terrestrial input used to distinguish relative proximity to a continental shoreline include the relationship between SiO_2 (%) and Zr (ppm) and the terrestrial input parameter (TIP; %) which is the sum of Al_2O_3, TiO_2, Na_2O and K_2O (%; after Hildred and Rice, 2012). These proxies assume that Zr and the oxides of Al, Ti, Na, and K are land-derived and immobile during diagenesis (Hildred and Rice, 2012; Tribovillard *et al.*, 2006), and that their relative increase/decrease can be related to sea level fluctuations and proximity of the basin to shoreline. A cross-plot of SiO_2 *vs.* Zr can indicate either a terrestrial source for the silica or a biogenic source, for positive and negative covariations, respectively. A high biogenic silica content in the sediments can indicate high bioproductivity in the water column by organisms that secrete silica tests (*e.g.*, radiolarian) and a low input of silica from terrestrial sources *i.e.*, further offshore. These terrestrial and silica source proxies would not apply in strata overwhelmed by a Zn-Pb-Ag mineralizing event, as silica can be sourced via hydrothermal inputs and oxides can be mobilized, thus erasing primary depositional characteristics (*e.g.*, Magnall *et al.*, 2015).

Redox conditions in sea bottom waters and degree of organic matter preservation can be cautiously identified from the total organic carbon content (TOC; weight %), under the premise that organic material is preserved under reducing conditions. Further, the enrichment factor (Ef) of Mo (*i.e.*, Mo normalized to Al using the formula $(Mo_{sample}/Al_{sample})/(Mo_{average\ shale}/Al_{average\ shale})$ from Tribovillard *et al.*, 2006) can be used to indicate redox conditions as Mo becomes relatively immobile and authigenically enriched as its solubility falls in oxygen-depleted water (Algeo and Rowe, 2012; Tribovillard *et al.*, 2006). Proxies for carbonate content, which can be used to indicate proximity to carbonate sediment sources, include CaO (%) and MgO (%); however distinguishing between primary and secondary carbonate is essential.

The marine $\delta^{13}C_{org}$ curve presented is used in an attempt to date and correlate Macmillan Pass Sapper Formation sediments to strata in other parts of Selwyn basin and beyond. The ratio of $^{13}C/^{12}C$ in the oceans and recorded in basinal sediments varies through time, and there are time intervals where well documented excursions, either positive or negative, have been identified regionally and/or globally (*e.g.*, Saltzman and Thomas, 2012). The Devonian Period has several excursions, often associated with extinction events (*e.g.*, basal Lochkovian positive excursion, late Eifelian Kačák-*otomari* negative excursion, Frasnian–Famennian Upper and Lower Kellwasser positive excursion events, and the terminal Devonian Hangenberg positive excursion; Saltzman and Thomas, 2012). A $\delta^{13}C_{org}$ excursion could indicate higher ocean bioproductivity and/or organic matter preservation as a result of high sea level, as the ratio of $^{13}C/^{12}C$ the ocean increases when there is a net deposition of organic matter globally (Saltzman and Thomas, 2012). Conversely, a negative $\delta^{13}C$ excursion could represent lower ocean bioproductivity and/or lower organic matter preservation because of relative sea level regression, as the $^{13}C/^{12}C$ ratio in the ocean will decrease when there is a net oxidation of organic matter globally. However, interpreting sea level from this limited data set beyond the immediate region is challenging.

Field transect

Thirteen kilometres northwest of the Tom property, a field traverse through Sapper Formation and Macmillan Pass volcanic suite rocks investigated uppermost Road River strata in the region (Fig. 2). One sample of volcaniclastic rock (63.2282°N, -130.3811°W) was analyzed for whole rock geochemistry at ALS Minerals using XRF, ICP-AES and ICP-MS techniques. A Devonian brachiopod sample from the upper contact of the Sapper Formation was submitted to Robert Blodgett, Anchorage, AK, for identification.

Conodont biostratigraphy

Eleven slides made for conodont identification and reported in Abbott (2013; Fig. 2) were re-examined as part of this reconnaissance study. These samples were processed previously in the Geological Survey of Canada's paleontological laboratory in Calgary, and were retrieved from the archives for this study. The samples examined are of Middle Devonian age, from the Sapper Formation (n = 2), the Portrait Lake Formation (Niddery Lake Member; n = 8) and a shale clast in the Macmillan Pass volcanic suite (n = 1). This particular age range was selected to assist in correlation of this time interval to other areas in Selwyn basin and Richardson trough, the focus of previous and ongoing YGS shale research.

Lithology and geochemistry of drill core

TS88-01

Lithology

Drillhole TS88-01 is collared in the Fuller Lake Member (Portrait Lake Formation) rocks, transects Zn-Pb-Ag mineralization between 524 and 554 m depth and terminates at a depth of 649.8 m in the Macmillan Pass Member shale facies (Portrait Lake Formation; Fig. 4a). The Macmillan Pass Member is mainly rhythmically interbedded packages of fining upwards fine to very fine sandstone and siliceous siltstone and shale. The colour of the weathered surface is alternating brown/red (sandstone), medium grey (siltstone) and black (shale) which gives the unit a striped appearance (sometimes called the 'pinstripe' unit; Fig. 4b). Overall this unit is well indurated and core is competent, although there are some more rubbly sections which are fractured. Pyrite cubes are visible in sandier intervals (Fig. 4b), and disseminated pyrite is observed in shale sections. Individual fining upward intervals are variable but are mainly 5 to 10 cm thick, beginning with a basal sandstone that scours into underlying shale, and occasionally displays flame and load structures (Fig. 4b), fining upwards to siliceous siltstone and shale. Sandstone becomes less prominent towards the top of the member.

The Fuller Lake Member is dominated by siliceous shale and radiolarian chert, with lesser siltstone and minor fine to medium sandstone. The strata occur in rhythmically fining upward packages of silty siliceous shale to shale (or sandstone to shale in minor instances), generally 5 to 15 cm thick. The chert and shale are black on fresh surfaces, and weather medium to dark grey.

Weathered faces and fractures are sometimes coated with a yellow or green, and locally a light blue, weathering residue. In sandier sections, the core weathers orange/brown. Sandstone comprises mainly quartz, chert and lithic grains, is poorly sorted, and is cemented by carbonate with lesser quartz and locally with pyrite. Overall the core is competent; however, there are minor fractured intervals, and intervals of recessive, very soft, wafer-thin shale at the top of some fining upward intervals. Disseminated, nodular and laminated pyrite occurs throughout the member. Minor brecciated fault sections occur particularly in the upper 250 m of the hole.

A Zn-Pb-Ag mineralized zone in the lower Fuller Lake Member is 26 m thick and occurs as laminated barite, sphalerite and pyrite, with >5% interlaminated shale (Fig. 4c). Barite is white to yellowish white in colour, and where laminated with sphalerite, it is pink and light brown. Laminae are crenulated to wavy in appearance. The lower and upper contacts of the mineralized zone are gradational where barite laminae increase/decrease over ~30 cm thicknesses, respectively.

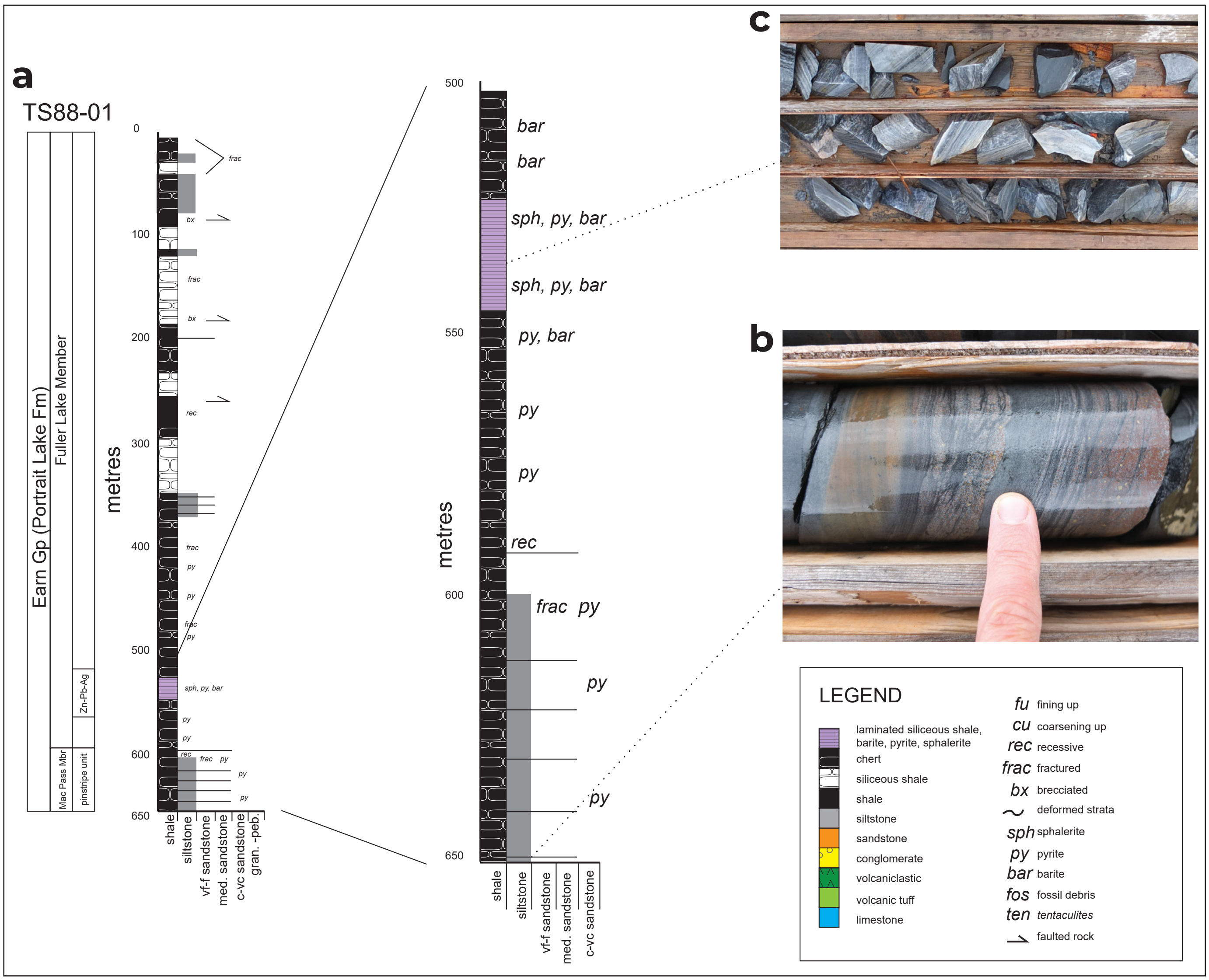

***Figure 4. (a)** Lithology log of the TS88-01 core. **(b)** Strata from the Macmillan Pass Member ('pinstripe unit') at the base of the core (643.2 m). Note the weathering colour of the sandstone (red), siltstone (orange) and shale (dark grey to black), which gives the core a unique striped appearance. Finger is pointing just below the base of a fining upward unit of sandstone to shale, where loading of sandstone onto shale is apparent. **(c)** Laminated barite, shale and sphalerite from the Zn-Pb-Ag mineralized unit (530 m).*

Geochemistry

Whole rock geochemistry was conducted on samples collected between 509 and 650 m (Macmillan Pass and Fuller Lake members, including the Zn-Pb-Ag zone). Selected geochemical data are shown in Figure 5 and a full data set is offered in Appendix A. The Macmillan Pass Member pinstripe unit (596–649.8 m) has an average of 73% SiO_2, 143 ppm Zr and a TIP of 15%. While SiO_2 values remain constant throughout the unit, Zr and TIP values overall decrease towards the top of the unit. Total organic content averages 1.3 wt% and values increase in the upper 2 m of the unit. The Ef Mo averages 7.2; values are more than double the average in the upper 2 m. Carbonate content in the unit is low; CaO and MgO average <1%, with a very slight increase in the interval 622–628 m. Elements associated with mineralization in this unit including Ba, Zn and Pb are low, averaging 0.6%, 7 ppm and 27 ppm, respectively.

The lower Fuller Lake Member (556–594 m) averages 75% SiO_2, 92 ppm Zr and 9% TIP, and all values decrease towards the top of the unit. TOC averages 3.8% with the highest value of 6.4% in a recessive, sooty shale unit at 590.6 m. Overall, TOC decreases slightly towards the top of the unit. The Ef Mo values average 29 and trend overall higher toward the top of the unit. Carbonate content is very low at <1% for both CaO and MgO. Elements associated with mineralization all increase significantly moving up in the lower Fuller Lake Member. Both Ba and Zn increase from minimal values to the upper limits of the instrumentation detection (5% and 10 000 ppm respectively) and Pb trends from <100 ppm to >300 ppm in the top 6 m in the unit.

The Zn-Pb-Ag mineralized interval (523–556 m) has an average of 29% SiO_2, 33 ppm Zn and 2.5% TIP, which are the lowest values of the strata measured in the core in this study. These values are not credible for use as proxies, as their presence does not represent primary

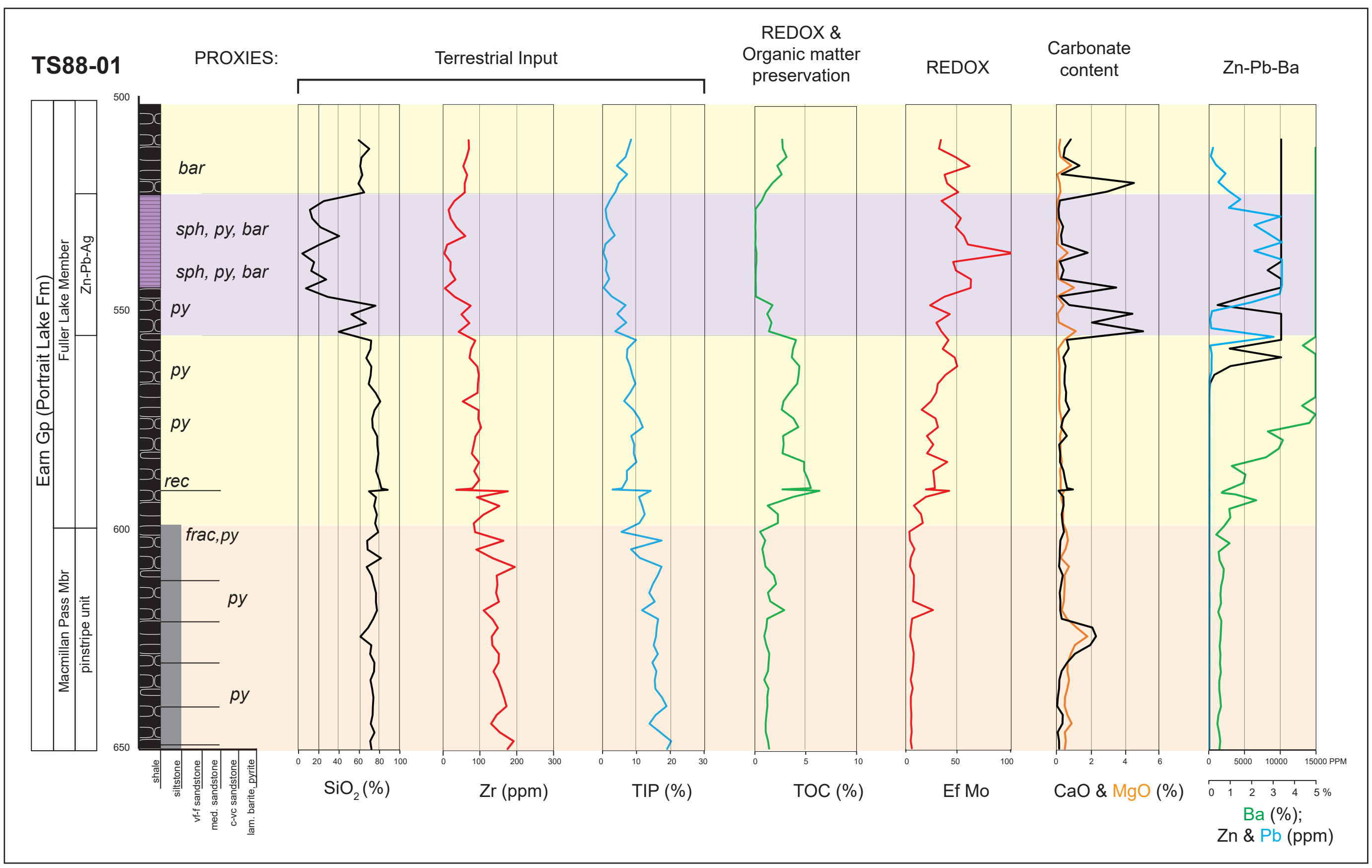

Figure 5. *Selected lithogeochemistry from the TS88-01 drillhole.*

depositional conditions. TOC values are also very low, averaging 0.5% while Ef Mo measures 49 with a peak value of 103 at 536 m. Carbonate content peaks in the base of the section at 51% CaO and 1.1% MgO, and trends downwards towards 0.2 and 0.1%, respectively, at the top of the unit. For elements associated with mineralization, Ba is consistently >5%, all but three samples of Zn are >10 000 ppm, and Pb is more variable, pushing the upper limits of the instrument at 10 000 ppm in five samples or being as low as 164 ppm. While Ba and Zn remain consistently high over the contact with the overlying Fuller Lake Member shale, Pb concentrations trend downward.

The upper Fuller Lake Member (510–523 m) averages 63% SiO_2, 63% Zr, 6.1% TIP and 2.3% TOC, all lower values than in the lower Fuller Lake Member below the Zn-Pb-Ag interval. Ef Mo is 43 and carbonate content decreases from 3.0% at the base to <1% at the top of the section, averaging 1.6%. MgO values are all <1%. Ba and Zn levels are all above the instrumentation thresholds of 5% and 10 000 ppm, respectively, and Pb declines from base to top from 4288 to 554 ppm, with an overall average of 1747 ppm.

SiO_2 and Zr values were plotted against each other to assess the source of silica and proximity to paleoshorelines. Zr is assigned as a proxy for a terrestrial source, whereby a positive SiO_2 vs. Zr relationship is suggestive of a land source for the silica and a negative relationship suggestive of a biological source, e.g. radiolarian, from within the water column (*e.g.*, Wright et *al.*, 2010; Fraser and Hutchison, 2017). The plotted data, grouped according to unit, are presented in Figure 6a. A strong positive trend ($R^2 = 0.90$) is shown for the mineralized interval, which is best interpreted as a “terrestrial + hydrothermal” silica source. A weak terrestrial trend occurs for the upper Fuller Lake Member ($R^2 = 0.16$), a weak biogenic trend is shown for the lower Fuller Lake Member ($R^2 = 0.21$), and no trend was noted for the Macmillan Pass Member ($R^2 = 0.06$).

TS91-014

Lithology

Drillhole TS91-014 is collared in a Zn-Pb-Ag mineralized zone of the lower Fuller Lake Member (Portrait Lake Fm) and terminates at a depth of 522.4 m in the Macmillan Pass Member shale (‘pinstripe’ unit; Fig. 7a). This core was logged to a depth of 394.8 m as strata below this are duplicated by faulting. The Macmillan Pass Member shale interval occurs as rhythmically interbedded packages of fining upwards, fine to very fine sandstone, siltstone and shale between 100 and 394 m depth. Sandstone intervals weather orange/red/brown, siltstone weathers medium grey and red, and shale weathers dark grey, and weathering gives the unit a striped appearance (Fig. 7b). Cycles are variable in thickness, mainly 2–30 cm thick, and are generally dominated by siltstone and silty shale, however, sandstone comprises 5–30% of the cycles. Siltstone and shale are planar laminated, and sandstone may be cross-laminated. Sandstone and siltstone grains are chert and quartz, which are cemented with carbonate. Cycle bases, particularly where sandstone is present, are often erosive and may show flame and load structures. The core is competent with brecciation of some faulted intervals. Pyrite is abundant, particularly in sandstone intervals, although it can be observed in all lithological units as nodules, laminae or dissemination.

A 2.5 m thick interval of chert pebble conglomerate with carbonate cement occurs at a depth of 142.35 m; which fines upward to coarse-grained sandstone. The Macmillan Pass Member conglomerate facies proper occurs as a thick interval between 49.8 and 100 m depth. The conglomerate is dominated by pebble-sized chert and lesser quartz and lithic (sandstone, siltstone, shale) clasts with localized cobbles (6 cm maximum clast length observed). Chert grains are black, grey and white, and quartz grains are white. Clasts are mainly subangular to subround. Sorting is poor, and both matrix and clast-supported strata occur (Fig. 7c). Chert pebble clasts in a deformed shale matrix with up to 20% sparry carbonate matrix and pervasive pyrite mineralization mark the basal contact of the Macmillan Pass Member. The contact appears relatively sharp and is interpreted as conformable.

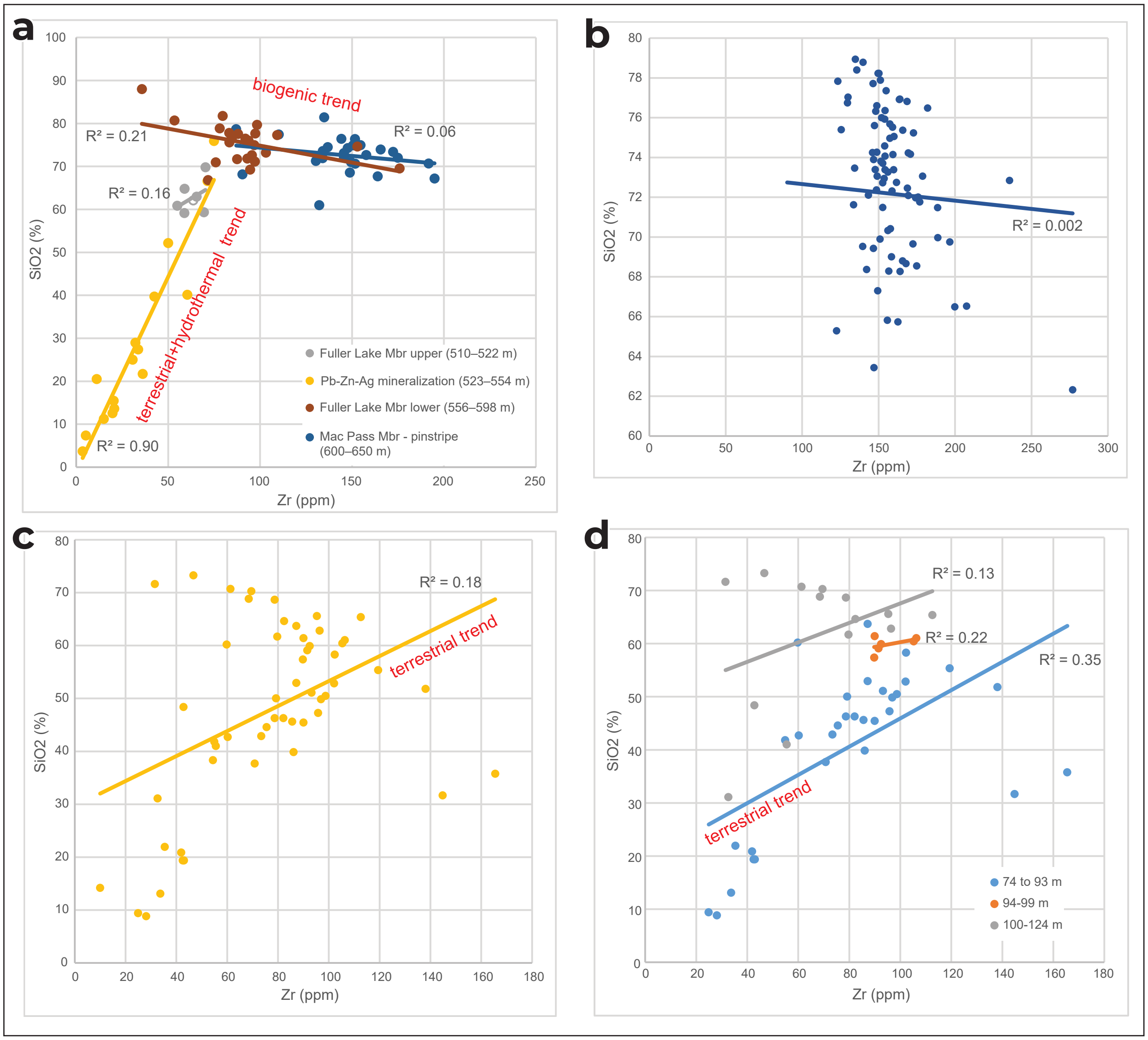

***Figure 6.** SiO_2 versus Zr cross-plots for the **(a)** TS88-01 drillhole; **(b)** TS91-014 drillhole; **(c)** TS91-17 drillhole (full data set); and **(d)** TS91-17 drillhole (divided data set).*

The Fuller Lake Member is a variably siliceous, black, laminated shale. Its lower contact is characterized by brecciated to stratified shale with abundant pervasive pyrite. The contact zone is unconsolidated, appears weathered or rotten, and has abundant grey and brown mineral precipitate. Below the Zn-Pb-Ag interval, the Fuller Lake shale has abundant pyrite, both laminated and pervasive, and is crosscut by ≤1 cm thick barite veins. The Zn-Pb-Ag unit is hosted by laminated shale and comprises wavy/crenulated laminae of shale, pyrite, sphalerite and barite, which occur as black, green, pink and white laminae, respectively (Fig. 7d). Small, synsedimentary faults and dewatering structures are observed. Shale becomes more dominant towards the upper part of the mineralized unit (Fig. 7e) and grades into a black, laminated siliceous shale that is unconformably overlain at surface by a post-glacial, Holocene thin (<1 m) unit of iron-stained ferricrete pebble conglomerate.

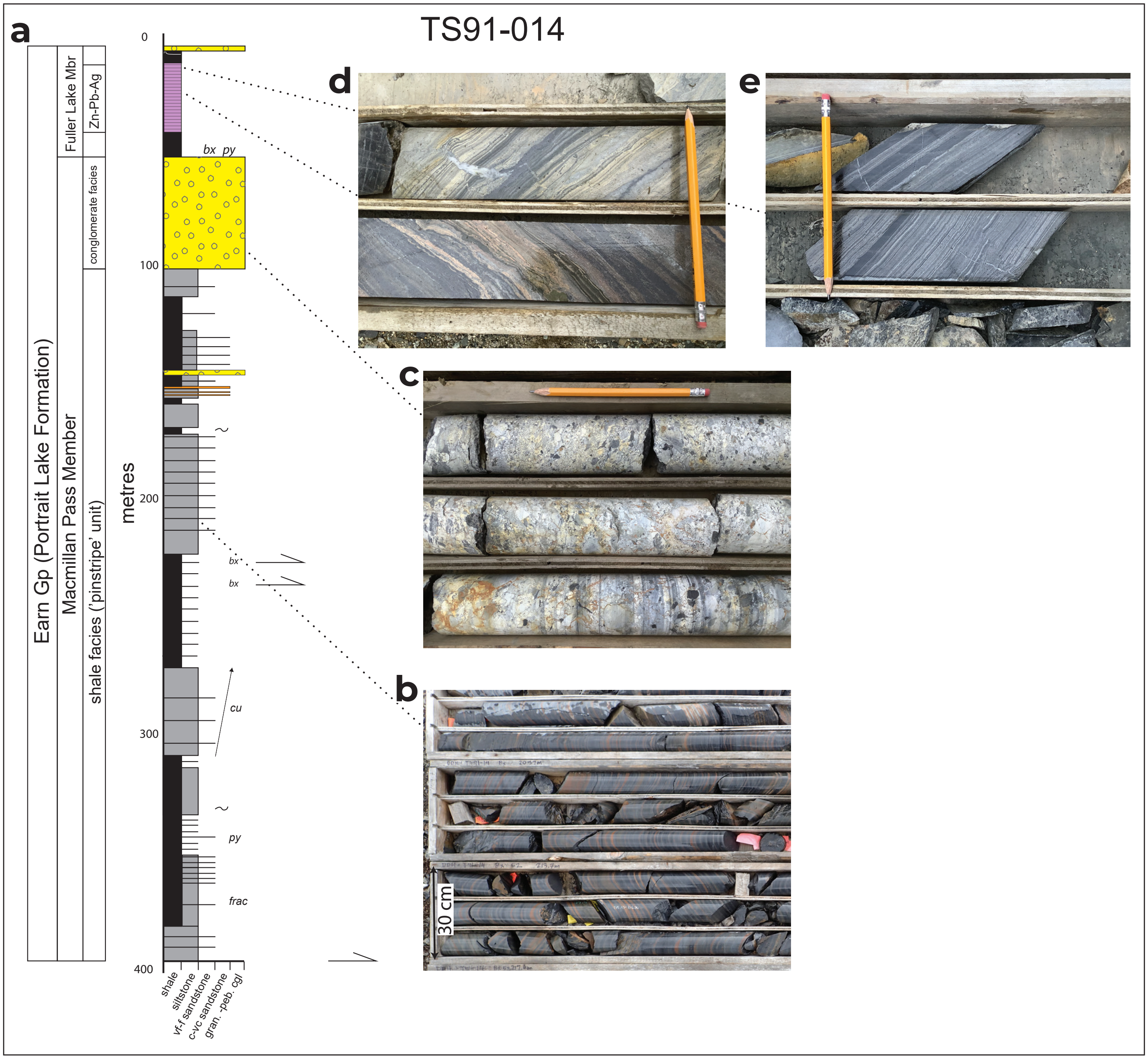

Figure 7. (a) *Lithology log of the TS91-014 core. Legend in Figure 4.* ***(b)*** *Macmillan Pass Member shale facies, showing 'pinstriped' nature of the core due to the interbedding of iron-oxidized sandstone and siltstone with shale (red and black laminae, respectively).* ***(c)*** *Chert pebble conglomerate of the Macmillan Pass Member conglomerate facies.* ***(d)*** *Stratified shale, pyrite, sphalerite and barite in the Fuller Lake Member, laminated pink-grey facies.* ***(e)*** *Stratified shale and barite in the uppermost laminated black facies as it grades upsection to a siliceous shale.*

Geochemistry

Geochemical analyses were conducted on samples collected between 103.6 and 394.0 m in the Macmillan Pass Member–pinstripe unit (Fig. 8). SiO_2 ranges from 54 to 79% with an average of 72%, and values become slightly more enriched near the top of the unit. Zr averages 157 ppm and ranges from 90 to 277 ppm. Zr enrichment is slightly elevated in the intervals between 286 and 210 m and 360.1 and 370 m; it is reduced in the upper part of the unit between 103.6 and 130 m. TIP values average 16%, ranging from 7 to 28%, with a very slight overall decrease towards the top of the unit. Average TOC values are very low in this unit at 0.8% with all but six values <1%; slightly higher values are observed in the top 47 m of the section. Ef Mo increases gradually from the base to the top of the unit and averages 3.2. Carbonate content is low at <1% with some slightly higher values associated with siltier intervals (e.g., 162 m, 186 m, 210 m and intermittently between 314 and 382 m). Ba concentration is constant throughout the interval averaging 0.3%. Zn concentration is below 180 ppm and is cyclical in nature with the highest value of 180 ppm at 114 m. Pb concentration shows an overall increasing trend upsection with a maximum value of 65 ppm at a depth of 134 m.

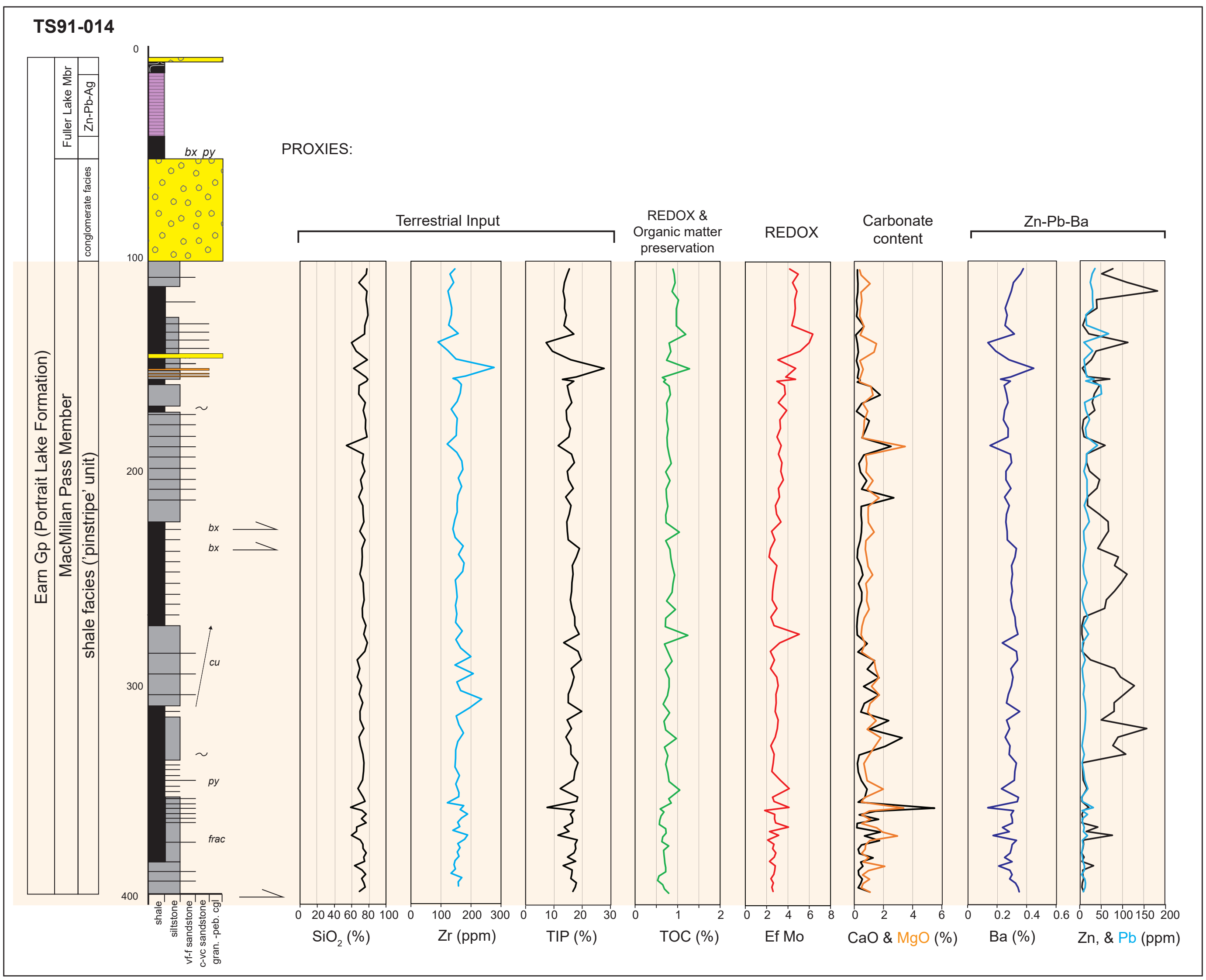

Figure 8. *Selected lithogeochemistry from the TS91-014 drillhole. Legend as in Figure 4.*

The SiO_2 versus Zr plot shows a scatter with no detrital or biologic trend for the silica (Fig. 6b). It is possible that plotting of specific intervals (e.g., fine grained or coarse grained) may indicate shorter episodes of one or the other but this level of detail is beyond the scope of this reconnaissance work.

TS91-17

Lithology

Of the core evaluated, hole TS91-17 covers the oldest stratigraphy. The hole is collared in the Macmillan Pass volcanic suite and terminates at a depth of 127 m in wackestone and micrite of the Sapper Formation (Road River Group; Fig. 9). Organic-rich interlaminated shale/mudstone, lesser siltstone and very minor fine sandstone characterize the Sapper Formation in this hole. Shale/mudstone is mainly dark grey to black on fresh surfaces, weathers dark grey and sometimes bluish-black, and varies between competent and very recessive and sooty. Shale is fissile while mudstone has no visible sedimentary structures. These fine-grained strata are often variably siliceous or calcareous, interbedded, especially towards the upper part of the unit. Siltstone is medium grey on fresh surfaces, weathers green and greenish-grey and is competent. Shale and siltstone are laminated in normally graded rhythmic successions. Mudstone has no visible sedimentary structures. Interbedded wackestone and micrite occur in the lower 2.5 m of the core (Fig. 9b). Wackestone contains fossil debris including crinoids, bivalves and bryozoans, and micrite is laminated with localized small fossil fragments.

The Sapper Formation is sharply overlain by the Macmillan Pass volcanic suite (Fig. 9c), which in this hole occurs as volcaniclastic rock comprising vesicular basalt clasts cemented by carbonate (Fig. 9d). This rock is resistant, medium grey on fresh surfaces and weathers greenish grey with variable brown/orange-staining. Basalt clasts are poorly sorted, range up to 15 mm in length (pebble-sized), and vary from angular to subround. The rock may be either matrix or clast-supported. The proportion of sparry carbonate cement is up to 85%, which also infills vesicles in basalt. The basal contact is sharp with the bottom 5 cm of the unit incorporating shale clasts. A 10 cm tuffaceous interval occurs at a depth 70.0 m, which is dark grey on fresh surfaces and weathers greenish-grey with a white and orange powdery residue. This tuff is very porous and forms a sharp contact, possibly a chilled margin, with the under and overlying volcaniclastic rocks.

Geochemistry

Systematic geochemical analysis was performed on the Sapper Formation up to its upper contact with the Macmillan Pass volcanic suite (Figs. 10 and 11). SiO_2 averages 48%, ranging from 9 to 73%. Higher SiO_2 values generally occur below 94 m, although not consistently. SiO_2 negatively correlates with CaO ($R^2 = 0.8$) showing an alternating pattern of siliceous shale interbedded with calcareous shale. These cycles are thicker below 94 m (e.g., 5–7 m thick) and thinner between 74 and 94 m (e.g., up to 2 m), although in some instances this may be an artifact of sample spacing. Zr values average 77 ppm with the highest values in the uppermost 4 m. A cross-plot of SiO_2 vs Zr shows that all samples trend weakly towards a terrestrial silica source ($R^2 = 0.18$; Fig. 6c), with samples becoming more strongly correlated in the upper parts of the hole at 74 to 93 m ($R^2 = 0.35$ vs 0.22 for samples from 94–99 m and $R^2 = 0.13$ for samples from 74–93 m; Fig. 6d). TIP values are <10% between 100 and 126.5 m, average 18% from 93–100 m, and average 10% in the upper part of the hole between 74 and 93 m. Average TOC for the data set is 4.7% with extremely high values of 8.1, 12.4 and 10.4% (average) associated with sooty, recessive shale intervals at 112, 84 and 74–75 m, respectively. Ef Mo values covary with TOC ($R^2 = 0.5$); the highest values (>200 ppm) occur from 120–123 m, 112, 84 and 74–75 m. Carbonate content is highest (>20%) in the lowermost 2 m of the section, is <20% between 93 and 125 m, and is variably high (maximum 47%) and low (minimum 4%) in the upper ~one-third of the data set (74–93 m). Ba averages 0.3% with a notable high value of 2.6% in a recessive shale at 106 m. Zn is mostly <30 ppm with exceptions up to 123 ppm associated with sooty shale intervals at 112, 84 and 74–75 m and a cherty shale at 88 m. Pb values average 43 ppm and range from 3–89 ppm. Ni is plotted with this data set as a redox sensitive element, which shows an overall increase in trend towards the top of the section, particularly in the

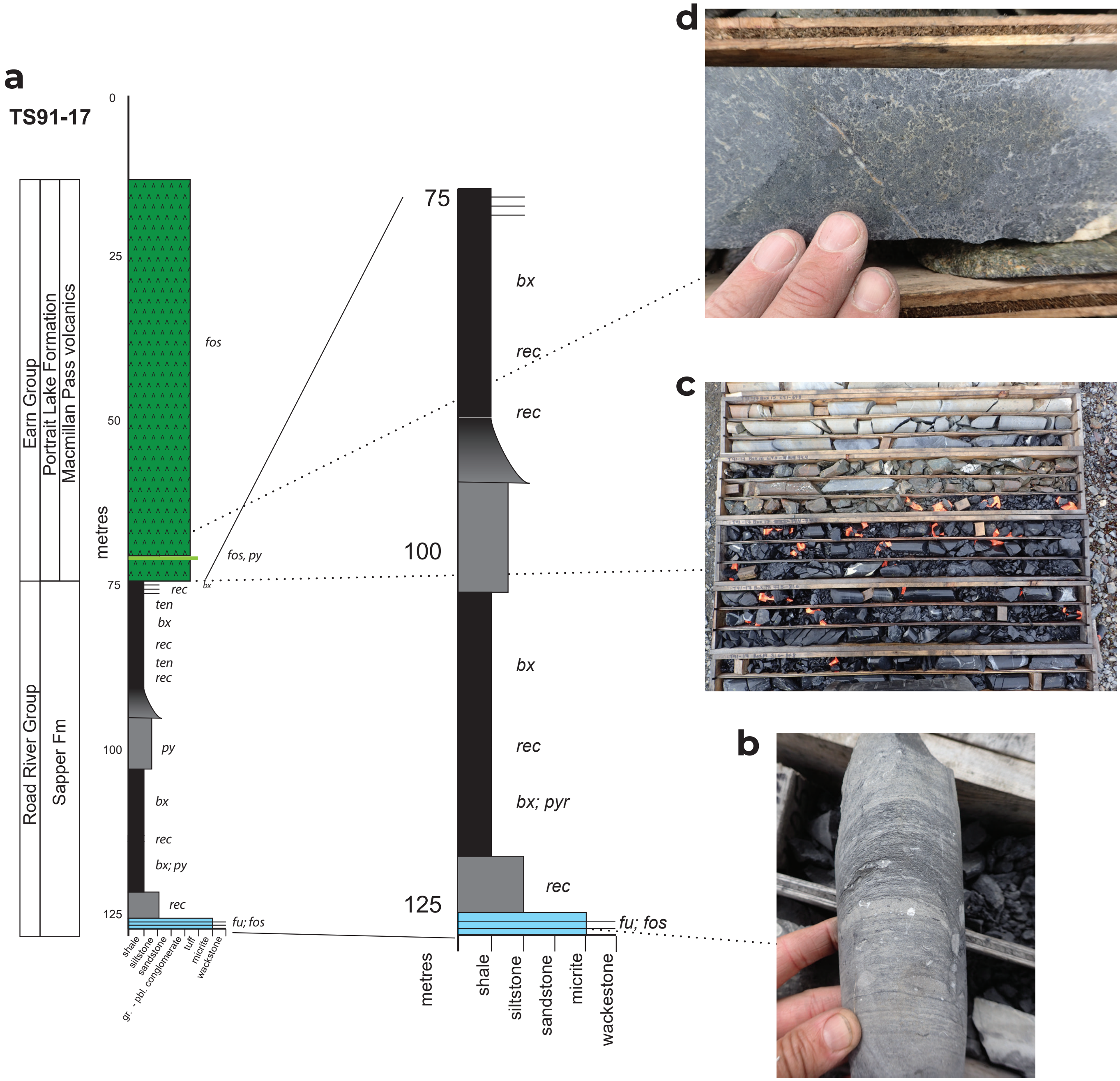

Figure 9. ***(a)*** *Lithology log of the TS91-17 core. Legend in Figure 4.* ***(b)*** *Micrite and fossiliferous wackestone at the base of the TS91-17 drillhole (124 m).* ***(c)*** *Contact zone between the Sapper Formation (black rocks in bottom two core boxes) and Macmillan Pass volcanic suite (grey rocks in upper two core boxes).* ***(d)*** *Close-up of volcaniclastic rocks from the Macmillan Pass volcanic suite (72 m).*

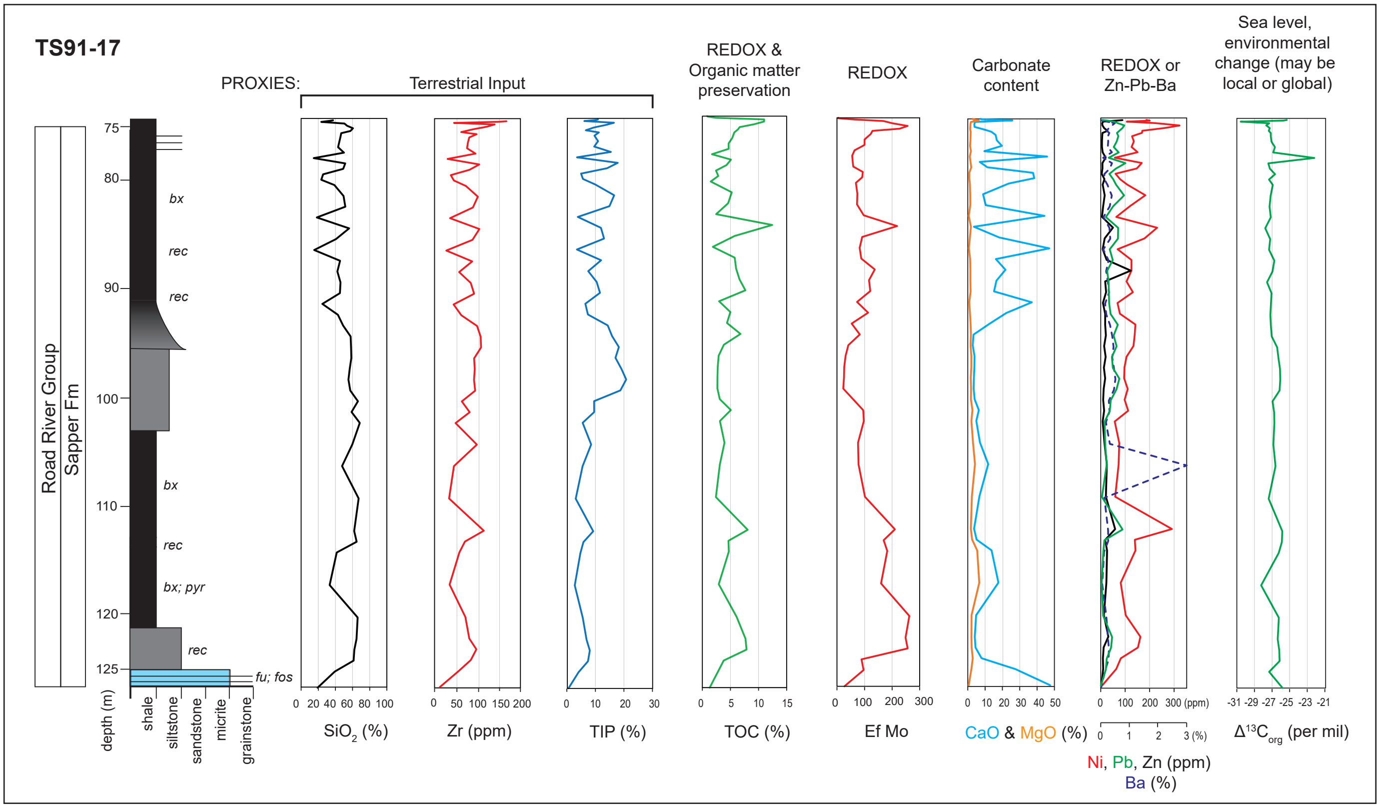

Figure 10. Selected lithogeochemistry from the TS91-17 drillhole. Legend as in Figure 4.

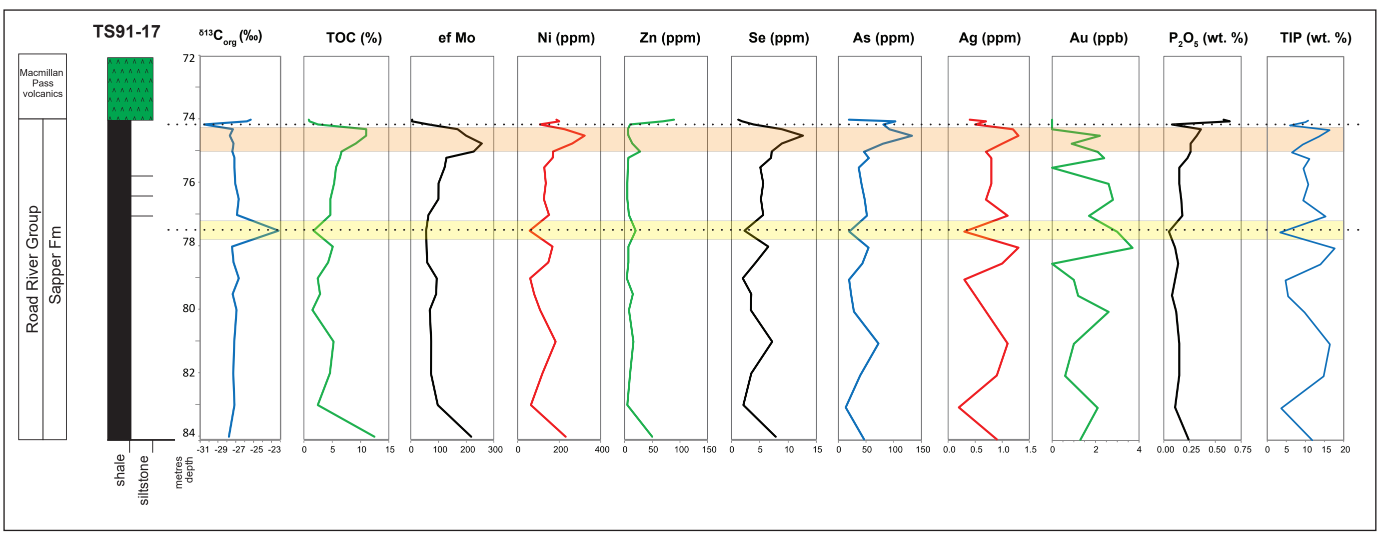

***Figure 11.** Geochemistry of the uppermost Sapper Formation from the TS91-17 drillhole. The orange highlighted box indicates the interval of enhanced trace element concentrations in the uppermost Sapper Formation, which immediately precedes a prominent negative 3.5‰ $\delta^{13}C_{org}$ excursion. The yellow highlighted box indicates the interval of lower trace element values and a positive 4.8‰ $\delta^{13}C_{org}$ excursion.*

upper 12 m (74–86 m). Ni spikes occur in sooty shale at 112 and 74.5 m (231 and 323 ppm, respectively). $\delta^{13}C_{org}$ values hover at -27‰ (average of -26.8). There are notable excursions in the uppermost part of the section including a positive one at 77.5 m (-22.2‰), and a negative/positive one at 74.15–74.0 m (-30.56‰ and -25.32‰). More minor excursions occur at 117 m (-28.24‰), 113 m (-25.89‰) and 97 m (-26.1‰).

Details of the trace element geochemistry (Ef Mo, Ni, Zn, Se, As, Ag, Au P_2O_5), TOC, TIP (%) and $\delta^{13}C_{org}$ values from the upper 10 m of the Sapper Formation are shown in Figure 11. There are significant concentration fluctuations in many of the data sets but the overall trend shows an up-section increase in elemental, TOC and TIP concentrations toward the upper contact with the overlying Macmillan Pass volcaniclastic rocks. In contrast, the $\delta^{13}C_{org}$ data show a relatively stable background state of ~-27‰, with a large positive excursion of 4.8‰ at 77.5 m and a prominent negative excursion of 3.5‰ at a depth of 74.15 m. The 77.5 m positive $\delta^{13}C_{org}$ excursion is associated with lower values in all trace elements, TIP, and TOC, except for Zn and Au (yellow highlighted section on Fig. 11). The negative excursion at 74.15 m is associated with a relative depletion in all elements, TOC and TIP, but interestingly is immediately preceded by prominent concentrations in all trace elements (except for P_2O_5 and Zn, which have subdued peaks), TIP and TOC (orange highlighted box on Fig. 11).

The Macmillan Pass volcanic/volcaniclastic rocks were not systematically analyzed from this hole; however, a field sample from immediately above the Sapper Formation contact (19-TF-13; 63.22817°N; -130.38109°W) was submitted for whole rock geochemistry (Fig. 12). The full geochemical data set is provided in Appendix D (sample ID 19-TF-13). The sample is pervasively altered to carbonate (19% CaO; 8% MgO) and has a loss on ignition of more than 15%, rendering the trace element concentrations (especially rare earths) unsuitable for interpretation of primary tectonic processes due to element mobility.

Figure 12. *Outcrop of Macmillan Pass volcanic suite (19-TF-13; 63.22817°N, -130.38109°W).*

Paleontology

Table 1 reports the samples re-examined for conodont zonal refinement[1] and includes Map ID numbers from Abbott (2013) for easy correlation to the bedrock map (Fig. 2; Abbott, 2013). Figure 13 displays the conodont biozonation ranges for each re-examined sample. All samples, except three, show some refinement to the age, albeit minor in some cases. Conodont biozones for two samples from the upper contact of the Sapper Formation range from *australis* to *ensensis* zones (middle–late Eifelian). The stratigraphically lowest Niddery Lake Member samples (Abbott, 2013; Nos. 33, 34, 35, 36) also cover some or all of this same range, with No. 33 ranging up to the *ansatus* (middle *varcus*) zone. Samples within the Niddery Lake Member (*i.e.*, not at the lower contact) range from *costatus* to *varcus* zones (latest Eifelian to early Givetian; Nos. 43 and 37), although two are much older *nothoperbonus-inversus* (No. 38) and *inversus*-*costatus* zones (No. 44) which

1 Note that a full description of conodont fossils is offered in Gouwy, 2020, available through the Yukon Geological Survey.

are Emsian and Emsian–Eifelian, respectively. It is important to note that the No. 38 sample was submitted with a (?)Road River designation so it may not be actually Niddery Lake Member. Samples 38 and 44 occur within the same bedrock polygon in Abbott (2013), which may suggest that the contact was approximated in the area, and that the samples actually are from the older Road River Group (Sapper Formation).

A single ventral valve of brachiopod collected from the contact between the Sapper Formation and Macmillan Pass volcanic suite is tentatively identified as *Spinatrypina*? sp. (Fig. 14). If correctly identified, the specimen is of late Early Devonian to Early Late Devonian in age and is widespread in rocks of this age in western North America (Blodgett, 2020).

Discussion

Paleoenvironmental interpretation

Sapper Formation, Macmillan Pass Member (shale facies or pinstripe unit), and the Fuller Lake Member geochemistry and sedimentology provide the means for a general characterization and paleoenvironmental interpretation of these Devonian shale intervals. As the nature of this study is reconnaissance, only high-level geochemical interpretations have been made, recognizing that the use of geochemical proxies has limitations and further studies will provide a more robust interpretation than is presented here.

The Macmillan Pass Member shale (pinstripe) unit is a siliceous unit (generally 70–80% SiO_2), that has little to no carbonate content, a significant terrestrial input (high TIP and Zr values) and redox indicators that suggest

Table 1. *Previous and current ages from 11 Devonian conodont slide samples re-examined for this study. Original data set from Abbott (2013). Shaded boxes under "Refined Age" column delineate a tighter age constraint as a result of this study.*

Abbott, 2013							**Gouwy, 2020**		
Map ID	**NTS 50K**	**GSC No.**	**Formation**	**Stratigraphic position**	**Latitude (°N)**	**Longitude (°W)**	**Previous Age**	**Refined Age**	**Conodont biozone ranges**
33	105O/7	C-087690	Portrait Lake Fm; Niddery Lake Mbr	lower part	63.2700	-130.5833	Middle Devonian–Eifelian	Middle Devonian, Eifelian–Givetian	*australis-ansatus*
34	105O/7	C-089951	Portrait Lake Fm; Niddery Lake Mbr	lower contact	63.2597	-130.1056	Middle Devonian–Eifelian	Middle Devonian, middle Eifelian	*australis-kockelianus*
35	105O/8	C-089962	Portrait Lake Fm; Niddery Lake Mbr	lower contact	63.2764	-130.2056	Middle Devonian–Eifelian	Middle Devonian, Eifelian	*australis-ensensis*
36	105O/1	C-089976	Portrait Lake Fm; Niddery Lake Mbr	lower contact	63.2250	-130.0833	Middle Devonian–Eifelian	Middle Devonian, middle Eifelian	*australis-kockelianus*
37	105O/7	C-087692	Portrait Lake Fm; Niddery Lake Mbr	within unit	63.2750	-130.5500	Middle Devonian–Givetian	Middle Devonian, Givetian	*rhenanus/varcus-latifossatus/ semialternans*
38	105O/7	C-087538	Portrait Lake Fm; Niddery Lake Mbr	within unit	63.3000	-130.5333**	late Early Devonian–Emsian	Early Devonian, Emsian	*nothoperbonus-inversus*
43	105O/8	C-102309	Portrait Lake Fm; Niddery Lake Mbr*	within unit	63.2833	-130.3833	Middle Devonian	Middle Devonian–Eifelian	*costatus-ensensis*
44	105O/7	C-087689	Portrait Lake Fm; Niddery Lake Mbr	within unit	63.2900	-130.5700	Early Devonian–Emsian	Early Devonian, middle-late Emsian	*inversus-costatus*
47	105O/7	C-087687	shale in Macmillan Pass volcanics	lower part of unit	63.0000	-130.0000	Middle Devonain, middle Eifelian–early Givetian	Middle Devonian, middle–late Eifelian	*kockelianus-ensensis*
48	105O/1	C-087554	Sapper Fm	upper contact	63.1700	-130.3500	Middle Devonian–Eifelian	Middle Devonian, middle–late Eifelian	*australis-ensensis*
49	105O/1	C-108165	Sapper Fm	upper contact	63.1806	-130.2833	Middle Devonian–Eifelian	Middle Devonian, middle–late Eifelian	*australis-kockelianus*

* may be Road River Group
** exact location uncertain

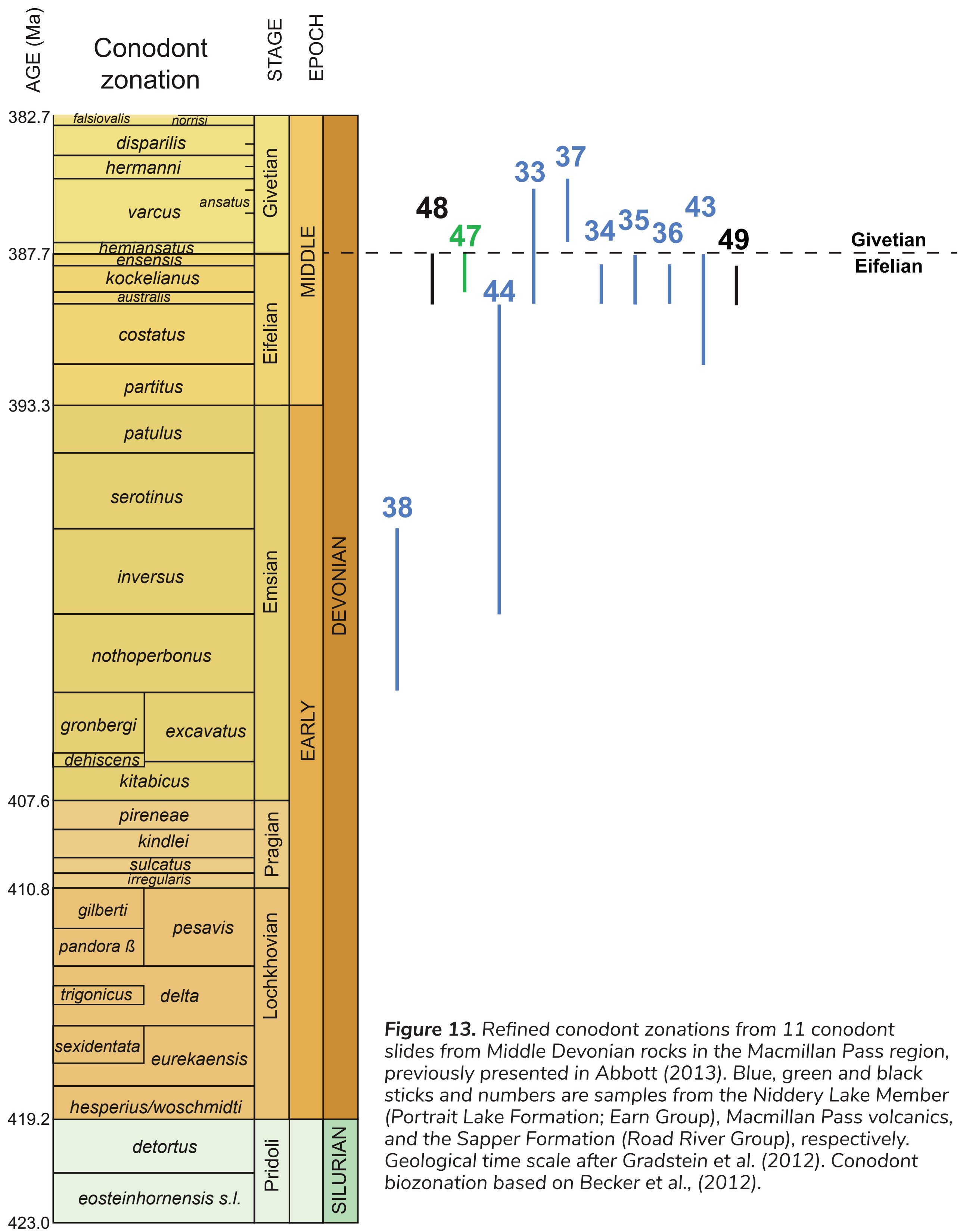

Figure 13. Refined conodont zonations from 11 conodont slides from Middle Devonian rocks in the Macmillan Pass region, previously presented in Abbott (2013). Blue, green and black sticks and numbers are samples from the Niddery Lake Member (Portrait Lake Formation; Earn Group), Macmillan Pass volcanics, and the Sapper Formation (Road River Group), respectively. Geological time scale after Gradstein et al. (2012). Conodont biozonation based on Becker et al., (2012).

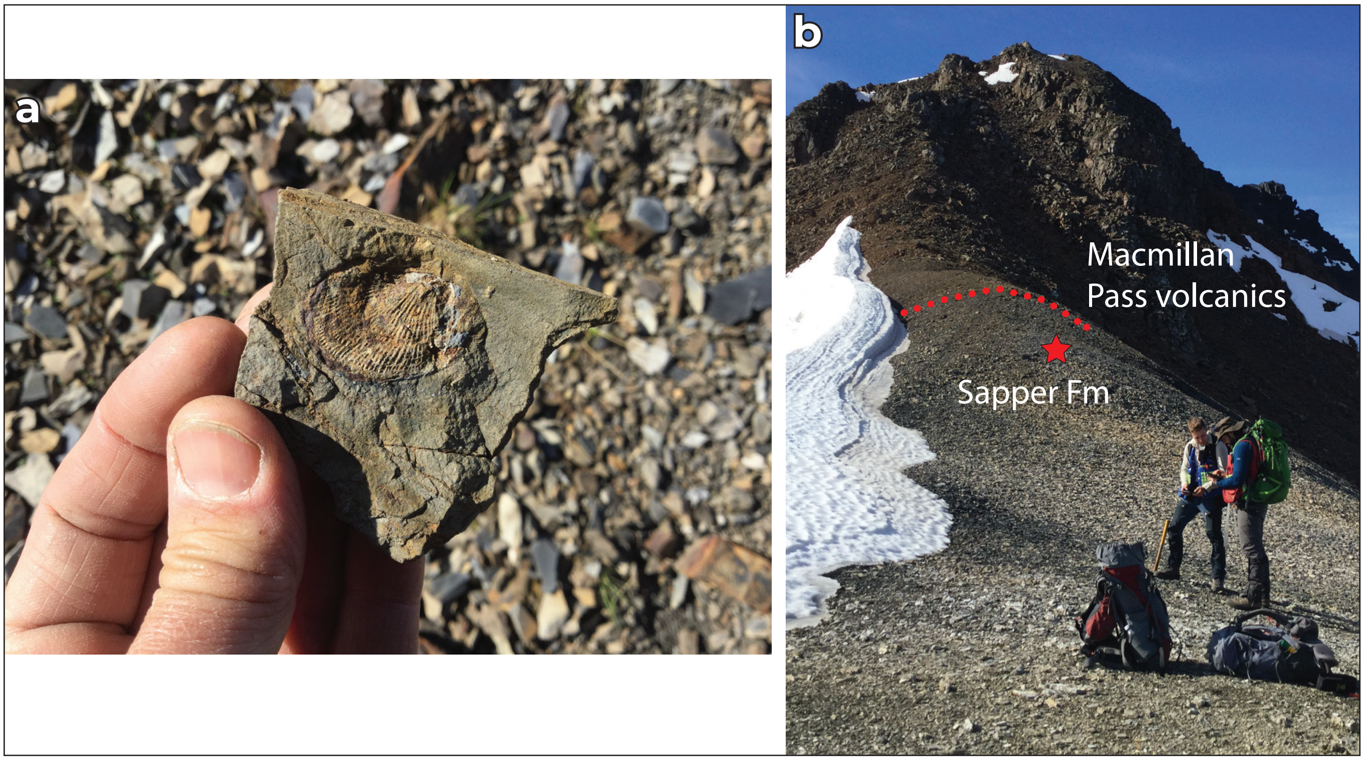

Figure 14. *Brachiopod sample in the uppermost Sapper Formation (63.1553°N, -130.1535°W) tentatively identified as Spinatrypina sp., late Early Devonian to Early Late Devonian.*

the depositional environment was oxic (low TOC and Ef Mo values). The combination of geochemistry with the sedimentology, which includes rhythmic fining upwards sandstone to shale successions and basal scours and load structures, suggests turbidity current deposition (Bouma units Tcde) onto a middle to outer shelf setting.

The Fuller Lake Member (Portrait Lake Formation), where not affected by Zn-Pb-Ag mineralization (*i.e.*, 556–596 m in TS88-01), is the most siliceous of the units investigated (average 75% SiO_2). The silica is likely biologically sourced, as shown by the moderate but notable negative SiO_2 *vs.* Zr trend and the low Zr and TIP average values (92 ppm and 9%, respectively). Redox indicators such as Ef Mo and TOC are moderate, and carbonate content insignificant. The rhythmically bedded siliceous shale and chert with lesser siltstone, lack of coarse-grained strata, and moderate indicators for anoxic conditions and biogenic chert suggest an outer slope to basinal setting where turbidity current deposition (Bouma units Tde) sourced both biogenic (radiolarian) and terrestrial silica, and periods of intermittent anoxia resulted in organic carbon preservation. Determination of euxinia (*i.e.*, anoxia with sulphur present) is difficult to determine with the data presented here, and unfortunately cannot be effectively compared with Magnall *et al.*'s (2018) paleoredox analysis of Fuller Lake Member strata at the Tom property. Their study employed proxies such as Fe-speciation and Mo isotopes to characterize the depositional environment of the host sediments of the massive sulphide deposits as ferruginous (*i.e.*, anoxia in the absence of sulphur) with the sulphur for metal-enrichment controlled instead by high primary productivity and enhanced carbon burial, as indicated by TOC/P ratios <106:1 (the Redfield ratio; Redfield, 1958). Interestingly, the TOC/P ratios determined in this current study do compare to the findings of Magnall et *al.* (2018), where values are lower than 106:1 (average 28:1), suggestive of effective carbon supply and burial. By inference, we could suggest anoxic or ferruginous conditions for Fuller Lake Member deposition; however, this interpretation is highly speculative without further research.

The Zn-Pb-Ag mineralizing event overwhelmed the background oceanic conditions during Fuller Lake Member deposition resulting in high concentrations of Ba, Pb, Zn and other elements. Other differences from Fuller Lake Member background conditions include lower SiO_2 and oxide concentrations, minimal to no organic matter preservation, moderate carbonate content and elevated Mo. Primary depositional characteristics cannot be effectively interpreted from the proxy data presented herein. The Fuller Lake Member chert above the Zn-Pb-Ag interval (510–523 m in TS88-01) still contains high amounts of Ba and Zn, and appears to be still affected by the mineralizing event. This suggests oceanic conditions are likely not at background levels but it appears all values are trending towards the lower Fuller Lake Member ones.

The Sapper Formation samples in TS91-17 show much more variability in geochemistry than the other units in this study and a four-fold division of the unit facilitates interpretation. The bottom two metres of the section is dominated by carbonate with disseminated fossil debris, suggesting off-shelf deposition in proximity to a carbonate source with very little terrestrial clastic input and under oxic conditions. Between 100 and 124 m depth, shale is moderately siliceous (average 62%) and the silica trends weakly towards a terrestrial source. Terrestrial input in this section is low (<10%), and organic matter content and Ef Mo values are high (4.8% and 149, respectively), suggesting less oxic conditions than farther up or at the base of the section, and likely intermittent anoxic or dysoxic conditions during deposition. Laminated shale and mudstone in rhythmic, normally graded intervals suggest distal turbidite deposition (Bouma units Tde) in a middle shelfal setting. A small excursion in the $\delta^{13}C_{org}$ curve at 112–113 m could indicate higher sea level as it is immediately followed by an increase in TOC and Ef Mo suggesting good organic matter preservation and thus anoxia. The interval from 94–99 m shows a coarser grained sediment (siltstone) fining up to a shale. It has the highest average TIP values of the section, while TOC is lower (average 3.6%) and Ef Mo and carbonate component are the lowest in the section. The trends throughout this interval suggest deposition on an inner to middle shelf transitioning to a lower shelf during a sea level transgression. The upper part of the section, from 74–92 m, shows a high degree of geochemical variability suggesting rapidly fluctuating sea level and associated terrestrial input, silica source, redox conditions, and proximity to a carbonate source. The paleoenvironmental significance of this upper section is discussed in more detail in the next section.

The Kačák Event in the Sapper Formation

Conodont biostratigraphy places the uppermost Sapper Formation in the terminal Eifelian *australis* to *ensensis* conodont zones. The latter half of this time period is marked globally by black shale deposition called the Kačák-*otomari* Event (herein Kačák; House, 1985; Walliser, 1985; Walliser and Bultynck, 2011). Kačák corresponds to a multi-phased global sea level rise with associated rapid facies changes, significant biotic turnover (*i.e.*, extinction followed by rapid radiation events), and anoxia which produced sediments rich in organic carbon (House, 1996; House, 2002; Desantis and Brett, 2011). The Kačák Event is marked by two phases. The first phase, the *otomari* Event, is based on the onset of the dacryoconarid lineage of *Nowakia otomari* that occurred at the boundary between the *kockelianus* and *ensensis* conondont zones (388.2 Ma; timescale from Becker *et al.*, 2012). The second is the Kačák Event *s.s.*, named after the Kačák Shale in the Bohemian Massif, immediately before the Eifelian–Givetian boundary (387.7 Ma), which is characterized by the onset of black shale deposition and numerous faunal extinctions among goniatid ammonites (*e.g.*, House, 1996; Walliser, 1996; Schöne, 1997; DeSantis, 2010; Elwood *et al.*, 2011). Evidence for the Kačák Event is recorded in Germany (*e.g.*, House, 1996; Schöne, 1997; Konigshof *et al.*, 2016), Spain (*e.g.*, House, 1996; Garcia-Lopez *et al.*, 2002), Czech Republic (Hladikova *et al.*, 1997), Belgium (Jamart and Denayer, 2020), Scotland and England (House, 1996; Marshall *et al.*, 2007), France (House, 1996), Austria (DeSantis and Brett, 2011), Morocco (House, 1996; Walliser and Bultynck, 2011; Becker *et al.*, 2013), Falkland Islands (Marshall, 2016), Brazil (Horodyski et *al.*, 2014), Bolivia (Troth *et al.*, 2011); China (House, 1996; Qie *et al.*, 2018), Australia (House, 1996) and Vietnam (Konigshof *et al.*, 2017). In North America it has been observed in the eastern United States as a three-part bioevent which includes (oldest to youngest) the Bakoven, Stony Hollow and Kačák Events that occur in the Upper Eifelian *australis*, *kockelianus* to *ensensis* conodont biozones, respectively (DeSantis and Brett, 2011). In Canada, it is likely recorded in the top of the Hume Formation and base of the Hare Indian Formation in the Mackenzie Mountains (Uyeno *et al.*, 2017), and possibly in an anomalous, metal-enriched horizon in Yukon at the contact between the Road River Group and Canol Formation (Fraser and Hutchison, 2017; Gadd *et al.*, 2019a); however, more work is required to determine proof of a biocrisis.

Robust studies characterizing the Kačák Event rely on documenting pelagic biostratigraphic changes (*i.e.*, conodonts and ammonoids), and geochemical, isotopic and magnetic susceptibility patterns, or combinations thereof, at a high sampling resolution over these thin intervals. The reconnaissance nature of this study, limited available core through these strata, and the lack of fossils does not allow for such detail. Certain indicators in the data suggest the Kačák and the Eifelian–Givetian boundary sediments may be present at the Tom property, including trace element enrichments over a thin stratigraphic interval, indicators for rapid sea level rise and subsequent anoxia, and a marked negative $\delta^{13}C_{org}$ excursion which is a hallmark characteristic at many locales. Thin, condensed sections caused by low to no sedimentation in a period of high sea level (*e.g.*, 50 cm at Mech Irdane, Morocco; Ellwood *et al.*, 2011; Walliser and Bultynck, 2011) and 30 cm in the Appalachian Basin, eastern U.S. (Bakoven member of the Union Springs Formation, *Macellus* subgroup; Sageman *et al.*, 2003) are a global geological expression of the Kačák in basinal settings. Due to the paleogeographical basinal setting of Selwyn basin during Middle Devonian time, we would expect a similar condensed section in the rock record. Elevated metal concentrations as a reduction in "normal" sedimentation (or terrigenous sediment starvation) caused by sea level transgression tends to favour enrichment of rare earth and heavy metals from allogenic sources (*e.g.*, windborne dust, volcanic ash, and cosmic dust) as well as from authigenic chemical reactions that are able to occur more effectively (Fraser and Hutchison, 2017; after Schutter, 1996). A zone of trace element enrichment, including Mo, Ni, Zn, Se, P, As, Ag, Au, Zn and P_2O_5 (orange box on Fig. 11), in the black shales of the uppermost Sapper Formation in drill hole TS91-17 suggests a condensed section of sedimentation. Note that Zn and P_2O_5 show only minor enrichments in phase with other elements but become more enriched at the top of the section.

Evidence for anoxia at marine Kačák localities are typically shown by sharp increases in concentration of redox-sensitive elements (*e.g.*, Mo, V, and U), and spikes in TOC which suggest significant organic carbon burial (*e.g.*, Mech Irdane in (Ellwood *et al.*, 2011), the Eifel area of Germany (Konigshof *et al.*, 2016) and the Barrandian basin in Czech Republic (Hladikova *et al.*, 1997)). In all of these localities, the trend towards anoxia is rapid, co-occurring over a thin stratigraphic interval, and consistent with a transgressive sea level. In the uppermost Sapper Formation in drillhole TS91-17, we see strong enrichments in redox sensitive elements Mo, U, V, and Ni (Fig. 11 and Appendix C), as well as a spike in TOC values (up to 11%) over a thin stratigraphic interval. A prominent negative $\delta^{13}C_{org}$ or $\delta^{13}C_{carb}$ in sediments is a diagnostic feature of the Kačák in many localities: New York State ($\delta^{13}C_{org}$ -2.0‰; Sageman *et al.*, 2003); the Eifel region in Germany ($\delta^{13}C_{carb}$ -4.0‰ and $\delta^{13}C_{org}$ -1.0‰; Konigshof *et al.*, 2016); the Ardennes region in Belgium ($\delta^{13}C_{carb}$ -3‰; Konigshof *et al.*, 2016); and at Mech Ardane, Morocco (~$\delta^{13}C_{carb}$ -8.0‰; Ellwood *et al.*, 2011). A negative $\delta^{13}C_{carb}$ excursion is also observed in brachiopod shells from Morocco and Germany (-1.5‰; van Geldern *et al.*, 2006). The shift in $\delta^{13}C_{org}$ values in the uppermost Sapper Formation in TS91-17 is -3.2‰, which is on par with the other excursions observed globally. These geochemical characteristics, combined with the age control from the refined conodont dates of samples at the Sapper Formation–Macmillan Pass volcanic suite contact make a strong case for the expression of the Kačák Event at the Tom property.

Is there a relationship between the $\delta^{13}C_{org}$ excursion in the Sapper Formation and the NiMo horizon?

The uppermost Sapper Formation at Macmillan Pass is coeval (within error) with the hyper-enriched black shale (HEBS) unit or 'NiMo' horizon observed regionally in Selwyn basin, Richardson trough and Kechika trough at the contact between the Road River Group and Canol Formation (or lowermost Portrait Lake Formation of the Earn Group). This is a thin (<14 cm, average ~3 cm thick), shale-hosted, stratabound Ni-Mo-Zn and PGE mineralization horizon, with anomalous Au, As, Ce, P, Ba and U (Hulbert et *al.*, 1992; Goodfellow et *al.*, 2010; Gadd et *al.*, 2019b; Henderson et *al.*, 2019). Re-Os geochronology and conodont biostratigraphy date the horizon as 385–390 Ma (Gadd et *al.*, 2019a). The horizon may be the expression of the combined Kačák and younger *pumilio* and Taghanic bioevents in an extremely condensed section (Gadd et *al.*, 2019a). The revised conodont dates from strata at the Sapper Formation–Macmillan Pass volcanic suite suggest that this contact and the NiMo horizon are time equivalent features in the basin, which should assist in future mapping and correlation exercises. The observation of two different expressions of the Kačák Event in the Laurentian margin, *i.e.*, sulphide mineralization versus black shale deposition, is beyond the focus of this study; it would involve considerations of paleo ocean chemistry, redox conditions, tectonics and paleogeography at a much larger scale.

Questions surrounding the influence of the Macmillan Pass volcanic suite

Unlike other NiMo localities in Selwyn basin and Richardson trough, volcanic/volcaniclastic rocks at Macmillan Pass sharply overlie the Road River Group. These volcanic rocks are interpreted to be the result of differential subsidence and block faulting on the margin of Laurentia, and the initiation of low temperature hydrothermal activity that reached a maximum during Zn-Pb-Ag deposition in the Late Devonian (Abbott and Turner, 1991). In the TS91-17 hole, the Macmillan Pass volcanic suite sharply overlies the Sapper Formation, with what appears to be a conformable contact. Abbott and Turner (1991) note that although the Middle Devonian volcanic rocks are mainly at the basal contact of the Earn Group and sharply overlie the Road River Group, they may also be intercalated with the uppermost Road River Group; at the Boundary Creek deposit the volcanic rocks are intercalated with chert conglomerate and diamictite in the Macmillan Pass Member. This suggests that volcanism was intermittent and not a single event. Two questions arise from the overlap in timing of volcanism with NiMo development in Selwyn basin and Richardson trough. The first question is whether this volcanism has created a local effect on trace metal concentrations and TOC, and an associated disturbance to the carbon partitioning at the Eifelian–Givetian boundary. If not, we may not be seeing the global Kačák Event in the upper Sapper Formation but rather a localized event. The second question is whether Middle Devonian volcanism at Macmillan Pass played a role in the development of the NiMo horizon elsewhere in the basin. Answering these questions are beyond the scope of this report, but would be interesting starting points for future Middle Devonian studies in Yukon.

Conclusions

Core logging, lithogeochemistry, and a reassessment of conodont data were conducted on Middle Devonian sediments at the Tom deposit, Macmillan Pass, Yukon. Updated descriptions and lithogeochemical characteristics of shale dominant units are presented, which can be used to assess depositional environment and that aid in regional mapping and correlation are presented herein.

The Macmillan Pass Member shale (pinstripe) unit is a siliceous, rhythmically interbedded fining upwards, fine to very fine sandstone and siliceous siltstone and shale unit that was deposited in a turbidity current onto a middle to outer shelf setting in an oxic environment.

The Fuller Lake Member (Portrait Lake Formation), where not affected by Zn-Pb-Ag mineralization, is a variably siliceous, black, laminated shale. The silica is likely biologically sourced from radiolarian combined with terrestrial input, and deposition is interpreted to be via turbidity currents into an outer slope to basinal setting far from a carbonate rock source. Redox proxies suggest periods of intermittent anoxia that resulted in intervals of enhanced organic material preservation. The Zn-Pb-Ag mineralizing event flooded Zn and Pb into the system, and is observed as interlaminated shale, barite, pyrite and sphalerite with associated carbonate.

Finally, the Sapper Formation of the Road River Group is a dominantly organic-rich interlaminated shale/mudstone with lesser siltstone and very fine sandstone and lesser limestone. It shows a range of depositional environments including off-shelf proximal to a carbonate source to turbidity current deposition on the middle to inner shelf. The terminal 20 m of the Sapper Formation is characterized by geochemical variability suggesting paleoenvironmental instability, including fluctuating sea level and associated proximity to carbonate and terrestrial sources, silica source, and redox conditions. This instability was followed by a volcanic event that may or may not have affected these uppermost sediments.

The uppermost Sapper Formation highlights a thin interval of metal enrichment, high TOC, markers for anoxia and a negative 3.5‰ $\delta^{13}C_{org}$ excursion that may be an expression of the Kačák Event. The Kačák is a global biocrisis spanning the Eifelian–Givetian boundary and characterized in the marine realm by a condensed section of sedimentation, sea-level instability, and pelagic faunal changes (*i.e.*, massive extinction followed by a radiation). Further study is required to determine whether the strata at Macmillan Pass reflect this global signal, or are localized and caused by volcanic activity. Also, further research into the hypothesis as to whether these strata are a local expression of geochemical events responsible for the NiMo horizon elsewhere in Selwyn basin and Richardson trough is required.

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Appendices (separate excel spreadsheet)

Appendix A.

Whole rock geochemistry from samples in the TS88-01 drillhole.

Appendix B.

Whole rock geochemistry from samples in the TS91-014 drillhole.

Appendix C.

Whole rock geochemistry and organic carbon isotopic signatures from samples in the TS91-17 drillhole.

Appendix D.

Whole rock geochemistry for the Macmillan Pass volcanic suite field sample, 19-TF-13.