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Foreword

The Geo-mapping for Energy and Minerals (GEM) program is laying the foundation for sustainable economic development in the North. The Program provides modern public geoscience that will set the stage for long-term decision making related to responsible land-use and resource development. Geoscience knowledge produced by GEM supports evidence-based exploration for new energy and mineral resources and enables northern communities to make informed decisions about their land, economy and society. Building upon the success of its first five-years, GEM has been renewed until 2020 to continue producing new, publically available, regional-scale geoscience knowledge in Canada's North.

During the 2018 field season, research scientists from the GEM program successfully carried out 18 research activities, 16 of which will produce an activity report and 14 of which included fieldwork. Activities applied a variety of geological, geochemical, and geophysical methods. These activities have been undertaken in collaboration with provincial and territorial governments, Northerners and their institutions, academia and the private sector. GEM will continue to work with these key partners as the program advances.

Introduction

The northern Cordillera comprises a collage of terranes that were accreted to the North American continental margin during the Mesozoic (Figure 1a). Each terrane has its own stratigraphy, tectonic history and mineral deposits, and is bounded by faults (Coney et al., 1980). In many cases the presently defined terrane boundaries are either multiply reactivated or late, steep, post-accretionary faults. For example, the Teslin Fault (Figure 2a), that separates Cache Creek and Stikinia from Quesnellia in Yukon has significant Cretaceous offset (ca. 125 km; Gabrielse et al., 2006). Identification of primary syn-accretionary terrane boundaries is hampered by inadequate knowledge of the internal composition of terranes stemming from improper assignment of late faults as terrane boundaries, rather than the original syn-accretionary faults.

The Stikinia bedrock (*a.k.a. Whence Stikinia*) activity is primarily focused on resolving the terrane boundaries between Stikinia and adjacent terranes in southern Yukon and north-western British Columbia (Figs. 1b and 2). In particular, the activity is investigating where and when Stikinia ends and adjacent terranes begin (Figure 2). Previous workers recognized four major tectonic boundaries in the study area: the Llewellyn, King Salmon, Nahlin and Teslin faults (Aitken, 1959; Mihalynuk et al., 2003; Mihalynuk et al., 1999; Mihalynuk et al., 2017; Monger, 1975). The Llewellyn Fault separates lower grade Stikinia on its eastern side from higher grade rocks generally assigned to the Yukon-Tanana terrane to the west (Figure 1a; Mihalynuk et al., 1999). The juxtaposition of high and low grade rocks along a steep fault suggests that there was significant transcurrent motion or that an older shear zone was displaced along a late fault. The King Salmon Fault (Figure 2) mostly marks the western edge of the Inklin Formation of the Laberge Group, which is an Early Jurassic deep marine sedimentary sequence deposited between Stikinia and Cache Creek terranes. The King Salmon Fault forms part of a fold and thrust belt, but uniquely carries the

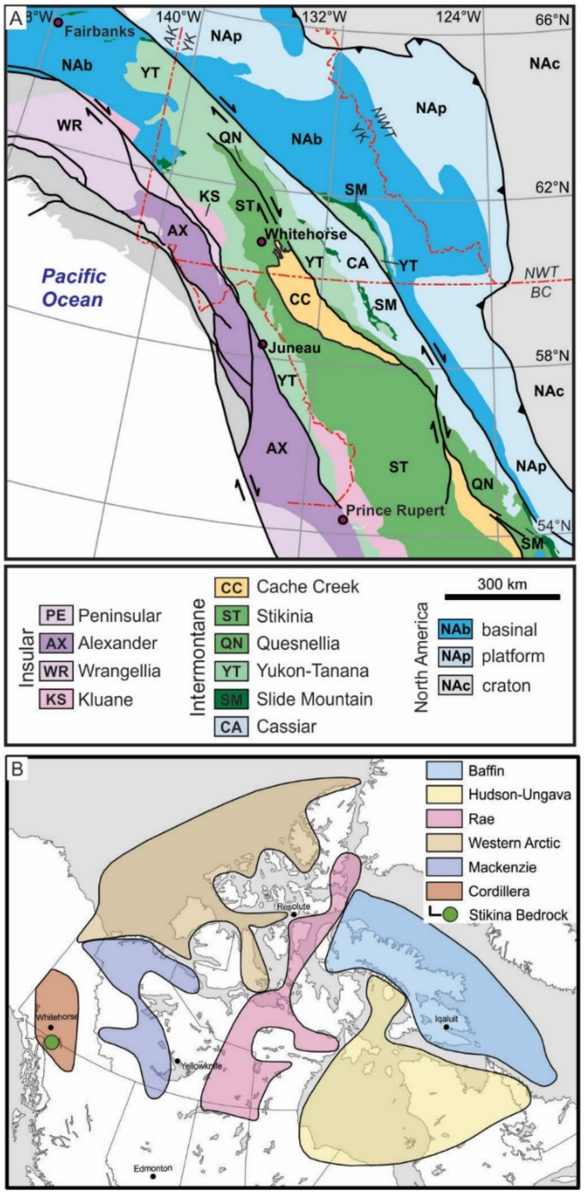

Figure 1 *A. Terranes of the Northern Cordillera (from Colpron and Nelson 2011). B. GEM2: Cordillera project and Stikinia Bedrock activity footprints.*

distinctive Sinwa Formation limestone in its hanging wall (Mihalynuk et al., 2017). The Nahlin Fault (Figure 2) has previously been interpreted as the western edge of the Cache Creek in northern British Columbia. Our recent mapping suggests that what is presently mapped as the Nahlin Fault is actually several distinct structures (Zagorevski et al., 2016). Near its type locality, the Nahlin fault emplaces Cache Creek ophiolitic rocks over the Laberge Group sedimentary rocks (Figure 2; e.g., Mihalynuk et al., 2003). In this area, the Nahlin fault likely forms part of the same fold and thrust belt as the King Salmon fault and does not represent a primary terrane boundary, especially since correlatives of ophiolitic rocks occur to the southwest of the fault (Childe and Thompson, 1997; English et al., 2010; Gabrielse, 1998; Schiarizza, 2011). To the northwest of the type locality, the boundary between the Cache Creek ophiolitic rocks and the Laberge Group is marked by the probably Cretaceous, transcurrent Silver Salmon fault (Figure 2; Zagorevski et al., 2016).

The Cretaceous (Gabrielse et al., 2006) Teslin fault separates Quesnellia from the Cache Creek terrane in the northeast portion of the study area (Figure 2). The Teslin Fault has a known Cretaceous transcurrent history and juxtaposes Late Triassic sedimentary rocks which are presumed to be different on the basis of underlying Paleozoic to Early Mesozoic rocks. The young history indicates that the Teslin Fault likely cuts and displaces terrane boundaries, similar to the Silver Salmon Fault.

The Llewellyn, King Salmon, Nahlin and Teslin faults thus do not correspond with primary, syn-accretionary terrane boundaries, but rather displace them. We have previously identified syn-accretionary terrane boundaries and suggested that post-Middle Triassic sequences likely represent overlap assemblages on top of already assembled terranes (Zagorevski et al., 2017). We are continuing to test linkages and differences in the terranes as presently defined in order to improve the tectonic framework for the northern Cordillera.

Summer 2018 fieldwork was predominantly focussed on three thematic problems that will facilitate reassessment of Cordilleran terranes: (i) the nature of the basement and volcanism within the Tethyan carbonate platform of the Cache Creek terrane; (ii) the Middle to Late Triassic overlap assemblage in Stikinia, Cache Creek and Quesnellia; and (iii) the nature and tectonic significance of Paleozoic rocks in the Yukon-Tanana terrane and their relationship to the Jurassic metamorphic detritus influx into the Laberge Group.

Volcanism in the Tethyan carbonate platform

Carboniferous to Permian limestone is a major constituent of the Cache Creek terrane and has been interpreted as atoll build-ups on ocean islands (Monger, 1975). The accepted model that

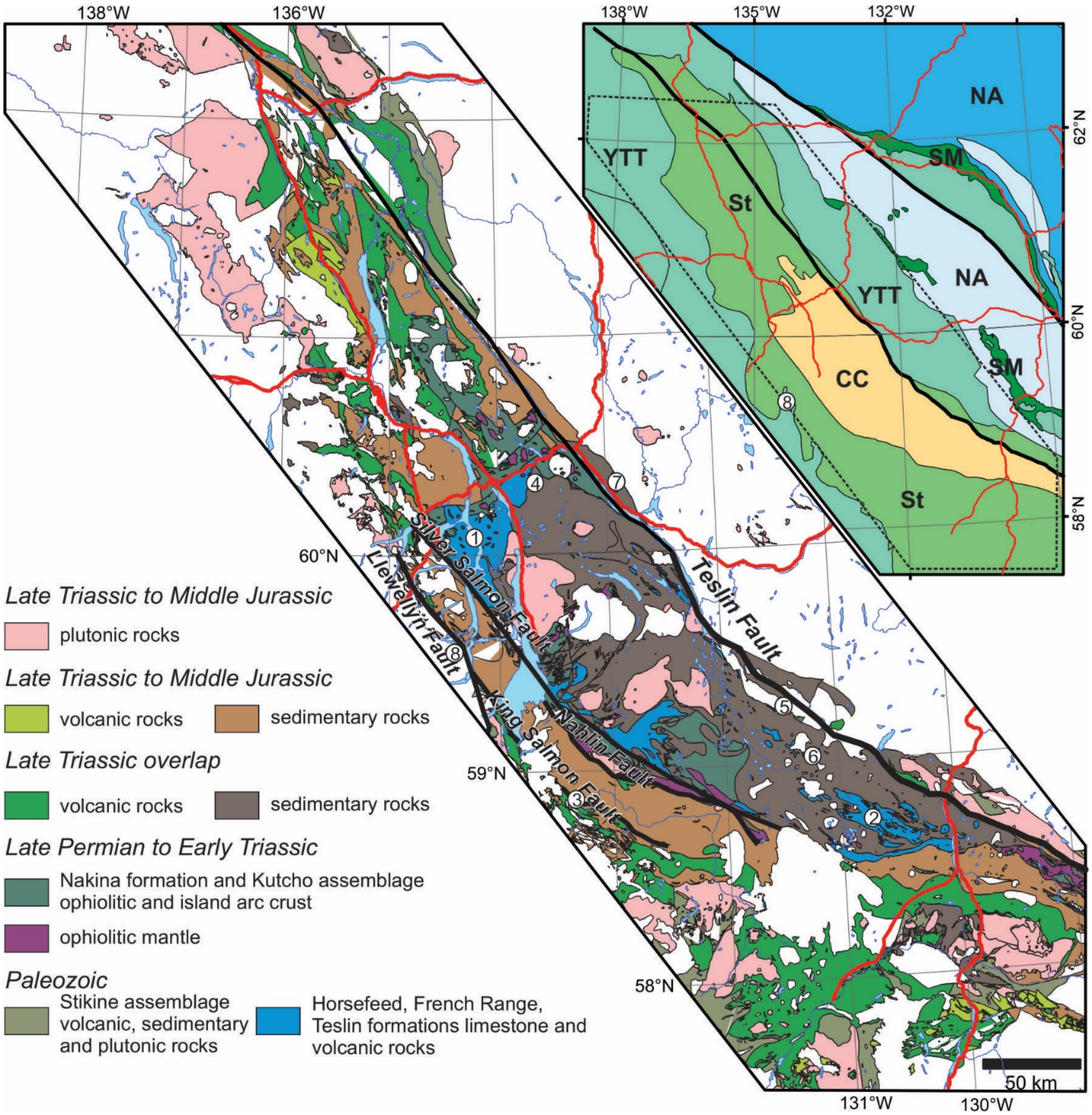

Figure 2 *Distribution of various tectono-stratigraphic units in the study area (simplified from Massey et al., 2005 and Colpron, 2015). 1. Tagish Lake, 2. French Range, 3. Mt Sinwa, 4. Dalayee Lake, 5. Aconitum Lake, 6. Badman Point, 7. Gabbro-peridotite in Shonektaw Formation. 8. Yukon-Tanana terrane in BC.*

the Tethyan carbonate platform limestones were deposited on top of ocean islands needs to be re-evaluated. Normally, atolls form once volcanism wanes and then stops altogether, leading to thermal subsidence of the volcanic edifice, with carbonate deposition keeping pace with the subsidence. However, the Carboniferous to Permian volcanic rocks are intercalated within the limestone suggesting that volcanism was episodically active throughout deposition of the carbonate platform (e.g., Monger, 1977). The Cache Creek carbonate platform is also anomalously large for atolls and carbonate banks in comparison to modern systems (Purdy and Winterer, 2001). The nature of the basement to the Horsefeed Formation, which is critical to assessing how exotic this platform is to adjacent terranes, has yet to be ascertained.

The exotic, Tethyan provenance of the Cache Creek carbonate platform was primarily inferred based on fusilinid and conodont faunas. Although fusilinid fauna have not been re-evaluated using modern taxonomy, "Tethyan" fusilinids are known in Laurentia (Davydov, 2014) where their occurrence is likely controlled by latitudinal rather than paleolongitudinal factors. Golding et al. (2016, 2017) compiled and updated the taxonomy of conodonts for the northern Cordillera to internally consistent, modern standards. Statistical analyses of conodont fauna from the Cache Creek terrane indicate that there is a great degree of heterogeneity within the terrane (Golding, 2018). Furthermore, Tethyan fauna in the Cache Creek terrane is only represented by one Triassic and one Permian conodont species, and lacks typical Tethyan faunal assemblage. Permian and Triassic faunas are qualitatively similar to those of other North American Cordilleran terranes and the North American continental margin (Golding, 2018). The results of modern statistical analysis of conodont faunas cast doubt on the strictly exotic origin of the Cache Creek carbonate platform that is deeply entrenched in literature (e.g., Johnston and Borel, 2007).

The nature of magmatism in the Cache Creek carbonate platform is also not necessarily indicative of an exotic origin. The adjacent Stikinia is locally characterised by within-plate volcanism during the Paleozoic (Gunning et al., 2006). Similarly, the Paleozoic Laurentian margin and the Yukon-Tanana terrane are also in-part characterized by OIB-like, continental rift magmatism (e.g., Piercey et al., 2004). Lack of data on the volcanic rocks from the Cache Creek carbonate platform in the study area generally precluded meaningful comparisons.

In 2018, we continued to conduct thematic mapping and sampling around Tagish Lake (Figure 2). This area is characterized by excellent exposures of intercalated Middle Pennsylvanian to Lower Permian Horsefeed Formation limestone and volcanic rocks (Golding et al., 2017; Monger, 1975; Golding, unpublished data). Volcanic rocks occur as variably haematized red-to-green mafic flows, volcaniclastic and epiclastic sedimentary rocks. Volcanic rocks are conformable with the surrounding limestone, exhibiting scouring and mixing with the limestone. Geochemistry of volcanic rocks from this area indicates that they are predominantly alkaline basalts, which are typical of continental rift and ocean island settings (Figure 3). Presence of small Nb anomalies may suggest that these rocks interacted with evolved

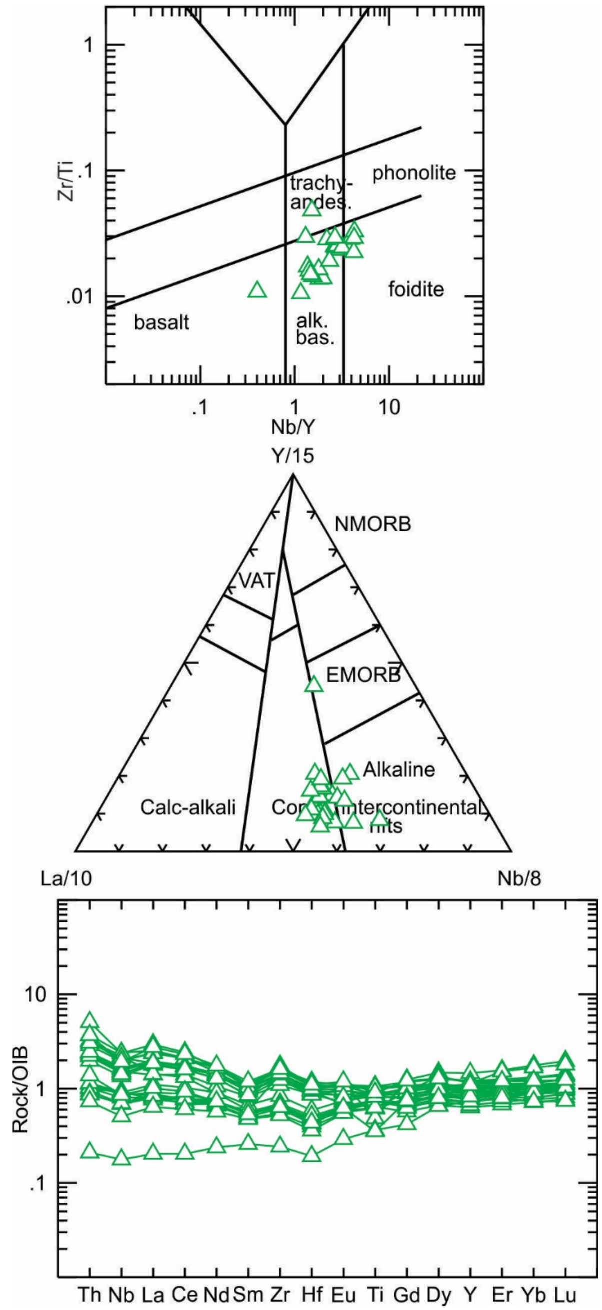

Figure 3 *Geochemical characteristics of volcanic rocks intercalated with Horsefeed Formation limestone in Tagish Lake area (diagrams from Cabanis and Lecolle, 1989; Pearce, 1996; Sun and McDonough, 1989)*

crust, but this needs to be confirmed through isotopic analyses. U-Pb zircon geochronology to determine the age of volcanism and provenance of the basement is in progress.

Late Triassic overlap assemblages in Stikinia, Cache Creek and Quesnellia

The closure of the Cache Creek Ocean and complete assembly of the Intermontane terranes is generally accepted to have occurred by the Middle Jurassic, based on the occurrence of blueschist facies rocks in the French Range area (Figure 2; Mihalynuk et al., 2004). However, the Laberge Group overlap sedimentation between Cache Creek and Stikinia had started significantly earlier (as early as Sinemurian; e.g., English, 2004), putting the sedimentary record at odds with the age of blueschist metamorphism. Specifically, if the Laberge Group does indeed overlap these terranes, then the basin had already closed prior to the Early Jurassic.

Mapping of the sedimentary rocks in the Cache Creek terrane indicates that chert-siliciclastic sequences, included in the Kedahda Formation and assumed to be Paleozoic (Monger, 1975), are predominantly Middle to Late Triassic. The Triassic age is based on numerous conodont, radiolaria and U-Pb zircon samples (Cordey et al., 1991; Golding et al., 2016; Golding et al., 2017; Gordey and Stevens, 1994; Jackson, 1992; N. Joyce, unpublished data). U-Pb zircon provenance of these rocks indicates sources that are similar to Cache Creek and Stikinia-Quesnellia (Zagorevski et al., 2016; N. Joyce, unpublished data). As such, these late Triassic sediments likely represent an overlap assemblage on already assembled, pre-Middle Triassic terranes.

In order to understand the tectonic significance of the overlap sediments we have continued thematic studies on the Late Triassic sedimentary rocks in Stikinia (Sinwa Formation), Cache Creek (Kedahda Formation) and time-equivalent rocks in Quesnellia (Shonektaw Formation). The purpose of these studies is to further characterize these sequences, clarify the nature of the contacts with their basement, understand their relationship to the current terrane concept, and eventually understand the reasons for distinct sedimentation patterns in adjacent sequences (limestone vs. chert dominated).

Late Triassic cover to Stikinia

Stikinia is characterized by volcanism throughout the Late Triassic. This volcanism abruptly slowed down or was terminated for a short period of time close to the Norian – Rhaetian boundary. Fieldwork was carried out at a number of Late Triassic localities in northern British Columbia and southern Yukon. In British Columbia, Late Triassic carbonates are assigned to the Sinwa Formation (Mihalynuk et al., 2017), whereas in Yukon these rocks have traditionally been assigned to the Hancock Member of the Aksala Formation, although recent regional mapping is revising the use of these names (Bordet, 2018). Relationships between the rocks of Yukon and northern B.C. are poorly constrained, due to the lack of detailed stratigraphic work on these formations thus far. In order to address this, and to improve correlation between the Sinwa and Aksala formations, sections were examined at Mt. Sinwa in B.C. (Mihalynuk et al., 2017), and at Lime Peak (Reid, 1985) and Hill 4308 (England, 1980) in Yukon. Samples were collected for conodont biostratigraphy, δ13C chemostratigraphy, and Re-Os chronostratigraphy.

The integrated stratigraphical study of the Sinwa and Aksala formations will allow meaningful regional correlations to be made across the Yukon – British Columbia border. This study will also improve the resolution of the Late Triassic timescale, and in particular the positioning of the boundary between the Norian and Rhaetian stages. Although the Norian – Rhaetian boundary is easily recognizable in Europe (e.g., Zaffani et al., 2017), data from North America is lacking. Furthermore, the carbon isotopes analyzed will provide insight into changes in climate and primary productivity during the Late Triassic, in the lead up to the mass extinction at the end of the period. The results of this study therefore have global implications.

Late Triassic cover to Cache Creek terrane

Radiolarian biostratigraphy of voluminous chert sequences in northern Cache Creek terrane demonstrated that a significant volume of chert is Middle to Late Triassic (e.g., Bloodgood et al., 1990; Cordey et al., 1991; Golding et al., 2016;

Mihalynuk et al., 2003) rather than Paleozoic as previously assumed (e.g., Aitken, 1959; Monger, 1975). Some workers recognized that chert is interbedded with volcaniclastic sandstone and conglomerate that contain pristine crystals of hornblende, clinopyroxene and feldspar (Monger, 1975; Mulligan, 1963). U-Pb detrital zircon provenance of multiple samples reveals provenance that is characteristic of Stikinia and Quesnellia (unpublished data). This strongly supports that the chert-volcaniclastic sediments form part of the regional overlap assemblage that stitches Paleozoic to Early Triassic Stikinia and Cache Creek terranes

In 2018, we expanded regional sampling of siliciclastic rocks to Dalayee Lake (YT), Snafu Creek (YT), Aconitum Lake (BC) and Badman Point (BC). All of these localities are characterized by quartz-bearing feldspathic wacke with abundant hornblende and minor biotite and clinopyroxene. Many samples contain hornblende-biotite-titanite porphyritic volcanic clasts (Figure 4a), and rare granophyre and myrmekite clasts indicative of erosion of volcanic and plutonic sources. Similarity of youngest U-Pb zircon and radiolarian ages in these rocks suggest essentially coeval magmatism and sedimentation. Mulligan (1963) noted common quartzite and gneiss clasts in these rocks indicating that the source area also had exposed metamorphic rocks.

Petrographic characteristics of these sedimentary rocks are similar to other Late Triassic sediments in the Cache Creek terrane. Aconitum Lake (BC) and Badman Point (BC) localities were treated by Gabrielse (1969) as typical of the Kedahda Formation siliciclastic facies suggesting that the age of Kedahda Formation near its type locality was mistakenly assigned to Paleozoic. We plan to confirm the age of these sediments through detrital zircon geochronology.

Late Triassic cover to Quesnellia

The Cretaceous (Gabrielse et al., 2006) Teslin fault separates Quesnellia from the Cache Creek terrane. Sedimentary rocks to the east of Teslin Lake were correlated with the Late Triassic Shonektaw Formation of Quesnellia. In Yukon, these rocks comprise predominantly Norian, imbricated siliciclastic and volcaniclastic

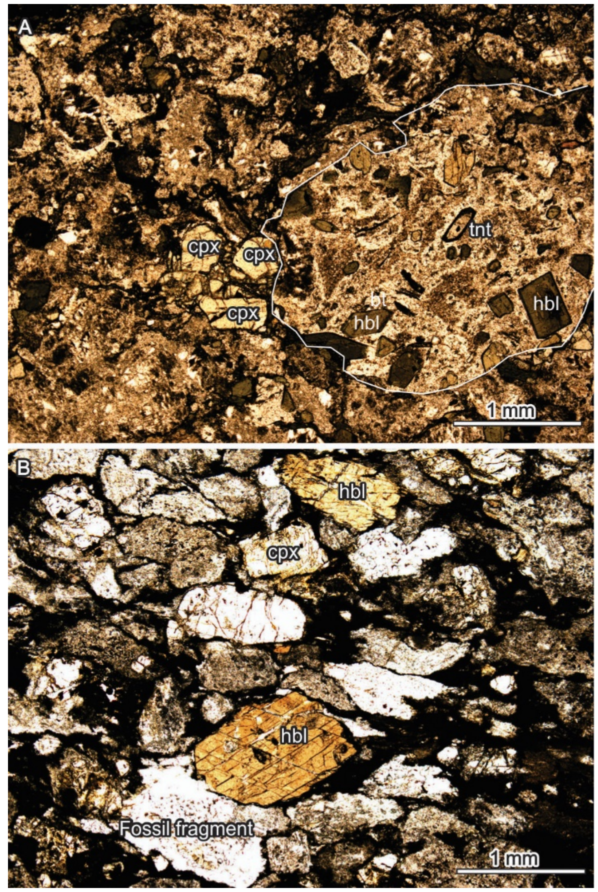

Figure 4 *A. Photomicrograph of Kedahda Formation sandstone containing clinopyroxene and hornblende-biotite-titanite porphyritic volcanic clasts (white outline). B. Photomicrograph of Shonektaw Formation sandstone containing clinopyroxene and hornblende.*

sedimentary rocks, chert, and limestone (Gordey and Stevens, 1994). The assignment of these rocks to Quesnellia rests largely on the relative abundance of hornblende, augite and chert compared to the adjacent Late Triassic Cache Creek terrane (Figure 4). Shonektaw formation thus presents a conundrum in the current terrane concept for the following reasons:

1. Terrane boundary to the east is a Cretaceous transcurrent fault with minimal vertical displacement (Gabrielse et al., 2006; White et al., 2012).
2. Coeval, lithologically similar rocks occur in the immediately adjacent Cache Creek terrane (e.g., Gordey and Stevens, 1994; Jackson, 1992; Monger, 1975; Mulligan, 1963; see following).
3. Shonektaw Formation in Yukon contains gabbro and peridotite (Gordey and Stevens, 1994)

previously interpreted as coeval or younger intrusions.

Results of the investigation of the gabbro and peridotite sequences indicate that petrographically and geochemically there is little difference between Cache Creek and Shonektaw gabbro-peridotite. Both areas are characterised by variably fresh to serpentinized harzburgite, dunite, wherlite, pyroxenite and cumulate gabbro with light rare-earth element depletion relative to MORB. Significantly, Shonektaw Formation augite-porphyritic tuffs rarely contain chlorite-tremolite-chromite clasts that represent entrained, altered, ultramafic rocks (Figure 5). This indicates that the Shonektaw Formation tuffs were deposited on top of already altered peridotites, a setting that is also inferred for the Late Triassic Kedahda Formation which overlaps ophiolites. We are continuing petrographic, geochemical and U-Pb zircon provenance investigations of the Shonektaw Formation in order to meaningfully compare it to Late Triassic sequences in the adjacent terranes. If the Shonektaw Formation forms part of the same overlap assemblage as Kedahda Formation and parts of the Stuhini-Lewes River group, then the presently drawn terrane boundaries represent displaced sedimentary facies rather than terranes.

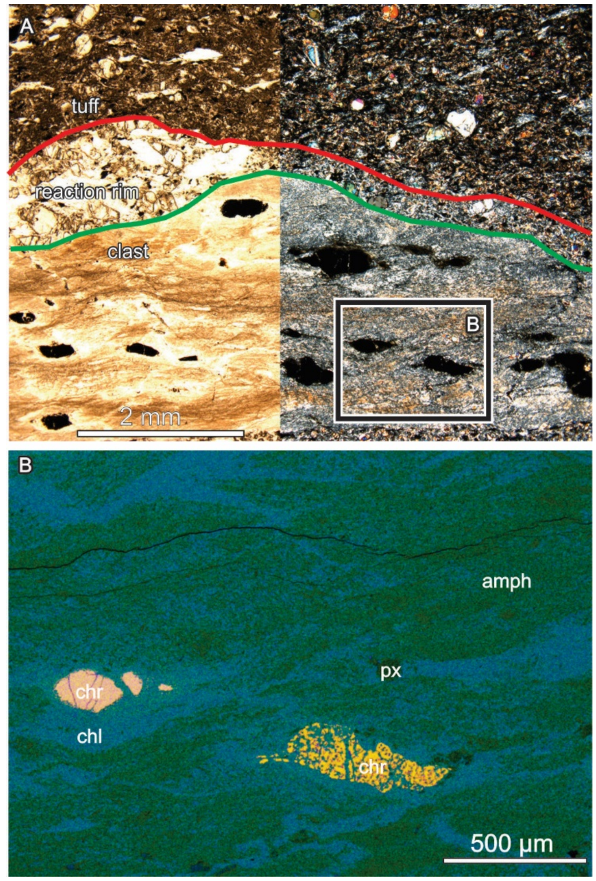

Figure 5 *A. Photomicrograph of ultramafic clast in Shonektaw Formation tuff. B. Composite X-ray map (BSE, Mg, Al, Cr) of ultramafic clast with large Al-rich and Al-poor chromite (orange and yellow respectively), chrome-rich chlorite (blue), and amphibole (green).*

Yukon-Tanana terrane Paleozoic rocks

In northwestern British Columbia, Stikinia is juxtaposed with the Yukon-Tanana terrane to the west along the Llewellyn fault (e.g., Mihalynuk et al., 1999), or further west, along the Wann River shear zone (Currie and Parrish, 1997). The timing of juxtaposition of the YTT and Stikinia and the exact boundary is poorly constrained. Jackson et al. (1991) proposed that Triassic Stikinia was built on top of YTT on the basis of low εNd values in sandstone which was presumed to be Middle to Late Triassic. Our investigations indicate that this sandstone is actually Lower Jurassic (N. Joyce, unpublished data). Currie (1994) suggested that Boundary Ranges suite metamorphic rocks immediately to the west of Llewellyn Fault represents metamorphosed Stikinia which was juxtaposed with the Florence Range suite metamorphic rocks (Yukon-Tanana terrane) along the Wann River shear zone. Boundary Ranges metamorphic rocks have been interpreted to be meta-volcanic and meta-pelitic rocks formed in an island arc setting correlative to the volcano-sedimentary basement of the Stikinia arc (Stikine assemblage; Currie and Parrish, 1993; Currie and Parrish, 1997). However, our investigations indicate Boundary Ranges suite formed in a mid-oceanic ridge or back-arc basin tectonic setting (Soucy La Roche, 2011) and was intruded by Late Devonian granitoids (Currie, 1994; Currie and Parrish, 1997; Joyce, unpublished data) indicating that it is distinctly different from Paleozoic to Mesozoic Stikinia (e.g., Logan et al., 2000).

Field work in the Florence Range and Boundary Ranges metamorphic suites was undertaken in summer 2018 to investigate the terrane affinity of these metamorphic rocks, re-assess the tectonic boundary separating them and to collect a detailed suite of samples to thoroughly characterize their tectono-metamorphic evolution.

The Florence Range metamorphic suite comprises middle- to upper-amphibolite facies biotite-muscovite quartzofeldspathic schist and gneiss with minor layers of garnet ± kyanite ± sillimanite bearing metapelite, quartzite, marble, calcsilicate gneiss and amphibolite. Protoliths of these metamorphic strata have been interpreted to represent a passive margin sedimentary sequence (Currie, 1994) and have been correlated to the Snowcap assemblage of the Yukon-Tanana terrane in Yukon.

The Boundary Ranges metamorphic suite is composed of greenschist to lower-amphibolite facies chlorite-actinolite ± garnet schist, muscovite-biotite ± garnet quartzofeldspathic schist and granitic orthogneiss.

The Wann River gneiss (270 ± 5 Ma, U-Pb zircon; Currie, 1992) forms an enigmatic unit in this area. It comprises a pervasively sheared hornblende-plagioclase banded gneiss that was interpreted as a meta-volcanic rock deposited at the top of the Boundary Ranges suite because of its finely layered nature. As such, it was assigned to Boundary Ranges suite (Currie, 1992; Currie, 1994; Currie and Parrish, 1997). The Wann River gneiss is also locally interlayered with Florence Range suite. However, this was attributed to tectonic imbrication (Currie, 1994).

The boundary between the Florence Range and Boundary Ranges metamorphic suite is marked by the Wann River shear zone (Currie and Parrish, 1993), which is a ~4 km thick folded shear zone with poorly developed top-to-the-south and sinistral shear-sense indicators (Currie and Parrish, 1993; Currie, 1994). The higher metamorphic grade of the Florence Range suite in the hanging wall compared to the Boundary Ranges suite in the footwall of the Wann River shear zone was previously interpreted to indicate thrust motion (Currie and Parrish, 1993; Currie, 1994). However, precise timing of metamorphism in these two suites is not constrained, therefore metamorphic grade cannot be used to constrain relative displacement unless metamorphism is proven to be coeval in the footwall and in the hanging wall. The age of motion on the Wann River shear zone was constrained on the basis of involvement of the Wann River gneiss (270 ± 5 Ma: Currie, 1992) and the locally deformed early Jurassic Hale Mountain granodiorite (185 ± 1 Ma U-Pb zircon: Currie, 1992).

Figure 6 *Strained feldspar porphyroclasts in the banded Wann River gneiss*

Our fieldwork was focused on updating the geological framework of the Yukon-Tanana terrane in British Columbia. Mapping of the Wann River gneiss revealed that it contains some layers with numerous cm-scale feldspar porphyroclasts. This strongly suggests that the Wann River gneiss is a meta-plutonic rock that has been sheared and has undergone extreme grain size reduction (Figure 6) rather than a volcanic rock. Wann River gneiss-like intrusions have been identified within the Florence Range suite, within the Wann River shear zone, and in contact with Boundary Ranges suite units. This suggests that the Wann River gneiss intruded and stitched Florence Range and Boundary Ranges metamorphic suites by Middle Permian. Geochemical and geochronological analyses on all units will test the link between these metamorphic suites in the Permian and will be used to compare the Wann River gneiss to the Permian Sulphur Creek plutonic suite in the Yukon-Tanana terrane in Yukon (Colpron et al., 2016).

In order to overcome the lack of macroscopic kinematic indicators along the Wann River shear zone, we collected a suite of quartz-rich samples across the shear zone to analyze quartz crystallographic preferred orientation. This method allows the determination of the sense of shear in rocks with poorly developed macroscopic shear sense indicators and the characterization of the temperature of deformation.

Finally, the metamorphic conditions in the Florence Range and Boundary Ranges metamorphic suites are only qualitatively characterized, whereas timing of metamorphism is loosely constrained between the Devonian and the early Jurassic (Currie, 1994). Common retrograde metamorphic overprint (e.g., garnet replaced by chlorite and biotite) hindered accurate pressure-temperature calculations (Currie, 1994), and abundant Cretaceous to Eocene plutonic rocks may have driven contact metamorphism that obscured metamorphic conditions during terrane assembly (Mihalynuk et al., 1999). We conducted detailed sampling of metamorphic rocks away from Cretaceous or younger plutons. Samples were collected with well-preserved garnet conducive to quantitative metamorphic petrology analyses and geochronology (phase equilibria modelling, garnet compositional isopleth thermobarometry, multi-equilibria thermobarometry, Lu/Hf and Sm/Nd garnet geochronology, monazite geochronology: e.g., Morneau, 2017).

Summary

Whence Stikinia aims to improve understanding of northern Cordilleran terrane interactions by looking past the previously assumed terrane boundaries and reassessing the underlying assumptions in the terrane assignments. Mapping and sample collections were predominantly focussed on the nature of the basement beneath and volcanism within the Paleozoic carbonate platform in the Cache Creek terrane, the Late Triassic overlap assemblage in Stikinia, Cache Creek and Quesnellia, as well as the nature and tectonic significance of Paleozoic rocks in the Yukon-Tanana terrane. The interim results from this study as outlined herein indicate that the previously interpreted terranes require significant reassessments.

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