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Characterization of volcanic and intrusive rocks across the British Columbia – Yukon border
GEM 2 Cordillera

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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 investment in responsible 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 summer 2016, GEM program has successfully carried out 17 research activities that include geological, geochemical and geophysical surveying. 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 collaborators as the program advances.

Introduction

Copper porphyry deposits are globally the most important source of Cu and Mo and a key source of Au-Ag. The most productive copper porphyry districts in the Canadian Cordillera are temporally associated with a geochemical transition from normal calc-alkaline to alkaline magmatism, which suggests a major change in subduction geometry and/or melting regime within the sub-arc lithosphere (e.g., Logan and Mihalynuk 2014a). This phenomenon is well documented in the Cordillera for volcanic arc rocks between about 195 and 215 Ma, as well as in both in older and younger magmatic system; however the tectonic trigger for the calc-alkaline to alkaline transition is poorly understood, especially in the northern Cordillera. In particular, the tectonic setting and metal endowment of prospective plutonic suites remain major knowledge gaps and impediments to effective porphyry exploration in the North.

Characterization of volcanic and intrusive rocks across the BC-Yukon border is an activity aimed at developing an updated regional geologic framework for magmatism in the Stikine and Yukon-Tanana terranes of southern Yukon and northern British Columbia (Fig. 1). A key outcome of the activity will be a study of the Mesozoic to Cenozoic arc belts in the northern Cordillera, from their volcanic cap to plutonic roots, especially where the calc-alkaline to alkaline transition has been documented and where potential for additional deposit discoveries remains high. Consequently, regional mapping and reconnaissance sampling in 2016 continued to be focussed on constraining the age and petrology of voluminous Late Triassic to Early Jurassic magmatism in northwestern Stikine terrane in Yukon and British Columbia.

Geological background

Prolific Mesozoic magmatism in the northwestern Stikine terrane can be broadly subdivided into Stikine, Copper Mountain, Texas Creek and Cone Mountain plutonic suites (Fig. 2; e.g., Woodsworth et al. 1991; Brown et al., 1992; Anderson 1993; Logan et al. 2000). These are temporally equivalent to the Stikine, Taylor Mountain, Aishihik, and Long Lake plutonic suites in Yukon and Alaska (e.g., Hart et al., 1995; Mihalynuk et al., 1999; Dusel-Bacon et al. 2007). Coeval volcanic and sedimentary rocks are included in the Late Triassic Stuhini (Souther, 1971; Brown et al., 1996) and Lewes River groups (Wheeler, 1961; Hart et al., 1995), and Jurassic Hazelton and Laberge groups (e.g., Brown et al., 1996; Colpron et al., 2015; Cutts et al., 2015). Here we use the 2016 version of the International Commission on Stratigraphy chronostratigraphic chart for absolute age limits of system, periods and stage boundaries.

Goals and objectives

Establishing regional geochronological coverage in the North is a critical step towards understanding regional tectonic controls on magmatic and linked sedimentary deposition and mineralization. To resolve gaps in our knowledge of the timing and genesis of magmatic suites, we have continued regional geochronological and geochemical studies focused on the Late Triassic and Early Jurassic plutonic suites and their volcano-sedimentary successions in Yukon and British Columbia. Our field sampling has been complemented by archived samples and unpublished legacy data.

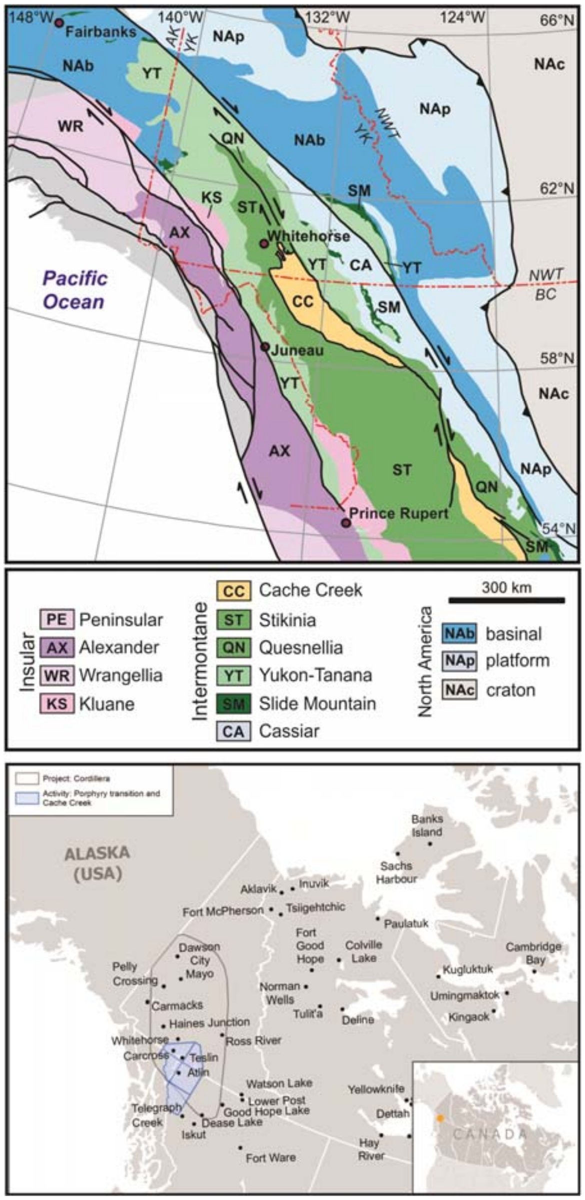

Figure 1 Terranes of the Northern Cordillera (from Colpron and Nelson, 2011). Bottom: GEM2: Cordillera project and Characterization of volcanic and intrusive rocks across the BC-Yukon border activity footprints.

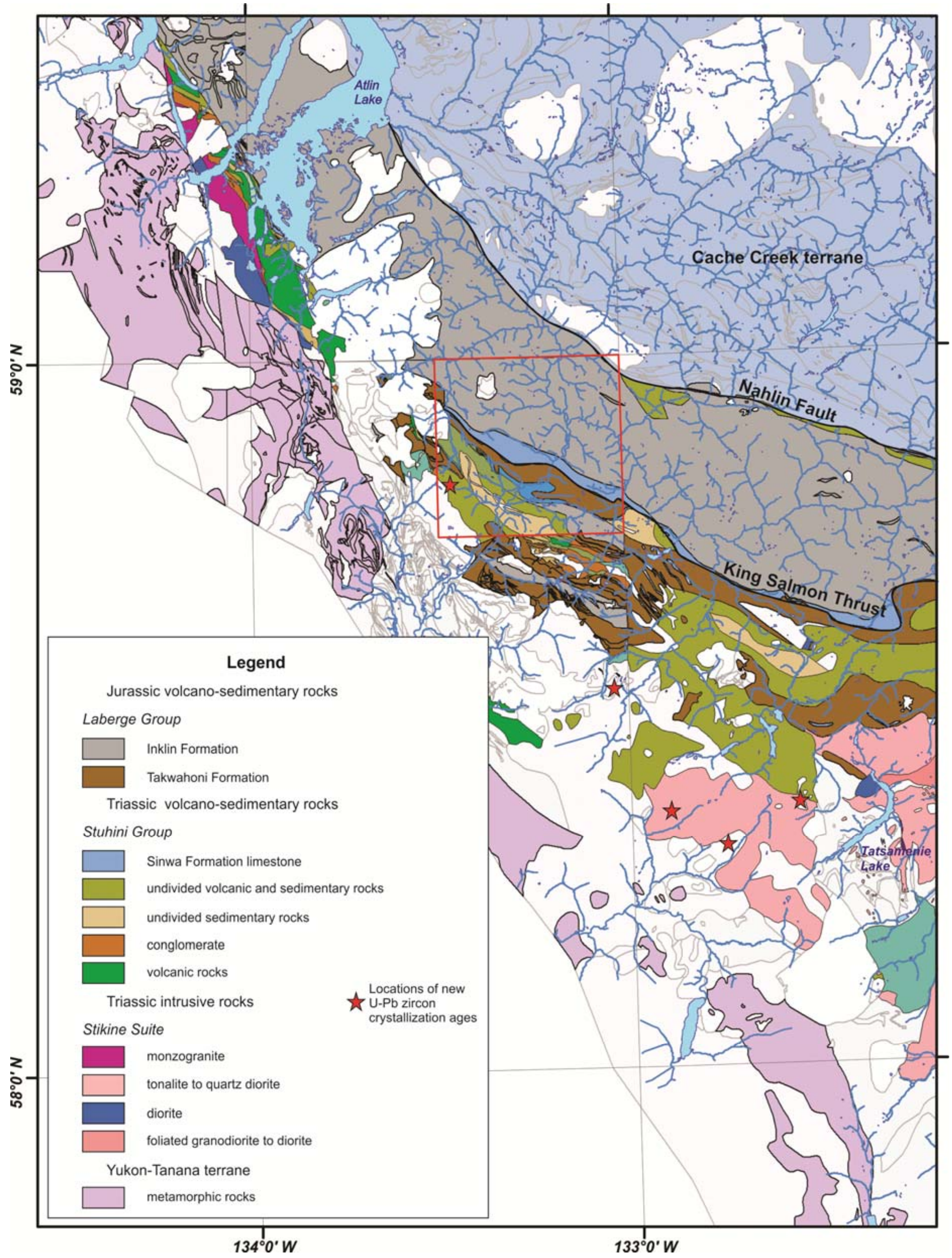

Figure 2 Simplified geology of the northern Stikine terrane from Tatsamenie Lake to Atlin Lake showing the distribution of Triassic and Early Jurassic plutonic suites and volcano-sedimentary rocks (modified from Massey et al., 2005). Inklin area is indicated by a red rectangle.

Preliminary results

Late Triassic Stikine plutonic suite (ca. 230-215 Ma)

The Stikine plutonic suite in Yukon is limited to small-volume plutons, such as the Tally Ho gabbro (ca. 214 Ma: Hart, 1996) and cumulate Pyroxene Mountain Suite (ca. 218 Ma $^{40}Ar/^{39}Ar$ cooling age: Ryan et al., 2013, 2014). Paucity of Stikine plutonic suite in Yukon is partly due to latest Triassic exhumation and erosion of the Stuhini-Lewes River arc as evidenced by an abundance of ca. 210 Ma detrital zircon in the upper Lewes River and Laberge groups (Hart et al. 1995; Colpron et al., 2015) and in Late Triassic to Early Jurassic siliciclastic rocks that overlap or are intercalated with the Cache Creek terrane.

In British Columbia, the Stikine plutonic suite (Figs. 2, 3a,b) comprises calc-alkaline, diorite to monzogranite plutons. Reconnaissance work on the Stikine plutonic suite in the Tatsamenie Lake and Atlin areas (Fig. 2) revealed a compositional diversity of magmatic rocks that range from gabbro to monzogranite and yield U-Pb crystallization and Re-Os mineralization ages ranging from 229.7 to 217.06 (Takaichi and Johnson, 2012; Takaichi, 2013; Zagorevski et al., 2015). Based on age constraints, mineralogy and texture, the Stikine Plutonic Suite can be divided into three broad units dominated by quartz diorite, granodiorite and monzogranite (*lTrSd, lTrSgd* and *lTrSmz* respectively). *lTrSd* is restricted to the Sheslay area, where it hosts porphyry-style mineralization at the Star Cu-Au deposit (229.7 Ma quartz diorite: Mihalynuk et al., 2016). A post-mineralization, trachytic hornblende quartz diorite yielded a similar U-Pb zircon crystallization age of 228.2 Ma (N. Joyce, unpublished data)

Hornblende - biotite tonalite – granodiorite - diorite *bodies* of Unit *lTrSgd* are exposed near Tatasamenie Lake and south of Telegraph Creek. This unit locally displays strong foliation (Figs. 2, 3a) and has a demonstrated age range of 222.62 to 219.80 Ma (Takaichi, 2013; Zagorevski et al., 2015; U-Pb zircon: Friedman, unpublished data). Some parts of these bodies were previously mapped as Eocene.

Unit lTrSmz is comprised of biotite monzogranite (Fig. 3b) that locally contains K-feldspar crystals up to a few cm long, and in some places displays cumulate layering. Three samples yielded ca. 217.06, 218.57, 219.87 Ma ages (U-Pb zircon: Friedman, unpublished data). These ages are within error of the compositionally similar bodies distributed into southern Yukon: Willison Bay pluton (U-Pb zircon, 216.6±4 Ma: Mihalynuk et al., 1997) and Tally Ho gabbro (ca. 214 Ma: Hart, 1996) to the northwest.

Re-analysis of Stikine plutonic suite hornblende and biotite separates archived from past K-Ar isotopic age determinations reveal a spread of new $^{40}Ar/^{39}Ar$ cooling ages ranging from ca. 229 to 171 Ma (hornblende) and ca. 231–169 Ma (biotite) (Joyce, unpublished data) suggesting that some of these plutonic rocks are not part of the Stikine suite and/or significant resetting of some of the plutonic rocks has occurred.

Middle to Late Triassic volcanism

Emplacement of Late Triassic plutonic suites was coeval with eruption of Stuhini Group arc basalt to andesite, minor basalt and picrite, and deposition of coeval sedimentary rocks (Fig. 3c,d; Souther, 1971). Basaltic to andesitic compositions predominate magmas erupted in island arc settings, whereas ultramafic magmas are rare. One such rare occurrence is the ultramafic (MgO =21–33 wt. %) tuff breccia, lapilli tuff, and ash tuff that were deposited as part of the Middle to Upper Triassic Stuhini Group (Milidragovic et al., 2016a). Despite their small volume, Stuhini Group ultramafic rocks

Figure 3 Representative photographs of the study area. A. Stikine plutonic suite foliated hornblende-biotite granodiorite, Tatsamenie Lake area. B. Mingling of Stikine Plutonic suite biotite monzogranite and gabbro, Atlin Lake area. C. Stuhini Group andesite breccia Inklin River area that yielded 217.49 Ma U-Pb zircon crystallization age (R. Friedman, unpublished data). D. Picrite lapilli tuff near Schaft Creek. E. UHP detritus bearing conglomerate, Eclogite Ridge. F. Foliated siliceous schist clast in Lower Triassic Takwahoni Formation, Atlin Lake area. G. Middle Triassic Stuhini Group fine-grained siliciclastic rocks (foreground) that yielded ca. 241 Ma U-Pb zircon provenance (N. Joyce, unpublished data; foreground) are unconformably overlain by the Takwahoni Formation (cliffs in background) south of King Salmon Thrust, Inklin River area. H. Quartz-gold vein in graphitic phyllite, Atlin area. Photo is ~6 cm across.

are key to the overall understanding of magma genesis in supra-subduction settings, and may be crucial in elucidating the tectonic processes that resulted in the Late Triassic episode of prolific porphyry Cu–Mo(–Au) mineralization in northwestern British Columbia.

New results by Milidragovic et al. (2016b) indicate that the ultramafic tuff in the Schaft Creek area formed by accumulation (20–65%) of olivine (91% Mg end member, Fo_{91}) into a subalkaline picritic parental magma with MgO ~16 wt. %. Despite the high MgO content of the parental liquid, accessory chromite phenocrysts record liquidus temperatures <1200°C, suggesting crystallization from relatively low temperature, hydrous melts. The estimated H_2O content of the primary picritic magma, inferred on the basis of olivine-liquid thermometry and thermal models for subduction zones, is 5–7 wt. % thus negating the need for catastrophic thermal perturbations in the mantle wedge (e.g., Logan and Mihalynuk, 2014). Instead, efficient release of water through slab dehydration at 2.5–3.0 GPa allows generation of picritic melts at ordinary mantle wedge temperatures through moderate degrees (F=0.10–0.15) of hydrous flux melting of a depleted mantle. The volatile-rich nature of the melt facilitated the near-adiabatic ascent of the picrites. The role of this process in generating other Stuhini Group picritic volcanic rocks, which lack strong vesiculation, is not known. Whether or not picrites signal a flux of metals from the mantle to the Stikinia crust, to accumulate in porphyry deposits, is a topic of ongoing investigation.

Future work will focus on constraining the petrological and geochemical character of Stikinia's sub-arc mantle by extending the sample set to other Middle to Late Triassic localities and volcano-plutonic suites (e.g. Stuhini and Lewes River Groups, Polaris Suite). Preliminary isotopic data (Sr-Nd-Hf-Pb) suggest that the Stuhini picrites were derived from a depleted mantle source comparable to the source of the broadly coeval Karmutsen Formation basalt of Wrangellia (Greene et al., 2009).

Late Triassic – Early Jurassic plutonic suites (204–180 Ma)

Late Triassic – Early Jurassic plutonic suites are voluminous in Yukon where they include the Minto and Long Lake suites (ca. 204–180 Ma: (Tempelman, 1974; Johnston and Erdmer, 1995; Hart, 1996; Johnston et al., 1996; Hood 2012; Ryan et al. 2013; N. Joyce, unpublished data; Chapman, 2015). GEM results are augmented by a comprehensive study of the chronology and composition of Jurassic plutonic suites, co-funded by Yukon Geological Survey and Geological Survey of Canada, now in its final year.

Reconnaissance U-Pb SHRIMP II and LA-ICPMS investigations of the Aishihik batholith demonstrate a range of crystallization ages from ca. 193 to 181 Ma, including presence of Mississippian inheritance, probably sourced from the Simpson Range plutonic suite host lithologies (Joyce et al., 2016). The obtained age range is significantly younger than the adjacent Minto plutonic suite necessitating subdivision of the Jurassic plutonic suites (Colpron et al., 2016). High precision CA-TIMS data continues to be collected throughout the Jurassic plutonic suites in combination with geochemical and Sr-Sm-Nd-Pb isotopic data (Colpron and Sack, unpublished data; Colpron et al., 2016) in order to fully characterize Jurassic magmatism and to constrain the tectonic context of Jurassic magmatism and mineralization. Specifically, isotopic studies may shed light on the timing of interaction between Intermontane terranes in Yukon.

Late Triassic to Early Jurassic Mineralization

Late Triassic to Early Jurassic magmatic rocks in Cordillera are metallogenically important as they are cogenetic with many well-known porphyry deposits. Jurassic plutonic suites in west-central Yukon are also recognized for their Cu-Au potential as they host Minto and Carmacks deposits, which represent atypical porphyry style mineralization. Previous studies of mineralized zones at the Minto deposit have not been conclusive as to its origin, but sulphur and lead isotopic composition of the mineralization confirm a magmatic source for its metals, and together with intrusive textures and geobarometry suggests a porphyry deposit that was deeply buried (Tafti and Mortensen, 2004). A study of the Carmacks deposit was initiated to better constrain the relationship of Jurassic plutonic suites and mineralization.

The Carmacks Copper Cu-Au-Ag oxide deposit is hosted within a NNW-trending, 3km-long, and 20-100 m-wide structural and lithological corridor. Interlayered amphibolite and quartz-plagioclase-biotite schist are the oldest rocks on the property. Unmineralized, foliated to massive metavolcanic rocks are also present, generally in the vicinity of the main mineralizing trend. These rocks are interpreted to represent protoliths to the amphibolite and the schist, which is intruded by petrographically distinct, biotite granodiorite and hornblende monzodiorite phases of the Early Jurassic Granite Mountain Batholith (Minto plutonic suite of Colpron et al., 2016). The biotite granodiorite does not host mineralization and is undeformed. The hornblende monzodiorite is also unmineralized and undeformed; however, it becomes closely intercalated with the amphibolite/schist unit at the igneous contact, forming hybrid rock similar in texture to migmatite. This migmatite hosts a significant part of copper mineralization, and, in some parts of the deposit, is the primary copper target.

At least two deformation events overprint mineralization. The first deformation event (D_1) is evident in the amphibolite and schist as a strongly developed NNW-trending, steeply dipping S_1 fabric. The second deformation event (D_2) is probably coeval with the formation of migmatites with ptygmatic F_2 folds. Narrow leucosome veins within the amphibolite/schist that would have formed the neosome during migmatization are also folded during F_2, together with formation of rare F_2 crenulation with poorly developed axial cleavage.

Mineralization occurs in two different forms. Hypogene mineralization within the amphibolite-schist is foliaform chalcopyrite stringers, whereas migmatite- hosted mineralization is net-textured consisting of chalcopyrite, bornite, and digenite. Preliminary Re-Os geochronological results span the Triassic - Jurassic boundary (R. Creaser, unpublished data). Future work will continue to provide geochronological and age constraints on the magmatism and related mineralization in this area.

Jurassic sedimentation

Triassic and older rocks of Stikine terrane are overlapped by the Early to Middle Jurassic Laberge Group (Figs. 2, 3), a series of sedimentary and volcanic strata deposited in the Whitehorse Trough. Coeval volcanic rocks in British Columbia are the Hazelton Group and in Yukon the Nordenskjöld tuffs. Mihalynuk et al. (1995) recognized a reverse stratigraphy in conglomeratic clasts in the Sinemurian to Bajocian Laberge Group, particularly well displayed in the Taku River area, where clasts change up stratigraphic section revealing progressively deeper levels of incision of the adjacent Stikine terrane. Clasts change from volcanic dominated at the base to plutonic dominated in the upper Pliensbachian, and then highly-strained granitoid and metamorphic clasts in the Toarcian. Detrital provenance abruptly switched in the Middle Jurassic with a change in paleoflow directions and a flood of Cache Creek-derived chert pebbles. Previous zircon provenance age determinations from plutonic clasts (Shirmohammad et al., 2011) confirm a proximal Stikinia source similar to Laberge Group in Yukon (Colpron et al., 2015). Coeval strata in the Eclogite Ridge-Atlin Lake area were investigated by Mihalynuk et al. (2002, 2003) and English et al., 2003, 2005) and, along the shores of Atlin Lake, are well-constrained by ammonite biostratigraphy (Johannson et al., 1997). In this area, Sinemurian to Pliensbachian Laberge Group strata were sourced from predominantly volcanic units, with significant limestone input in the Sinemurian, and a major influx of plutonic detritus appearing in the Late Pleinsbachian. Metamorphic influx in this area is marked by a distinctive unit of garnetiferous wacke that is in part derived from garnet peridotite and ultra-high pressure eclogite sources (Canil et al., 2005; Canil et al., 2006; MacKenzie et al., 2005) and isolated exposures of granitoid and siliceous schist conglomerate (Fig. 3e,f).

Kellett et al. (in prep) investigated the source of the eclogite detritus in the Laberge Group by integrating a range of thermobarometric techniques (garnet-clinopyroxene ion exchange thermometry, Zr-in-rutile thermometry, quartz inclusion barometry and phase equilibria modeling) with in situ rutile cooling and detrital zircon crystallization U-Pb ages to constrain a source-to-sink path for the eclogite clasts. The results indicate that the eclogite reached peak metamorphic conditions of 2.1–2.9 GPa and 750–820 °C after ca. 202 Ma, cooled through Pb closure in rutile at ≥611 °C and were deposited into the basin at ca. 181 Ma. This history rules out many possible sources for the clasts, and implies minimum cooling and exhumation rates of 38 °C/myr and 3.7 km/myr, respectively, consistent with rates reported for subduction-related eclogite worldwide. Zircon provenance of the Eclogite Ridge member supports previous suggestion of predominantly Stikine terrane sources, however new Sm-Nd isotopic data also indicate a significant component of continental source in rocks containing metamorphic detritus (εNd -1.0 to -18.6: Zagorevski, unpublished data). Similar εNd results were obtained by Jackson et al. (1991) from Jurassic strata along Willison Bay. The most likely source for the clasts is the Yukon Tanana terrane – Stikine terrane suture that was formed and exhumed between 202 and 181 Ma.

Thermochronology of the eclogite detritus was complemented by U-Th/He dating of detrital zircon and apatite of the Laberge Group to constrain sediment source ages and burial through exhumation history of the basin. Preliminary U-Th/He dating of zircon and apatite, which provide cooling ages of ~180 °C and 60 °C, respectively, indicate resetting of detrital zircon ages towards the Taku River area (Lisadele Lake) suggesting higher peak basin temperatures in this part of the basin. Young resetting is also apparent along the footwall of the King Salmon thrust, and may help to constrain the timing of thrust motion. This dataset will be expanded in the near future, and ultimately combined with fission track dating of zircon and apatite into 1D thermal diffusion models that will be used to test post-assembly tectonic models for the Laberge Group.

King Salmon Thrust

The regional-scale King Salmon thrust is moderately north to northeast-dipping and emplaces the deep water Inklin Formation (Thorstad and Gabrielse, 1986) and/or Sinwa Formation (Souther, 1971; Bultman, 1979) over conglomeratic Takwahoni Formation (Souther, 1971). In the Inklin River area (Fig. 2), a study of the King Salmon thrust continued to test the tectono-stratigraphic relations from footwall to hangingwall. Our aim is to fully understand the structural interplay between the Stuhini Group and the Takwahoni and Inklin formations (Figs. 3g), those parts of the Laberge Group that are coeval with parts of the Hazelton Group, and the extents to which the regional thrusts could have tectonically buried the mineralized Late Triassic arc. Preliminary mapping confirms that a fold and thrust belt developed along the western Whitehorse Trough (e.g. Mihalynuk, Mountjoy et al., 1999; English et al., 2005). Middle Triassic sedimentary rocks in the footwall of the King Salmon Thrust yielded ca. 241 Ma provenance (N. Joyce, unpublished data; Fig. 3g), potentially suggesting a link with the Late Permian to Middle Triassic Kutcho arc. Above the King Salmon Fault, the fold and thrust belt appears to structurally thicken the latest Triassic (Norian-Rhaetian) Sinwa Formation limestone, and may repeat the limestone at the basin margin.

Coral fauna collected from the Upper Triassic Sinwa Formation have been identified as species previously known only from Nevada (G. Stanley, unpublished data). Sections were measured and systematically sampled for conodonts at Willison Bay on Atlin Lake and at Sinwa Mountain, in order to determine the duration of limestone deposition, locate the Norian-Rhaetian boundary, and to demonstrate thrust repetition within the limestone belt.

Cretaceous Magmatism and mineralization

Cretaceous intrusions are economically important in the Atlin-Whitehorse region. Rich copper skarns of the Whitehorse Copper belt are related to intrusion of the Whitehorse pluton of the Whitehorse Plutonic suite (108-112Ma; Hart, 1996, 1997). Near Atlin, the Surprise Lake batholith includes the polyphase Mount Leonard stock, host to the Adanac molybdenum deposit, for which recent U/Pb age determinations range from 81.6 ±1.1 to 77.5 ±1.0 Ma, and Re/Os age of mineralization are 70.87 ±0.36 to 69.72 ±0.35 Ma (Smith and Arehart, 2010, errors are 2σ). The crystallization age is consistent with an age reported by Mihalynuk et al. (1992) in which four grains overlapped concordia between 69 and 81 Ma. Pyroxene-bearing lamprophyre dykes cutting the Middle Jurassic Fourth of July batholith are intimately associated with mineralization at the past-producing Atlin Ruffner mine (MINFILE 104N011). Au-Ag-rich massive base metal massive sulphide veins at Atlin Ruffner occur along the margins of mafic dykes variously described as pyroxene-bearing lamprophyre, diabase or gabbroic (McIvor, 1989) and where the dykes are brecciated, as sulphide cementing lamprophyre clasts. Because lamprophyre dykes cutting the Fourth of July batholith were not observed to extend beyond the batholith, they were all considered to be co-magmatic products of late batholith crystallization (Mihalynuk et al., 1999), a contention confirmed by dates on two separate dykes, each about 17 km from the Atlin Ruffner mine (Harris et al. 2003). However, mapping in 2016 showed that lamprophyre dikes are regionally distributed west of the Fourth of July batholith, and are especially conspicuous where cutting intrusions of presumed Late Cretaceous age and where extending into massive limestone of the Cache Creek terrane. Because they cut intrusions of inferred Late Cretaceous age, this suite of lamprophyre dykes is tentatively assigned an age of Late Cretaceous or younger - a geological inference that is still to be confirmed by isotopic dating. To test age inferences, the lamprophyre dikes were sampled, including at the Atlin Ruffner mine. In the GEM study area beyond the Atlin camp, the affiliation of lamprophyre dykes with mineralization has yet to be evaluated.

Placer streams in the Atlin camp surround the Surprise Lake batholith and minerals intergrown with gold in placer nuggets include cassiterite and thorite, both commonly affiliated with the batholith, but not elsewhere in the area. Such observations led Sack and Mihalynuk (2004) to question if sporadic fine lode gold known within altered ultramafic rocks near Atlin, was the principal source of the Atlin placers, or if the source might be less restricted geologically, including mineralized zones within the broader thermal metamorphic halo of the Surprise Lake Batholith. In 2016, coarse lode gold was discovered in calcareous black phyllite bedrock (Fig. 3h) during placer mining on Otter Creek (Peter Shorts and Glen, pers. comm.), proving that ultramafic rocks are not a prerequisite for lode gold deposition. GEM work in progress will attempt to date fine-grained white mica at the margins of the gold-quartz vein and to characterize the lithologic / structural setting and mineralogy of the environment of gold deposition.

Conclusions

Reconnaissance and detailed mapping and sampling efforts conducted as part of the *Characterization of volcanic and intrusive rocks across the BC-Yukon border* activity have focused on the Mesozoic plutonic suites and their ancient arc and flanking environments in Yukon and northwest British Columbia. Preliminary results of field and geochronological work (on both newly collected and archival materials) demonstrate the value of subdividing plutonic and volcanic suites based on petrography and timing relationships; both key to revealing potential metal endowment of various stages in the volcanic arc evolution. Significant results to date include detailed characterization of Jurassic and Triassic plutonic suites and related volcanic rocks (Cutts et al., 2015; Joyce et al., 2016; Martin et al., 2016; Mihalynuk et al., 2016; Milidragovic et al., 2016a), improved understanding of mantle conditions (Milidragovic et al., 2016b) and improved understanding of tectonic interactions between terranes (Kellett et al., in prep) during latest Triassic and Jurassic times.

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References

Anderson, R.G. 1993. A Mesozoic stratigraphic and plutonic framework for northwestern Stikinia (Iskut River area), northwestern British Columbia, Canada. *In* Mesozoic paleogeography of the western United States, II:. *Edited by* G.C. Dunne and K.A. McDougall. Society of Economic Paleontologists and Mineralogists, Pacific Section, Los Angeles, CA. pp. 477-494.

Brown, D.A., Gunning, M.H., and Greig, C.J. 1996. The Stikine project: geology of western Telegraph Creek map area, northwestern British Columbia (NTS104G/5, 6, 11W 12 and 13). British Columbia Ministry of Energy, Mines and Petroleum Resources, Bulletin 95, 183 p.

Bultman, T.R. (1979): Geology and tectonic history of the Whitehorse Trough west of Atlin; unpublished Ph.D. thesis, Yale University, 284 pages.

Chapman, J.B., 2015. Syn-magmatic deformation and structural relationships within Jurassic granitoid rocks of the Aishihik batholith, Yukon. Geological Survey of Canada, Open File 7961.

Cohen, K.M., Finney, S.C., Gibbard, P.L. and Fan, J.-X. 2016; updated from 2013. The ICS International Chronostratigraphic Chart. Episodes 36: 199-204.

Colpron, M., Crowley, J.L., Gehrels, G., Long, D.G.F., Murphy, D.C., Beranek, L., and Bickerton, L. 2015. Birth of the Northern Cordilleran Orogen, as recorded by detrital zircons in Jurassic synorogenic strata and regional exhumation in Yukon. Lithosphere. doi: 10.1130/l451.1.

Coulson, I.M., Russell, J.K., and Dipple, G.M. 1999. Origins of the Zippa Mountain Pluton; a Late Triassic, arc-derived, ultrapotassic magma from the Canadian Cordillera. Canadian Journal of Earth Sciences 36: 1415-1434.

Dusel-Bacon, C., Slack, J.F., Aleinikoff, J.N., and Mortensen, J.K. 2007. Mesozoic magmatism and base-metal mineralization in the Fortymile mining district, eastern Alaska; initial results of petrographic, geochemical, and isotopic studies in the Mount Veta area. U. S. Geological Survey Professional Paper.

Greene. A.R., Scoates, J.S., Weis, D., Nixon, G.T., and Kieffer, B., 2009. Melting history and magmatic evolution of basalts and picrites from the accreted Wrangellia oceanic plateau, Vancouver Island, Canada. Journal of Petrology 50: 467-505.

Harris, M. J., MacNiocaill, C., Symons, D. T. A., Blackburn, W. H., Hart, C. J. R., Villeneuve, M., Torsvik, T. H., and van der Pluijm, B. A., 2003. Travels of the Cache Creek Terrane; a paleomagnetic, geobarometric and ^{40}Ar/^{39}Ar study of the Jurassic Fourth of July Batholith, Canadian Cordillera: Tectonophysics, 362, p. 137-159

Hart, C.J.R. 1996. Magmatic and tectonic evolution of the Intermontane Superterrane and Coast Plutonic Complex in southern Yukon Territory. M.Sc. thesis, University of British Columbia, Vancouver.

Hart, C. J. R., 1997, A transect across Northern Stikinia: Geology of the Northern Whitehorse map area, Southern Yukon Territory (105D/13-16): Bulletin - Exploration and Geological Services Division, Yukon region, 8, 113 p.

Hart, C.J.R., Miller, D.M., Dickie, J.R., Ghosh, D.K., Armstrong, R.L., and Busby, C. 1995. Provenance constraints for Whitehorse Trough conglomerate; U-Pb zircon dates and initial Sr ratios of granitic clasts in Jurassic Laberge Group, Yukon Territory. Special Paper - Geological Society of America 299: 47-63.

Hood, S.B. 2012. Mid-crustal Cu-Au mineralisation during episodic pluton emplacement, hydrothermal fluid flow, and ductile deformation at the Minto Deposit, YT, Canada. M.Sc. thesis, University of British Columbia.

Jackson, J. L., Gehrels, G. E., Patchett, P. J., and Mihalynuk, M. G., 1991. Stratigraphic and isotopic link between the northern Stikine Terrane and an ancient continental margin assemblage, Canadian Cordillera: Geology 19: 1177-1180.

Joyce, N.L., Colpron, M., Allan, M.M., Sack, P.J., Crowley, J.L and Chapman, J.B., 2016. New U-Pb zircon dates from the Aishihik batholith, southern Yukon. In: Yukon Exploration and Geology 2015, K.E. MacFarlane and M.G. Nordling (eds.), Yukon Geological Survey, p. 131-149.

Logan, J.M., Drobe, J.R., and McClelland, W.C. 2000. Geology of the Forrest Kerr-Mess Creek area, northwestern British Columbia (NTS 104B/10,15 & 104G/2 & 7W). British Columbia Ministry of Energy and Mines, Energy and Minerals Division, Geological Survey Branch, Bulletin 104, 163 p.

Logan, J.M., and Koyanagi, V.M. 1994. Geology and mineral deposits of the Galore Creek area (104G/3, 4). Ministry of Energy, Mines and Petroleum Resources, Bulletin 92, 95 p.

Logan, J.M., and Mihalynuk, M.G. 2014a. Tectonic controls on early Mesozoic paired alkaline porphyry deposit belts (Cu-Au + or - Ag-Pt-Pd-Mo) within the Canadian Cordillera. Economic Geology and the Bulletin of the Society of Economic Geologists 109(4): 827-858.

Logan, J.M., and Mihalynuk, M.G. 2014b. Tectonic controls on Early Mesozoic paired alkaline porphyry deposit belts (Cu-Au ± Ag-Pt-Pd-Mo) within the Canadian Cordillera. Economic Geology 109: 827-858.

Logan, J.M., Moynihan, D.P., Diakow, L.J., and Van Straaten, B.I. 2012. Dease Lake - Little Tuya River Geology, NTS 104J/ 08 & 07E. Geoscience BC Map 2012-08-1 and British Columbia Geological Survey Open File 2012-04, 1 sheet.

Massey, N.W.D., MacIntyre, D.G., Desjardins, P.J. and Cooney, R.T., 2005: Digital Map of British Columbia: Whole Province, B.C. Ministry of Energy and Mines, GeoFile 2005-1.

Martin, K., Zagorevski, A., Mihalynuk, M.G., and Creaser, R., 2016. Circa 180 Ma Ag-Bi-Pb-Mo-Cu-bearing quartz veins in a post-thrust calc-alkaline intrusion near Surprise Mountain, Iskut River area, northwestern British Columbia. In: Geological Fieldwork 2015, British Columbia Geological Survey Paper 2016-1, pp. 77-94.

McIvor, D., 1989. 1988 Summary Report. The Results of a Diamond Drilling Program on the Pictou Property, (Mining Lease 32) Atlin Mining Division, British Columbia. Homestake Mineral Development Co. Ltd. in-house report.

Mihalynuk, M.G., Lefebure, D.V., Gabites, J.E., Orchard, M.J., Tozer, E.T., McMillan, W.J., and

McArthur, J.G. 1997. Age of the Willison Bay Pluton and overlying sediments; implications for the Carnian stage boundary. Geological Fieldwork 1996, Paper 1997-1, 171-179.

Mihalynuk, M.G., Zagorevski, A., and Cordey, F. 2012. Geology of the Hoodoo Mountain area (NTS 104B/14). Geological Fieldwork 2011, BC Ministry of Forests, Mines and Lands, Paper 2012-1: 45-67.

Mihalynuk, M.G., Zagorevski, A., Joyce, N.L. and Creaser, R.A., 2016. Age of magmatism and mineralization at the Star (Sheslay, Copper Creek) copper porphyry prospect: inception of the Late Triassic mineralized arc. In: Geological Fieldwork 2015, British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2016-1, pp. 65-75.

Mihalynuk, M.G., Mountjoy, K.J., Smith, M.T., Currie, L.D., Gabites, J.E., Tipper, H.W., Orchard, M.J., Poulton, T.P., and Cordey, F. 1999. Geology and mineral resources of the Tagish Lake area (NTS 104M/8,9,10E, 15 and 104N/12W), northwestern British Columbia. Bulletin - British Columbia Ministry of Energy and Mines, Energy and Minerals Division, Geological Survey Branch.

Mihalynuk, M.G., Johnston, S.T., Lowe, C., Cordey, F., English, J.M., Devine, F.A.M., Larson, K., and Merran, Y. 2002. Atlin TGI; Part II, Preliminary results from the Atlin Targeted Geoscience Initiative, Nakina area, Northwest British Columbia. Geological Fieldwork 2001, Paper 2002-1: 5-18

Mihalynuk, M. G., Johnston, S. T., English, J. M., Cordey, F., Villeneuve, M. E., Rui, L., and Orchard, M. J., 2003, Atlin TGI; Part II, Regional geology and mineralization of the Nakina area (NTS 104N/2W and 3): Geological Fieldwork 2002, Paper 2003-1, 9-37.

Mihalynuk, M.G., Smith, M., Gabites, J.E., Runkle, D. and Lefebure, D., 1992, Age of emplacement and basement character of the Cache Creek terrane as constrained by new isotopic and geochemical data; Canadian Journal of Earth Sciences, 29, pages 2463-2477.

Milidragovic, D., Chapman, J.B., Bichlamier, S., Canil, D., and Zagorevski, A., in press. H2O-driven generation of picritic melts in the Middle to Late Triassic Stuhini arc of the Stikine terrane, British Columbia, Canada. Earth and Planetary Science Letters (2016).

Oliver, J., and Gabites, J. 1993. Geochronology of rocks and polyphase deformation, Bearskin (Muddy) and Tatsamenie Lakes District, northwestern British Columbia (104K/8, 1). Paper - Ministry of Energy, Mines and Petroleum Resources, 177-189.

Ryan, J.J., Zagorevski, A., Williams, S.P., Roots, C., Ciolkiewicz, W., Hayward, N., and Chapman, J.B. 2013. Geology, Stevenson Ridge (northeast part), Yukon. Geological Survey of Canada, Canadian Geoscience Map.

Ryan, J.J., Zagorevski, A., Roots, C.F., and Joyce, N., 2014. Paleozoic tectonostratigraphy of the northern Stevenson Ridge area, Yukon; Geological Survey of Canada, Current Research 2014-4, 13 p.

Sack, P.J. and Mihalynuk, M.G., 2004, Proximal gold-cassiterite nuggets and composition of the Feather Creek placer gravels: clues to a lode source near Atlin, B.C., Geological Fieldwork 2003, Paper 2004-1, 147-162.

Scott, J.E., Richards, J.P., Heaman, L.M., Creaser, R.A., and Salazar, G.S. 2008. The Schaft Creek porphyry Cu-Mo-(Au) deposit, northwestern British Columbia. Exploration and Mining Geology 17(3-4): 34.

Shirmohammad, F., Wierzbowski, A., Smith, P. L., Anderson, R. G., McNicoll, V. J., Pienkowski, G., Sha, J., and Wang, Y., 2011. The Jurassic succession at Lisadele Lake (Tulsequah map area, British Columbia, Canada) and its bearing on the tectonic evolution of the Stikine Terrane: Volumina Jurassica, 9, p. 43-60.T

Tafti, R. and Mortensen, J.K., 2004. Early Jurassic porphyry(?) copper (-gold) deposits at Minto and Williams Creek, Carmacks Copper Belt, western Yukon. In: Yukon Exploration and Geology 2003, D.S. Emond and L.L. Lewis (eds.), Yukon Geological Survey, 289-303.

Takaichi, M. and Johnson, C., 2012, Teck Assessment Report on the 2011/2012 Geological, Geochemical, and Geophysical program at the Eagle Property, BC, Canada, British Columbia Geological Survey Assessment Report Indexing System, Report 33330, 383 p.

Takaichi, M., 2013, Teck Assessment Report on the 2012 Geological , Geochemical, and Geo-physical Program at the Eagle Property, BC, Canada, British Columbia Geological Survey Assessment Report Indexing System, Report 34266, 366 p.

Thorstad, L.E., and Gabrielse, H., 1986, The Upper Triassic Kutcho Formation, Cassiar Mountains, north-central British Columbia; Geological Survey of Canada, Paper 86-16, 53 p.

Woodsworth, G.J., Anderson, R.G., and Armstrong, R.L. 1991. Plutonic regimes. *In* Geology of the Cordilleran Orogen in Canada. *Edited by* H. Gabrielse and C.J. Yorath. Geological Survey of Canada. pp. 491-531.

Zagorevski, A., Mihalynuk, M.G., Joyce, N., Martin, K., 2014. Characterization of volcanic and intrusive rocks across the British Columbia – Yukon border, GEM 2 Cordillera; Geological Survey of Canada, Open File 7697, 8 p.

Zagorevski, A., Mihalynuk, M.G., Joyce, N., Kellett, D., Milidragovic, D., 2015. Characterization of volcanic and intrusive rocks across the British Columbia – Yukon border, GEM 2 Cordillera; Geological Survey of Canada, Open File 7956, 11 p.