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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 2015, 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 is temporally associated with a geochemical transition from normal calc-alkaline to alkaline magmatism (e.g., Logan and Mihalynuk 2014a), which suggests a major change in subduction geometry and/or melting regime within the sub-arc lithosphere. This phenomenon is well documented in the Cordillera for volcanic arc rocks between about 200 and 220 Ma, as well as in both in older and younger magmatic system; however the significance of 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 volcanic cap to plutonic roots study of the Mesozoic to Cenozoic arc belts in the northern Cordillera, especially where the calc-alkaline to alkaline transition has been documented and where potential for additional deposit discoveries remains high. Consequently, systematic mapping and regional

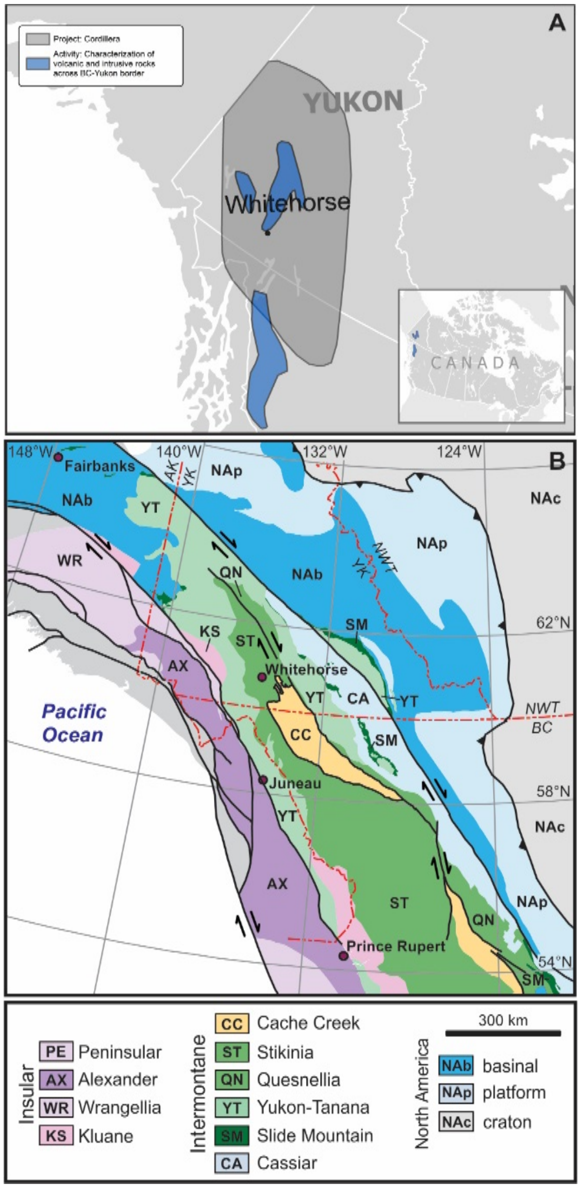

Figure 1 A. Cordillera project footprint. B. Terranes of the Northern Cordillera (from Colpron and Nelson, 2011).

reconnaissance sampling in 2015 were 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 (in BC: Souther, 1971; Brown et al., 1996) and Lewes River groups (in Yukon: Wheeler, 1961; Hart et al., 1995), and Jurassic Hazelton and Laberge groups (e.g., Brown et al., 1996; Cutts et al., 2015).

Goals and objectives

Establishing regional geochronological coverage in the North is the first step towards understanding regional tectonic controls on magmatic and linked sedimentary deposition and mineralization. Importance of these data is highlighted by the mineral exploration industry where field programs rely heavily on correct identification of metal-rich magmatic suites. To resolve these gaps in our knowledge of the timing and genesis of magmatic suites, we have initiated reconnaissance geochronological and geochemical studies focused at present on the Late Triassic and Early Jurassic plutonic suites known to be most highly mineralized, and their volcano-sedimentary successions in Yukon and British Columbia. Our field sampling has been complemented by archived sample collections and legacy data.

Preliminary results

Stikine, Polaris and Pyroxene Mountain plutonic suite (ca. 228-215 Ma)

The Stikine plutonic suite in Yukon is limited to small volume plutons, such as the Tally Ho gabbro (ca. 214 Ma: Hart, 1996). Stocks, dykes and sills of Pyroxene Mountain Suite clinopyroxenite and hornblendite (Ryan et al., 2013) likely represent cumulate rocks to the Stikine plutonic suite. Paucity of Stikine plutonic

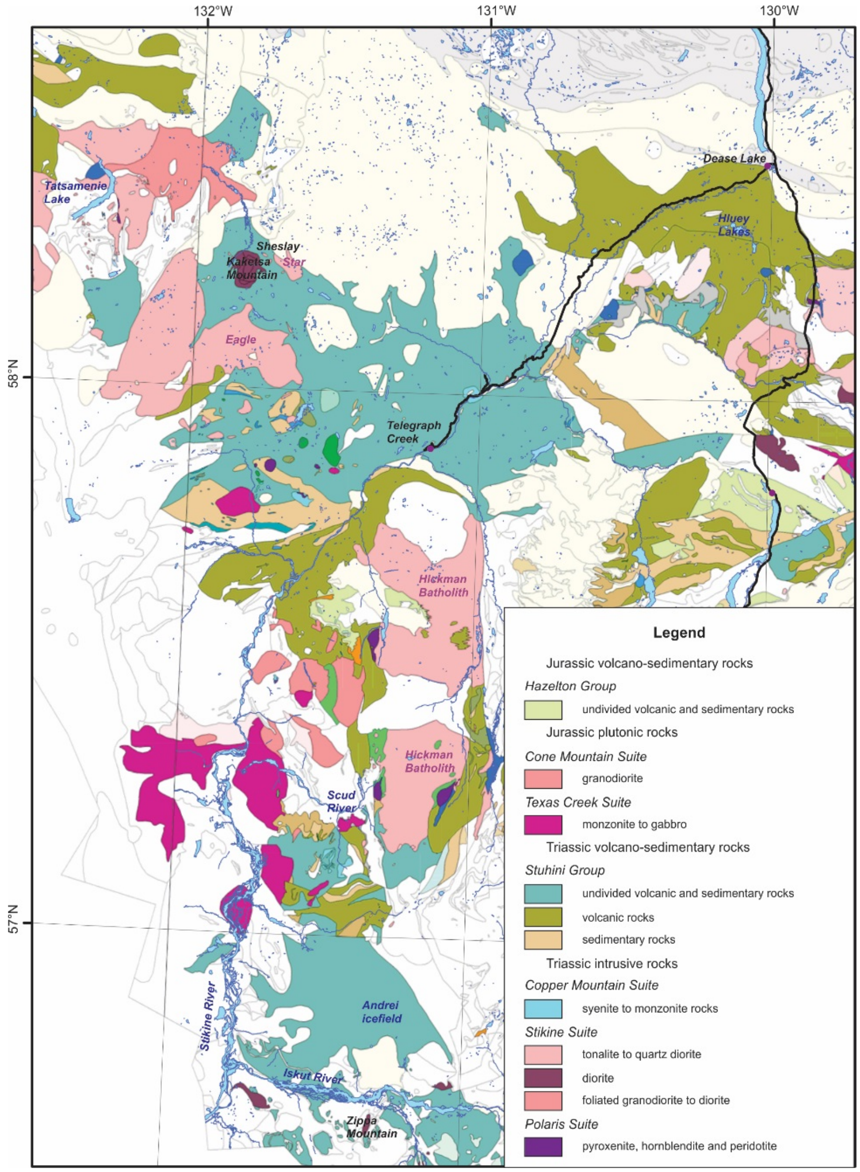

Figure 2 Simplified geology of the northern Stikine terrane from Tatsamenie Lake to Iskut River showing the distribution of Triassic and Early Jurassic plutonic suites and volcano-sedimentary rocks (modified from Massey et al., 2005)

suite in Yukon may partly be due to latest Triassic exhumation and erosion of the Stuhini-Lewes River arc as evidenced by an abundance of ca. 210 Ma zircon in the granitoid clast-rich Mandanna Member conglomerate of the Lewes River Group (N. Joyce, unpublished data; Colpron et al., 2015) and abundant ca. 215-208 Ma boulders of K-feldspar porphyritic biotite granite in the overlying Jurassic Whitehorse Trough (Hart et al. 1995). Farther to the northwest, the Taylor Mountain batholith granodiorite in Alaska represents a continuation of Late Triassic magmatism that may be equivalent to the Stuhini-Lewes River arc (ca. 212 Ma in Dusel-Bacon et al., 2007). In west-central Yukon, Pyroxene Mountain suite hornblendite yielded ca. 218 Ma $^{40}Ar/^{39}Ar$ cooling age (Ryan et al., 2014).

In British Columbia, the Stikine plutonic suite (Figs. 2, 3) comprises calc-alkaline diorite to monzogranite plutons. Only sparse in the north,

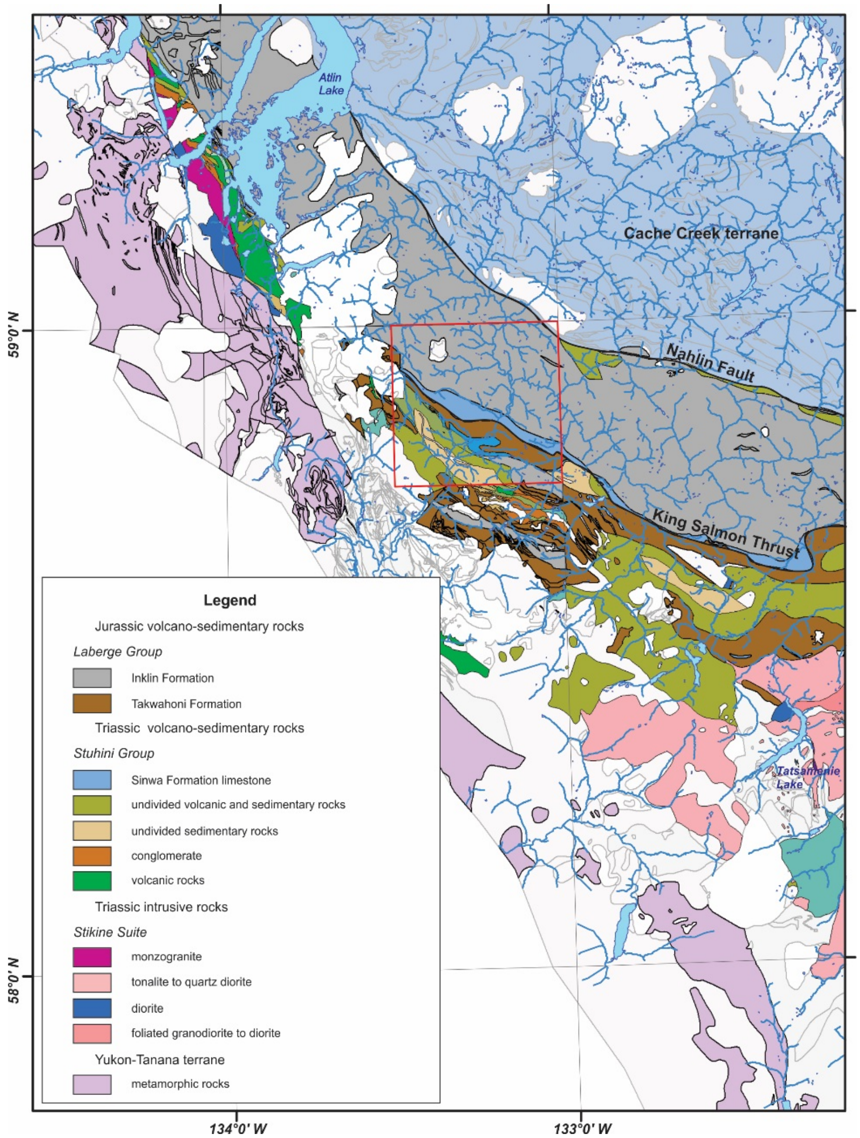

Figure 3 Simplified geology of the northern Stikine terrane from Tatsamene Lake to Atlin Lake showing the distribution of Triassic and Early Jurassic plutonic suites and volcano-sedimentary rocks (modified from Massey et al., 2005). Inklin area is indicated by a red rectangle.

these plutons become widespread south of 58°30’N. The Stikine suite is locally associated with ultramafic rocks including pyroxenite, hornblendite and minor dunite assigned to the Polaris suite by Woodsworth et al. (1991). The Stikine plutonic suite is known to host Cu-Mo mineralization (e.g., ca. 222 Ma Schaft Creek: Scott et al., 2008; ca. 219 Ma Icy Pass: Oliver and Gabites, 1993).

Reconnaissance work on the Stikine plutonic suite in the Iskut, Telegraph Creek, Sheslay Tatsamenie Lake and Atlin areas (Figs. 2, 3) revealed a compositional diversity from gabbro to monzogranite (Zagorevski et al., 2014). Based on constituent mineralogy and texture they comprise three units: lTrSd, lTrSgd, lTrSmz. *Unit lTrSd* is isotropic to weakly foliated hornblende±biotite gabbro, diorite and quartz diorite (Fig. 3B). Two samples of unit lTrSd yielded 229.7 and 225.99 Ma ages (U-Pb zircon: Joyce and Friedman,

Figure 4 Representative photographs of the Stikine terrane. A. Stikine plutonic suite foliated hornblende-biotite granodiorite, Tatsamenie Lake area. B. Multiple phases of magma in Stikine Plutonic Suite, Tatsamenie Lake area. C. Mingling of Stikine Plutonic suite biotite monzogranite and gabbro, Atlin Lake area. D. Highly deformed siliceous schist clast in Jurassic conglomerate, Atlin Lake area. E. Stuhini Group (?) andesite breccia Inklin River area. F. Limestone and chert form prominent marker horizons in the Inklin River area. G. Inklin Formation deep water cross-bedded calcilutite. H. Limestone-granite-chert conglomerate interbeded with coarse sandstone in the Inklin Formation north of King Salmon Thrust, Inlin River area.

unpublished data). These rocks are associated with porphyry-style mineralization at the Star Cu-Au deposit and, to the west, underlie Kaketsa Mountain (Fig. 2). Mineralization from the Star Cu-Au deposit yielded a 227.2 Ma age (Re-Os molybdenum: Creaser, unpublished data). These ages are similar to Stikine plutonic suite intrusive rocks at the Eagle property (227.2±0.7, 225.45±0.31 Ma: Takaichi and Johnson, 2012; Takaichi, 2013).

Unit lTrSgd, exposed east of Tatasamenie Lake and south of Telegraph Creek, is characterized by locally strongly foliated hornblende-biotite tonalite-granodiorite-diorite (Figs. 2, 4a,b). Two samples of this type yielded 222.00 and 219.80 Ma ages (U-Pb zircon; Friedman, unpublished data). A generally unfoliated quartz-diorite at the Eagle property (Fig. 2) is of similar age: 221.5±1.5 Ma: (Takaichi, 2013) and ca. 222 Ma (Joyce, unpublished data)

Unit lTrSmz is comprised of biotite monzogranite that locally contains K-feldspar up to a few cm long (Fig. 4c) which may display 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 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 samples archived from past K-Ar isotopic age determinations on hornblende and biotite revealed a spread of new $^{40}Ar/^{39}Ar$ cooling ages ranging from ca. 229 to 171 Ma and ca. 231-169 Ma for respectively (Joyce, unpublished data) suggesting mis-correlation or significant resetting of some of the plutonic rocks.

Copper Mountain plutonic suite (215-200 Ma)

Plutonic and hypabyssal rocks of the Copper Mountain suite (Fig. 2) are compositionally diverse, typically form small-volume alkaline bodies (Anderson, 1993; Logan et al., 2000; Woodsworth et al., 1991), and are locally associated with volcanic and epiclastic rocks (Logan and Koyanagi 1994; Mihalynuk et al. 2012). Copper Mountain suite plutons range from pyroxenite, gabbro and monzodiorite to biotite syenite (Anderson, 1993; Logan et al., 2000; Woodsworth et al., 1991), and distinctive silica undersaturated, feldspathoid-bearing dykes and stocks. This suite is highly prospective for Cu-Au porphyry deposits as exemplified by the Galore Creek deposit (ca. 210 Ma: Logan and Mihalynuk 2014b).

Regional distribution of the silica-saturated members is poorly constrained, but these alkaline plutons appear to form a north-trending belt from Zippa Mountain to Telegraph Creek. Similar alkaline plutons have not yet been recognized north of ~58º30"N. Preliminary $^{40}Ar/^{39}Ar$ analyses yielded biotite cooling ages ranging from 218 to 198 Ma (Joyce, unpublished data).

Jurassic plutonic suites (200-180 Ma)

Jurassic plutonic suites are voluminous in Yukon where they are represented by the Aishihik and Long Lake suites (ca. 201-180 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). A comprehensive study of the chronology and composition of Jurassic plutonic suites is being co-funded by Yukon Geological Survey and Geological Survey of Canada (Sack et al., in prep), Mineral Deposits Research Unit, University of British Columbia and Copper North Mining Corp. (N. Kovaks and M. Allen).

Correlative rocks in British Columbia include the Texas Creek and Cone Mountain suites (Fig. 2) where they comprise diverse lithologies ranging from granodiorite to K-feldspar megacrystic monzogranite to syenite (Brown et al., 1992; Anderson, 1993; Logan et al., 2000; Woodsworth et al., 1991). These plutons have variable alkaline to calc-alkaline affinities. They are exposed in a broad northwest trending belt in NW British Columbia (e.g, Logan et al. 2000). These suites are associated with precious metal vein mineralization at past-producing Silbak, Premier, Johnny Mountain and Snip mines and at the massive, recently permitted, KSM (Kerr-Sulphurets-Mitchell) cluster of porphyry deposits. $^{40}Ar/^{39}Ar$ analysis of some previously mapped Jurassic plutons reveals Eocene cooling ages indicating either miscorrelation or resetting by the Sloko-Hyder plutonic suite. Examination of mineralized hornblende-biotite granodiorite in the Iskut River area (Fig. 2) revealed ca. 182 Ma biotite cooling and 180.2 Ma mineralization age (Re-Os molybdenite: Creaser, unpublished data; Martin, 2015).

Stuhini Group

Emplacement of Late Triassic Stikine plutonic suite was coeval with arc volcanism comprising the predominantly subaqueous, mafic to felsic volcanic and related sedimentary rocks which are included in the Stuhini Group (Souther, 1971). Ultramafic rocks were emplaced as pyroclastic olivine-rich picritic tuff within the Middle to Upper Triassic Stuhini Group and are principally exposed along the eastern margin of the Hickman Batholith, ~130 km south-west of the town of Dease Lake (Fig. 2; Logan et al., 2000). The Hickman Batholith also contains scattered ultramafic intrusions of the Polaris Suite (Nixon et al., 1989; Logan and Koyanagi, 1994; Brown et al., 1996), to which the nearby ultramafic tuffs may be genetically related. Extrusive ultramafic (picritic) rocks have been interpreted as evidence for tearing of oceanic lithosphere subducted beneath the Stikine terrane in Late Triassic (Logan and Mihalynuk, 2014). If correct, the distinctive picritic rocks potentially comprise a distinctive time marker in the evolution of the Stikine terrane and its metal endowment. A study aimed specifically at the age and petrogenesis of the Late Triassic ultramafic rocks led by D. Milidragovic will offer reveal the mantle conditions during emplacement of Cu ± Au-Mo-Ag deposits along the length of the arc, and will test the recently proposed slab-tear model of Logan and Mihalynuk (2014).

One component of the 2015 field study focused on several sections of serpentinized, mafic to ultramafic lapilli tuffs and minor flows around the Hickman Batholith, including a <100 m thick succession in the Mess Lake facies (Logan et al., 2000) of the Stuhini Group. Another study component focused on detailed mapping of the Yehiniko peridotite body which revealed no intrusive (cumulate) ultramafic rocks; rather, ultramafic pyroclastic rocks were identified. Recognition of multiple restricted localities with picritic volcanic rocks indicates that ultramafic volcanism, was widespread, albeit not volumetrically significant, throughout NW Stikinia.

Preliminary results indicate that the olivine-rich lapilli tuffs and lapilli breccias were emplaced during at least 4 eruptive cycles, with limited depositional activity between each cycle. Some picritic samples appear to be fresh, containing unaltered glass that is well suited for geochemical studies (both major and trace) and determination of eruptive volatile contents. U-Pb and Sm-Nd geochronology will be applied to constrain the age of emplacement of the ultramafic rocks, and isotopic studies (Rb-Sr and Sm-Nd) will be used to assess the contributions of different reservoirs during petrogenesis of ultramafic magmas.

Hazelton and Laberge Group

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 Aishihik Suite and Nordenskjold tuffs. Deposition and subsequent deformation of the Whitehorse Trough records the collapse and accretion of the Stikine arc to western margin of ancestral North America. Provenance studies indicate that the Laberge Group strata were predominantly derived from Triassic and older volcanic, plutonic and sedimentary rocks in adjacent Stikine terrane. Several sections were investigated in detail and sampled in order to constrain the exhumation history of these sources. Selected traverses include Lisadele Lake, Eclogite Ridge-Atlin Lake, Willison Bay and Carcross-Whitehorse (Fig. 3).

Sinemurian to Bajocian Laberge Group strata in the Lisadele Lake area are superbly exposed and well-constrained by ammonite biostratigraphy (Mihalynuk et al., 1995; Mihalynuk et al., 1999; Mihalynuk et al., 2004; Shirmohammad et al., 2011). Mihalynuk et al. (1995) recognized a reverse stratigraphy in conglomeratic clasts as they changed up stratigraphic section revealing progressively deeper levels of Stikinian arc incision. They change from volcanic dominated at the base to plutonic dominated in the upper Pliensbachian, and then highly-strained granitoid metamorphic in the Toarcian. Zircon age provenance determinations from plutonic clasts (Shirmohammad et al., 2011) confirm a proximal Stikinia source and rapid dissection of the volcanic arc and its roots. Building on this work, a suite of metamorphic cobbles was sampled with the aim of constraining metamorphic source terrain(s) through petrography and geochronology. Exhumation history of the source region(s) will be further investigated through zircon double dating (zircon U-Pb + U/Th-He).

Laberge Group strata of the Eclogite Ridge-Atlin Lake area was investigated by Mihalynuk et al. (2002, 2003) and English et al., 2003, 2005) and along the shores of Atlin Lake is well-constrained by ammonite biostratigraphy (Johannson et al., 1997). In this area, Sinemurian to Pleinsbachian 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. 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) was reinvestigated with the purpose of constraining the age of the eclogitic detritus and thermal evolution of the source terrains. Our initial field observations indicate that rare detrital garnet does occur outside of the mapped Eclogite Ridge Formation, suggesting either mis-assignment of stratigraphic units or multiple influxes of metamorphic detritus.

Mihalynuk et al. (1999) investigated the stratigraphy of the Stuhini Group in the Willison Bay-Llewelyn Glacier area where miscorrelation led to an interpretation of Norian exhumation of the Triassic Willison Bay pluton. U-Pb SHRIMP analyses of sandstone from "basal Stuhini Group" conglomerate in this area yielded Jurassic depositional ages (Joyce, unpublished data); thereby identifying a previously unrecognized section of basal Laberge Group west of the King Salmon thrust. Jackson et al. (1991) sampled these strata along Willison Bay and obtained negative εNd values suggesting a continental source component. Re-investigation of the basal Laberge Group indicates that the Willison Bay pluton and adjacent contact metamorphosed Stuhini Group volcanic rocks are primary sediment sources. Correlative conglomerate identified at the receding toe of the Llewelyn glacier has similar clast provenance, but additionally, a distinctive horizon containing siliceous mylonite/schist metamorphic clasts

(Fig. 4d) similar to the adjacent Boundary Ranges metamorphic suite (correlated with the Yukon-Tanana terrane). This horizon was sampled and will also be investigated through petrography and geochronology to characterize metamorphic sources of 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 area (Fig. 3), a study of the King Salmon thrust was initiated to identify the tectono-stratigraphic relations from footwall to hangingwall. Our aim is to fully understand structural interplay of Stuhini Group (Fig. 4e, f) and Takwahoni and Inklin formations (Figs. 4g, h; Laberge Group, coeval with parts of the Hazelton Group) and the extents to which the regional thrust tectonically buries the mineralized Late Triassic arc. Preliminary mapping indicates development of a complex fold and thrust belt along the western Whitehorse Trough, consistent with previous structural studies (e.g. Mihalynuk, Mountjoy et al., 1999; English et al., 2005).

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 characterizing the Mesozoic plutonic suites and their ancient arc 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. Regional plutonic, volcano-stratigraphic and structural syntheses (A. Zagorevski, M. Mihalynuk (BCGS)) will frame detailed on-going studies of ultramafic and mafic volcanic petrogenesis (D. Milidragovic), sedimentary successions (D. Kellett); and plutonic episodes (P. Sack (YGS), M. Colpron (YGS), D. Milidragovic, N. Kovaks (MDRU), J. Chapman).

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