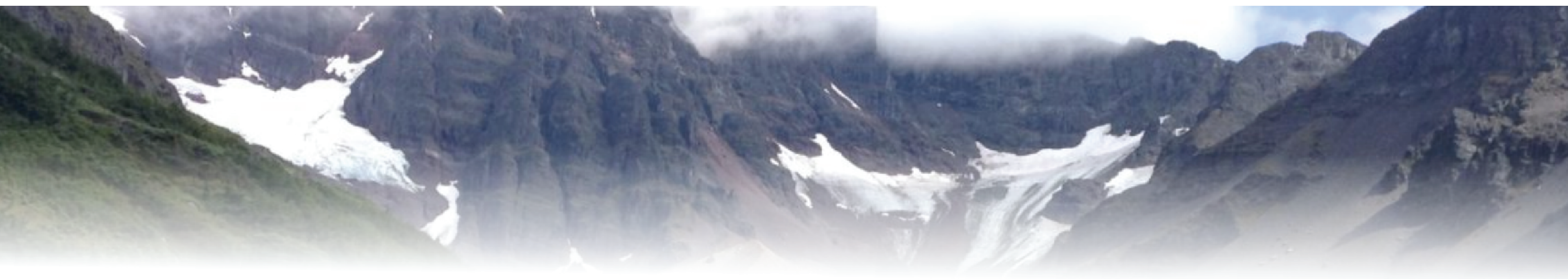
Orogeny to Ore

Cordilleran Tectonics Workshop 2017
February 24-26

hosted by

Mineral Deposit Research Unit
Department of Earth, Ocean & Atmospheric Sciences
University of British Columbia



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Cordilleran Tectonics Workshop 2017
February 24-26

Welcome to the Point Grey campus of The University of British Columbia for the 2017 Cordilleran Tectonics Workshop! The CTW is a uniquely informal but technically rigorous occasion for researchers from various universities, government agencies, and private industry to share and discuss the latest scientific developments in the assembly of the North American Cordillera.

The theme of CTW 2017 is *Orogeny to Ore*, in recognition of the inseparable relationship between the tectonic history of the Cordillera and the formation of its diverse mineral endowment.

We are especially fortunate to preface the CTW 2017 program with a Friday night colloquium, featuring three internationally recognized giants of Cordilleran research: **Jim Mortensen**, **Jim Monger,** and **Rich Goldfarb**. What better way to whet your appetites for a weekend of geological delight!

On behalf of the Mineral Deposit Research Unit, The Department of Earth, Ocean & Atmospheric Sciences, and The University of British Columbia, welcome!

The CTW 2017 Organizing Committee:

Joel Angen
Craig Hart
Libby Sharman
Murray Allan

a place of mind

UBC

MDRU
Mineral Deposit Research Unit

CTW 2017 at a glance

FRIDAY FEB 24 - CTW COLLOQUIUM *(Earth Sciences Building, Room 1012)*

5:00pm: **Registration and Poster set-up**

6:30 - 8:30pm: **Technical Presentations**

Jim Mortensen: *The Northern Cordillera as a Natural Laboratory for the Tectonics and Metallogeny of Orogenic Belts*

Jim Monger: *Deciphering Canadian Cordilleran tectonics: past, present and future*

Richard Goldfarb: *Growth of the North American Cordillera and metallogenic evolution along an active continental margin*

8:30-10:00pm: **Questions & Discussion / Wine & Cheese Social**

SATURDAY FEB 25 - CTW TECHNICAL SESSION *(Earth Sciences Building, Room 1012)*

7:30am: **Light Breakfast and Registration**

8:30am - 4:00pm: **Technical Presentations**

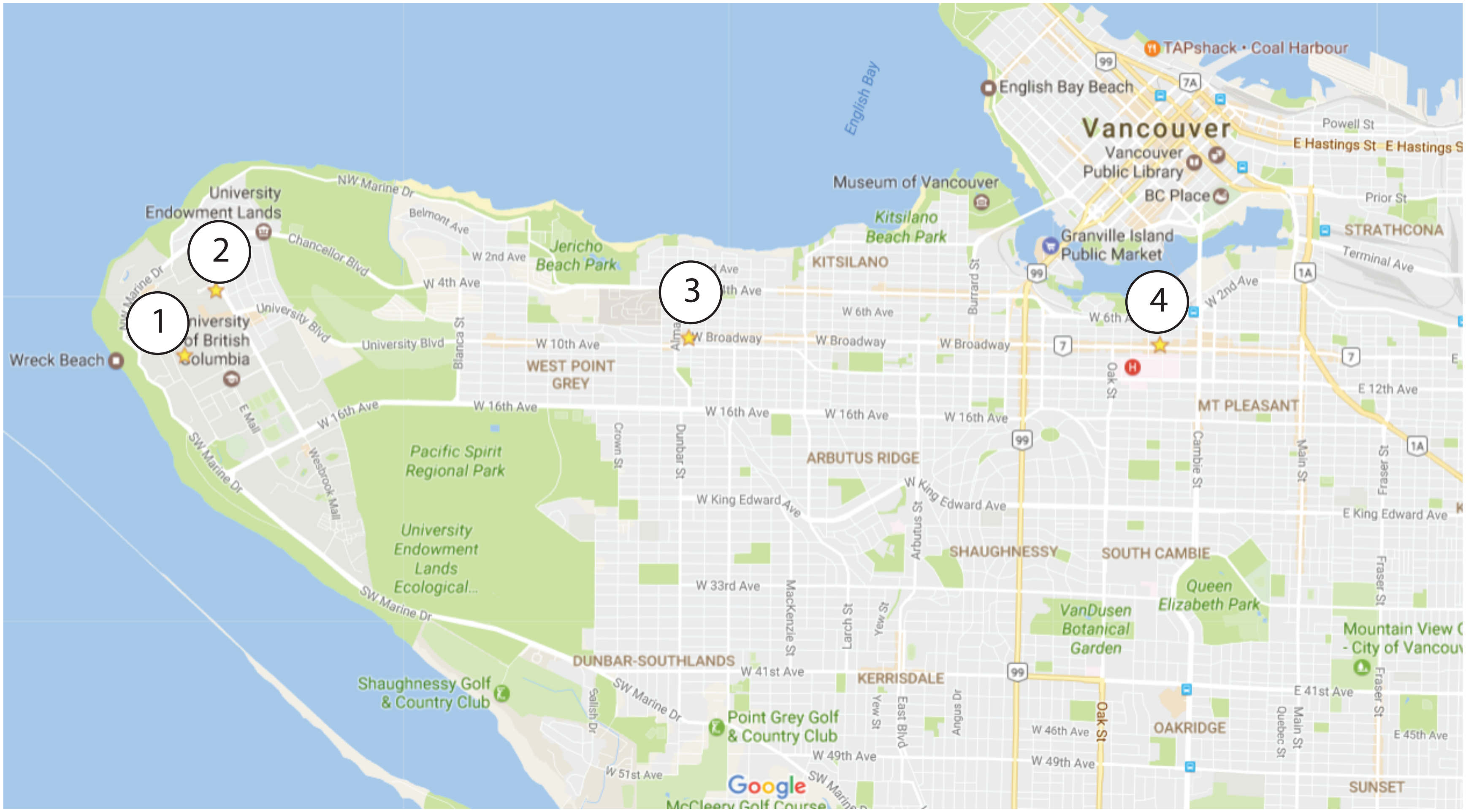
4:00pm: **Posters**

6:00pm: **Dinner at Athene's Restaurant (3618 West Broadway @ Alma St.)**

SUNDAY FEB 26 - CTW TECHNICAL SESSION *(Earth Sciences Building, Room 1012)*

7:30am: **Light Breakfast**

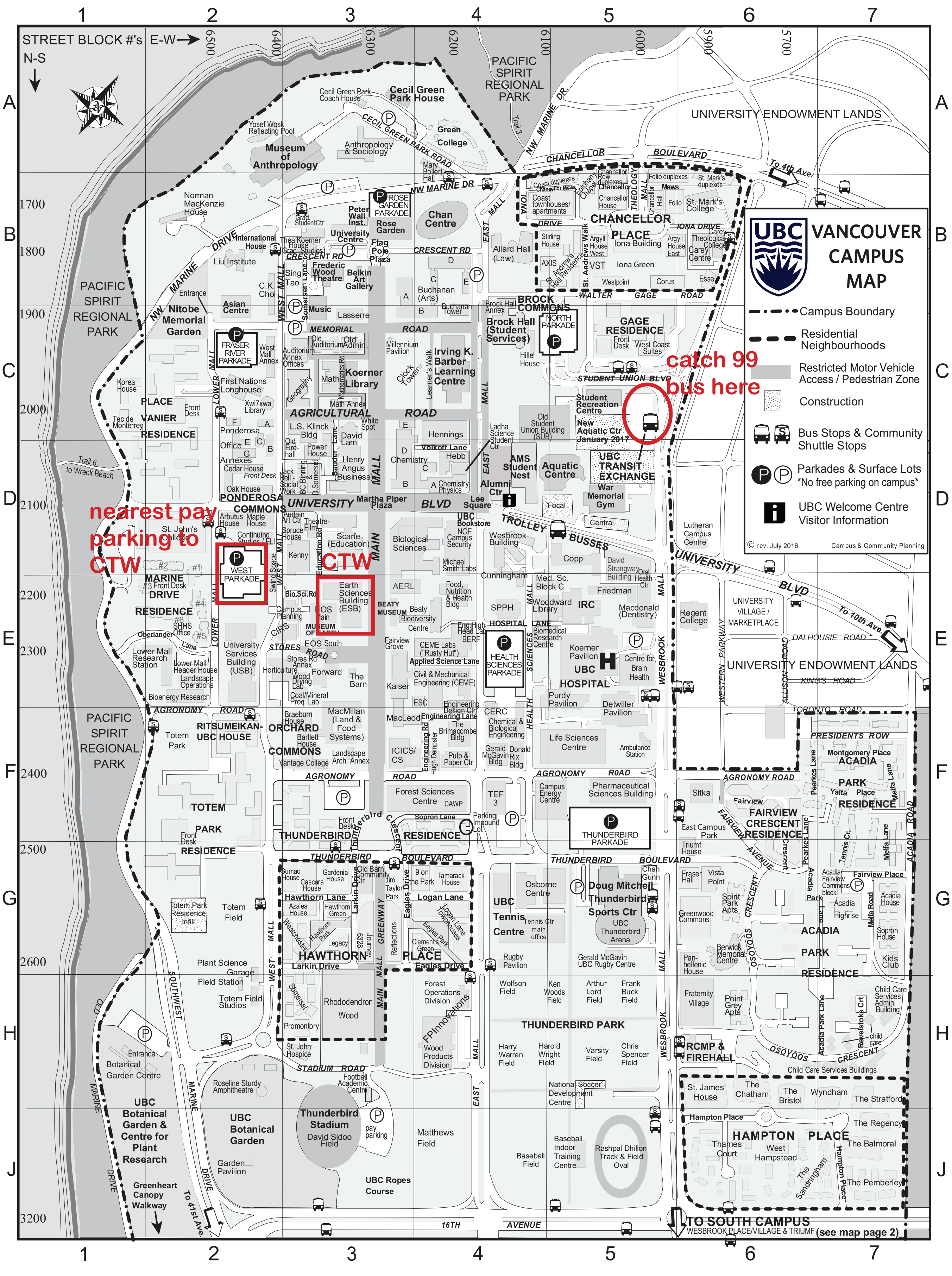
8:30am - 12:00pm: **Technical Presentations**



1. Earth Sciences Building (2207 Main Mall, University of British Columbia)
2. UBC Bus Loop
3. Athene’s (3618 West Broadway @ Alma St.)
4. Holiday Inn Vancouver - Centre (711 W. Broadway @ Heather St.)

ACCESS TO UBC BY BUS (Regular single passenger fare is $2.75)
From Holiday Inn: 99 B-Line bus (nearest stop is on north side of Broadway, 1 block west of hotel between Willow and Laurel St.)
From Downtown: 44 bus from Burrard St.

ACCESS TO ATHENE’S RESTAURANT FROM UBC
Walk to UBC busloop from Earth Sciences Building (~10 minutes) - see detailed UBC map
Take 99 bus / get off at Alma St. stop (~17 minutes) - Athene’s is right there!


UBC VANCOUVER CAMPUS MAP
Campus Boundary
Residential Neighbourhoods
Restricted Motor Vehicle Access / Pedestrian Zone
Construction
Bus Stops & Community Shuttle Stops
Parkades & Surface Lots *No free parking on campus*
UBC Welcome Centre Visitor Information
rev. July 2016
Campus & Community Planning
STREET BLOCK #'s E-W
N-S
catch 99 bus here
nearest pay parking to CTW
CTW
UBC TRANSIT EXCHANGE
WEST PARKADE
Earth Sciences Building (ESB)
PACIFIC SPIRIT REGIONAL PARK
UNIVERSITY ENDOWMENT LANDS
Museum of Anthropology
Nitobe Memorial Garden
Chan Centre
CHANCELLOR PLACE
GAGE RESIDENCE
Irving K. Barber Learning Centre
Koerner Library
UNIVERSITY BLVD
AMS Student Nest
Aquatic Centre
MARINE DRIVE RESIDENCE
TOTEM PARK RESIDENCE
ORCHARD COMMONS
THUNDERBIRD RESIDENCE
HAWTHORN PLACE
UBC HOSPITAL
Doug Mitchell Thunderbird Sports Ctr
THUNDERBIRD PARK
UBC Botanical Garden
Thunderbird Stadium
ACADIA PARK RESIDENCE
FAIRVIEW CRESCENT RESIDENCE
HAMPTON PLACE
TO SOUTH CAMPUS WESBROOK PLACE/VILLAGE & TRIUMF (see map page 2)
To 4th Ave.
To 10th Ave.
To 41st Ave.
16TH AVENUE
1 2 3 4 5 6 7
A B C D E F G H J

CTW 2017 Program

Friday, February 24

5:00 PM		Registration and poster setup	ESB Atrium
6:30 AM	Peacock, Simon	Introduction	ESB 1012
6:30 PM	Mortensen, Jim	The Northern Cordillera as a Natural Laboratory for the Tectonics and Metallogeny of Orogenic Belts	ESB 1012
7:10 PM	Monger, Jim	Deciphering Canadian Cordilleran tectonics: past, present and future	ESB 1012
7:50 PM	Goldfarb, Richard	Growth of the North American Cordillera and Metallogenic Evolution along an Active Continental Margin	ESB 1012
8:30 PM		Wine and cheese social	ESB Atrium

Saturday, February 25

7:30 AM		Light Breakfast and Registration	ESB Atrium
8:30 AM	Hyndman, Roy	Lower crust detachment and channel flow everywhere in the North American Cordillera: The crust moves independently of the mantle as	ESB 1012
9:10 AM	Boggs, Katherine	The Canadian Cordillera Array is Coming Soon!	ESB 1012
9:30 AM	Hickey, Ken	In-situ monazite dating of sediment-hosted stratiform Cu mineralization in the Redstone copperbelt, Northwest Territories, Canada: Cupriferous fluid flow late in the evolution of a Neoproterozoic sedimentary basin	ESB 1012
10:00 AM		Coffee	ESB Atrium
10:30 AM	Campbell, Roderick	Early Paleozoic volcanic rocks of the Kechika group, Pelly Mountains, Yukon: A record of post-breakup magmatism within the ancestral North American margin	ESB 1012
10:50 AM	Jones, James	Lithotectonic associations of the Ladue River unit and new evidence of Permian (ca. 267–257 Ma) magmatism, deformation, and metamorphism in east-central Alaska	ESB 1012
11:10 AM	Nelson, JoAnne	Composite pericratonic basement of west-central Stikinia and its influence on Jurassic magma conduits: Examples from the Terrace-Ecstall and Anyox areas	ESB 1012
11:30 AM	van Straaten, Bram	Triassic to Jurassic arc volcanism and porphyry prospectivity in northwestern British Columbia	ESB 1012
12:00 PM		Lunch	ESB Atrium
1:00 PM	Colpron, Maurice	Late Triassic to Middle Jurassic magmatism in the Intermontane terranes of Yukon	ESB 1012
1:20 PM	Bordet, Esther	Geochemical characterization of Triassic volcanic arc rocks of Stikinia in Yukon	ESB 1012
1:40 PM	Kovacs, Nikolett	From subduction to exhumation: the geological evolution of the Carmacks Copper deposit	ESB 1012
2:00 PM	Moher, Meghan	Cretaceous exhumation of the Aishihik batholith, central Yukon resolved through low temperature (U-Th)/He thermochronology	ESB 1012
2:20 PM		Coffee	ESB Atrium
3:00 PM	Schiarizza, Paul	Geologic setting of the Granite Mountain batholith, host to the Gibraltar porphyry Cu-Mo deposit, south-central British Columbia	ESB 1012
3:20 AM	Kennedy, Lori	Structural geology and timing of deformation at the Gibraltar Cu-Mo porphyry deposit	ESB 1012
3:40 PM	Allan, Murray	Mesozoic Orogenic Gold Systems of British Columbia: Structural Setting and Tectonic Implications	ESB 1012
4:00 PM		Posters	ESB Atrium
6:00 PM		Dinner	Athene's

Sunday, February 26th

7:30 AM		Light Breakfast	ESB Atrium
8:30 AM	Penner, Barry	Preliminary Structural Constraints on the Geometry of Selwyn Basin from Summit Lake to Howard's Pass, Nahanni Map Sheet (NTS 105I), NWT	ESB 1012
8:50 AM	Warren, Marian	Integrating basement structure, "Antler" foreland events and Cretaceous deformation and diagenesis for economic success in the Alberta foreland basin	ESB 1012
9:10 AM	Pryer, Laurence	The evolution of "mid" Cretaceous Omineca Magmatic Belt granites in the Northern Canadian Cordillera: A product of mantle lithosphere delamination	ESB 1012
9:30 AM	Lee, Well-Shen	Mid-Cretaceous gold-bearing veins in the Dawson Range, Yukon	ESB 1012
10:00 AM		Coffee	ESB Atrium
10:30 AM	Angen, Joel	Structural Framework and Magmatic Constraints on Mineralized Porphyry Systems in the Western Skeena Arch	ESB 1012
10:50 AM	Israel, Steve	Early Tertiary tectonic and magmatic evolution of southwest Yukon	ESB 1012
11:10 AM	Vice, Lianna	New insights into the Mesozoic to Paleocene tectono-metamorphic evolution of the Kluhini and Takhanne River map areas of southwestern Yukon	ESB 1012
11:30 AM	Wilson, Alexander	Glaciovolcanism in the Northern Cascade Volcanic Arc: Terrestrial Paleo-environment Reconstruction.	ESB 1012
12:00 PM		End of workshop	

Keynote Speaker Biographies

James (Jim) K. Mortensen grew up on a ranch near Smithers, British Columbia. He obtained BASc and MASc degrees in Geological Engineering at the University of British Columbia (1977, 1979) and a PhD in Geological Sciences at the University of California – Santa Barbara (1983). After completing his PhD, Jim taught mineral deposits at UBC for two years before taking a position as a Research Scientist with the Geological Survey of Canada in Ottawa in 1985. He moved back to UBC as a Research Professor in 1992. Jim has more than forty years of field experience focused on regional tectonic and metallogenic studies, which have focused mainly in the northern Cordillera and the Canadian Shield, as well as Spain, Portugal, New Zealand, Australia, China, Mexico and Tibet. His main expertise includes orogenic and intrusion-related gold and VHMS deposits, and the application of geochronology and radiogenic isotopes in tectonic and mineral deposit research.

Jim Monger grew up near Reading, England. He obtained a B.Sc from Reading University in 1959, M.Sc. from the University of Kansas in 1961 and Ph.D. from The University of British Columbia in 1966. He joined the Vancouver office of the Geological Survey of Canada (GSC) as a research geologist in 1965. He officially retired in 1995 but remained active as an emeritus scientist with the GSC and as an adjunct professor and sessional lecturer at Simon Fraser University and the University of Victoria. Jim has authored or coauthored over 50 refereed articles including seminal works on the development of tectonic concepts in the northern Cordillera. He served as the chairman for the Global Geoscience Transects Project from 1986 to 1991 and held several roles with the Canadian LITHOPROBE Project between 1988 and 1993. Jim was the recipient of the Geological Association of Canada's Logan Medal in 2003.

Richard J. Goldfarb was a research geologist with the Minerals Program of the U.S. Geological Survey for 36 years. He has conducted studies on the distribution of gold deposits throughout the world, compiling some of the most comprehensive global descriptions of their spatial-temporal setting and evaluating their controlling factors. His research has been focused on global metallogeny, geology of ore deposits in the North American Cordillera with emphasis on orogenic gold, distribution and geology of lode gold deposits in China and elsewhere in Asia, and fluid inclusion and stable isotope applications to the understanding of ore genesis. Rich has senior authored and co-authored more than 225 papers on mineral resources, with many recognized as the authoritative research on orogenic gold and on aspects of regional metallogeny. He has served as President of the Society of Economic Geologists, is a past Silver Medalist and lecturer of the Society, has served as chief editor of Mineralium Deposita, is presently on the editorial board of Economic Geology and was one of the co-editors of the Economic Geology One Hundredth Anniversary Volume. He received his BS in geology from Bucknell University, MS in hydrology from MacKay School of Mines, and PhD in geology from the University of Colorado. Presently, he is an adjunct professor at Colorado School of Mines and China University of Geosciences Beijing, as well as an independent consultant.

The Northern Cordillera as a Natural Laboratory for the Tectonics and Metallogeny of Orogenic Belts

Jim Mortensen, Professor Emeritus, University of British Columbia

A remarkable number of the fundamental concepts that are now widely accepted concerning the tectonics and metallogeny of orogenic belts were actually developed in the northern Cordillera. For example, the initial concept of terranes and the role they play in the growth of orogens are now applied throughout the world; however, the terrane concept derives largely from early studies in the northern Cordillera, where geologists recognized that rock units that we now refer to as Wrangellia are completely different from those in adjacent areas and are most reasonably interpreted to have been formed elsewhere and transported into their current position by tectonic processes.

Why has this region continued to generate such a wealth of fundamental tectonic and metallogenic concepts and models? Some of the key factors that have contributed to this include: 1) very diverse geology, resulting from active tectonism in a multitude of settings from mid-Proterozoic to the present; 2) (mostly) excellent exposure and preservation of critical lithotectonic assemblages and structural/tectonic settings; 3) world-class examples of a very wide range of mineral deposit types, including SEDEX, VMS, porphyry, skarn, orogenic gold, and many other styles; 4) availability of high resolution regional airborne and ground geophysical surveys to support regional geological mapping; 5) availability of high quality seismic reflection/refraction surveys, including TACT and Lithoprobe; 6) availability of a very detailed geochronological and biochronological age database; 7) the strength and commitment of the various geological surveys over the years; 8) a very high level of mineral, coal and hydrocarbon exploration activity; and 9) the willingness and enthusiasm of the exploration industry to participate in consortium-based research.

Cordilleran tectonic research has also benefited greatly from the contributions from a number of “contrarians”, who have gleefully weighed in with what sometimes appear heretical, or at least non-conformist, ideas, such as oroclinal bending of orogens, ribbon continents, and slab windows and walls. Some of these ideas have, or will, survive the test of time and others not; however, the constant input of fresh new ideas has provided a constant stimulation and challenge to Cordilleran researchers. Application of new analytical or surveying techniques, such as the campaign-style regional monitoring of real-time displacements of different parts of the Cordillera using GPS methods (part of the Earthscope program, presently underway in Alaska and adjacent parts of Yukon), continue to force researchers to rethink some of our long-held ideas and models.

An additional and very critical factor that has contributed to the wealth of tectonic and metallogenic ideas that has come out of northern Cordilleran research is the rather unusual willingness and eagerness of Cordilleran researchers to openly share their ideas and data with each other. Regular informal meetings such as the Cordilleran Tectonic Workshop have provided important forums where ideas are presented, discussed and debated in a (for the most part) non-confrontational setting. The Workshop has also been critical for introducing young researchers to Cordilleran geology and to the geoscientific community that make it such a stimulating and vibrant area in which to do research.

Deciphering Canadian Cordilleran tectonics: past, present and future

Jim Monger, emeritus scientist, Geological Survey of Canada; jimonger@shaw.ca

In the beginning: Geological mapping in the Appalachians in the 1850s* had led by ~1875 to the deterministic concept of the *geosynclinal cycle*: deposition in a linear trough or *geosyncline* followed by *orogeny* as recorded by deformation, metamorphism, plutonism, uplift and erosion. For nearly 100 years this remained the favoured general tectonic concept in North America. Distribution of rock units in the Canadian Cordillera was outlined between 1872 and 1901. By 1947, the thick succession of sedimentary rocks in the eastern Cordillera was called the *miogeosyncline* and volcanic/sedimentary assemblages in the axial and western Cordillera named the *eugeosyncline***.** Eastern (Columbian) and western (Pacific) orogens were identified (1961; 1972) as later Mesozoic components of the Cordilleran orogen.

Epiphany: During the 1950s - 60s remote-sensing mapping of the little known 2/3^{rds} of Earth's surface beneath the oceans resulted in the two key discoveries – *spreading ridges* (1963) and *transform faults* (1965) – that led directly to the Plate Tectonic hypothesis. The new hypothesis, introduced in January 1970 to Vancouver's geological community at the first meeting of the Cordilleran Section, Geological Association of Canada, had immediate influence on interpretations of Canadian Cordilleran tectonics.

Tectonic assemblages: Knowledge of *actualistic* (1963) rock assemblages forming in today's tectonic settings was used to identify ancient analogues. By ~1970, the *miogeocline* has been recognized as an intraplate continent-ocean margin and the *eugeosyncline* as composed of *island arc* and *ocean floor* rocks (Fig. **A**). Rock and isotope chemistry (mostly) supported these initial interpretations. In addition, some arc assemblages were paired (1978) with ocean floor rocks accumulated in coeval *accretionary complexes*. *Tectonic Assemblage Maps* of the Canadian Cordillera (1981, 1991) show rocks of different ages grouped in their inferred tectonic settings.

Orogenic collages and terranes: Long-term plate interactions typically create tectonic disorder, the product of which is a space-time puzzle called an *orogenic collage* (1974). In the Canadian Cordilleran collage, arc-related magmatic rocks record up to 600 million years of plate convergence, and disorder was demonstrated in 1971 by Permian ocean floor rocks in the axial Cordillera that host fossils with Tethyan (or Asian) affinity sandwiched between coeval arc-related rocks with fossils akin to those in the southwestern United States. Collage analysis identifies internally consistent "puzzle pieces" called *terranes* (**B**), a term used first with this sense in the Cordillera (1972). By 1980, terranes were recognized from Mexico to Alaska and the concept became exported to other orogens. Implicit in the concept is the uncertain or "suspect" paleogeographic relationships between terranes and the old continental margin. Terrane linkages (*overlap assemblages, stitching plutons,* etc.) show that most major terranes had been accreted to the old continental margin by 174 Ma (**C**), although their present distribution reflects post-accretion displacement along the margin. Structural restorations, paleobiogeography, paleomagnetism and, more recently, detrital zircon provenance studies have been employed since ~1970 in attempts to determine paleogeographic locations of terranes relative to the old margin. Geophysical profiles of Cordilleran crust acquired mainly during the 1990s under the aegis of *Lithoprobe* and linked to surface geology, suggest that terranes are disposed vertically in relatively thin (<10 km) thrust sheets.

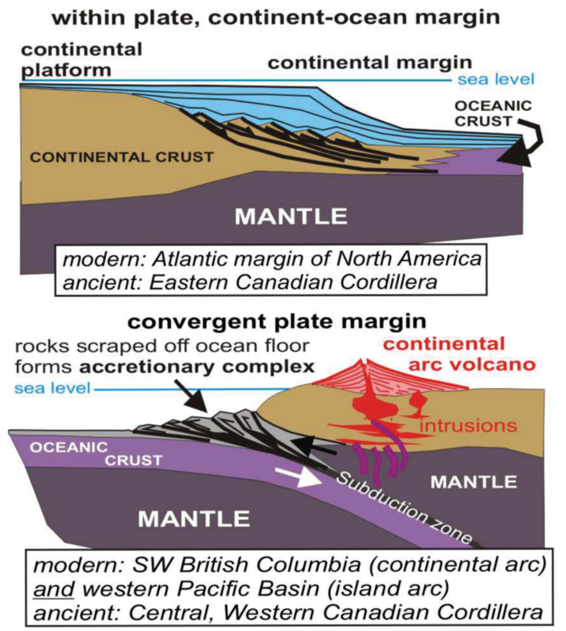
Pre-Cordilleran evolution: On a planet whose surface features appear to be largely controlled by plate tectonics, causes of Cordilleran orogenesis are best understood in their global context. The Cordilleran birthplace was created ~700 Ma when the ~1 Ga old *Rodinia supercontinent* rifted and its components drifted apart to open the ancestor of the Pacific basin (1972). Great thicknesses of sediment now preserved in the eastern Cordillera were deposited along the long-lived (~700-400 Ma) intraplate continent-ocean boundary (1966; 1981). Between ~390-360 Ma a convergent plate margin was initiated and recorded by arc rocks emplaced from California to Alaska mostly in oceanward parts of the old continental margin (by 1988). By ~350 Ma, as continents were starting to re-combine into the *Pangea supercontinent*, the arc became separated from the old margin by a back-arc basin (preserved as Slide Mountain terrane; 1977). Analogies have long been drawn (1972; 1985; **D**) with today's western Pacific basin, where island arcs are separated from the Asian continent by *back-arc basins*. The roughly similar late Paleozoic stratigraphic and fossil records of major arc terranes (Quesnel, Stikine, Wrangellia - the latter amalgamated with the exotic Alexander terrane by 350 Ma) suggest (1994; 2001) that by ~300 Ma a single island-arc chain extended from the continental margin in what is now southwestern California across the northeastern Ancestral Pacific Ocean (aka *Panthalassa*). All major arc terranes in the Canadian Cordillera appear to be displaced segments of that chain and were assembled between ~250-174 Ma along the old continental margin to provide the foundation for younger continental arcs.

Cordilleran orogenesis: Minimal ages of terrane linkages, show that the major arc terranes had been accreted before Cordilleran emergence in later Mesozoic time. Time of accretion of the arc terranes to the old continental margin overlaps time of Pangea break-up as recorded by rifting in the Appalachian region as old as 240 Ma, initial opening of the Central Atlantic Ocean ~190 Ma (2012), and subsequent drifting apart of Africa and North America. Although arc-continent collisions leave regional imprints and had been suggested (1979; 1982) as causes of Cordilleran orogenesis, the Cordillera is some 8,000 km long and up to 1600 km wide and far larger than any terrane. As recognized by some "continental drifters" (1910; 1926) and in plate tectonic terms by 1971, Cordilleran mountain-building most likely reflects Pacific-ward advance of the *Laurasian-North American Plate (LNAP)* away from Africa which, surrounded by intraplate continent-ocean margins on three sides, geographically may be the least mobile continent. Convective currents in the asthenosphere probably acted on the 200-300 km deep lithospheric "keel" below the old continental part of the LNAP to drive the plate toward and over the Ancestral Pacific floor (2002; **E**). Coupling **(D)** between the converging ocean floor and LNAP, combined with weak arc lithosphere in the leading edge of the overriding plate, resulted in compression, crustal thickening, uplift and erosion. Initially (~170-160 Ma) orogenesis occurred in the region of overlap between accreted terranes and the outer old continental margin, but by ~100 Ma the entire Cordillera was above sea-level with exception of marginal regions. Mostly oblique convergence between ~160-110 Ma caused *sinistral transpression* that may reflect counter-clockwise rotation of LNAP (2015). Between ~75-55 Ma, coupling between the North America Plate and northward-moving Kula and Pacific plates (1970) caused *dextral transpression*, and after ~55 Ma strike-slip faulting and related transtension dominated.

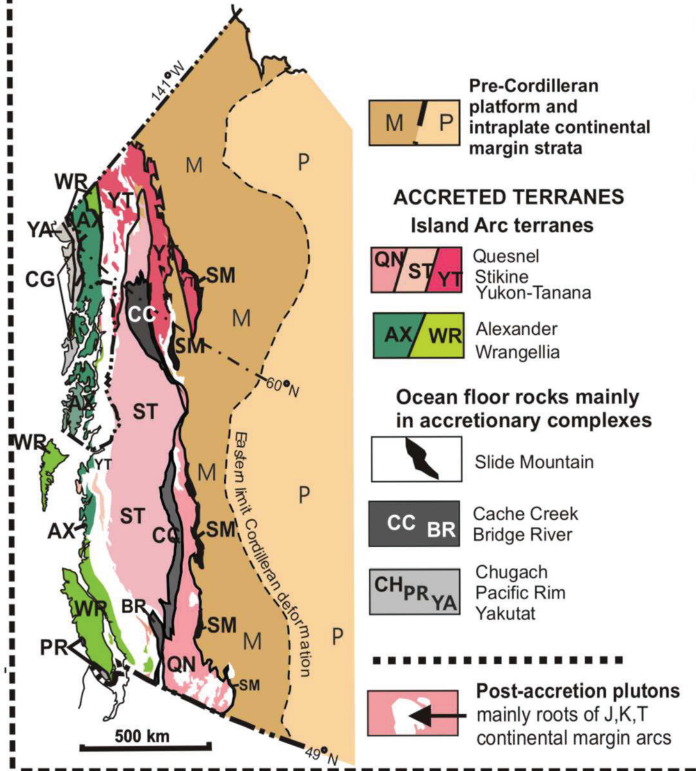
The Future: *Seismic tomography* has been used for ~30 years and can detect thermal/compositional anomalies in the lower mantle. Subducted oceanic lithosphere in the outer ~670 km of Earth can be traced in places into cooler (higher velocity) regions in the lower mantle and core (2002, 2013). Conversely, "non-plate" features such as *mantle plumes* and *large igneous provinces* appear mostly to be associated with the margins of sub-Pacific and sub-African *large low shear-velocity provinces* in the mantle at the core-mantle boundary (2010, 2015). A "whole Earth" picture of global tectonics (1982) should accommodate both.

****N.B.*** Dates above (e.g. 1947) refer to times when advances were published.

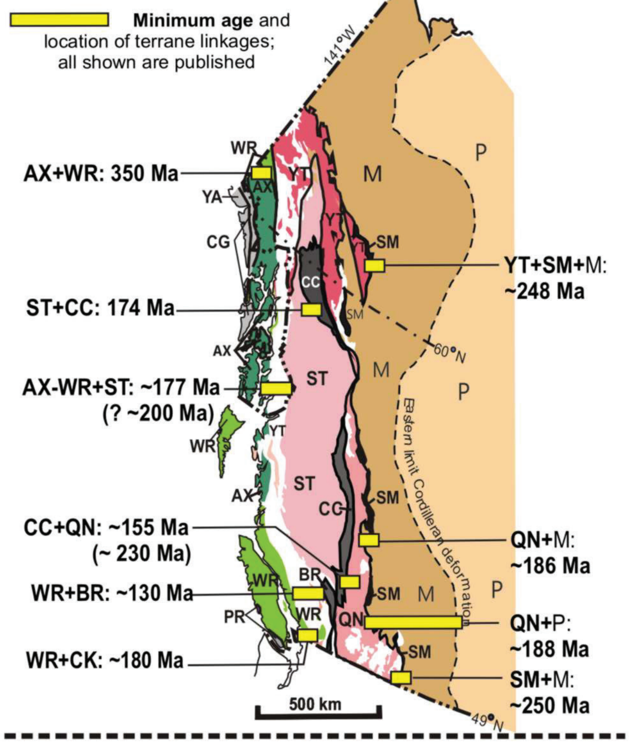
A Identify **modern analogues** of tectonic settings in which most Cordilleran rocks formed



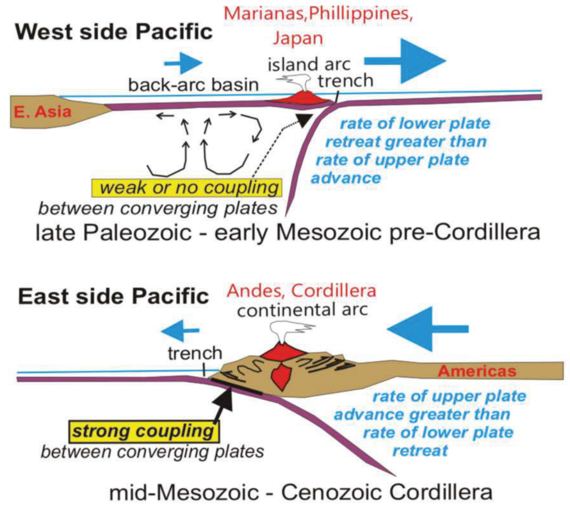
B Identify regions called **terranes** within which rocks have been together since their formation



C **Terrane linkages** record the minimum time of terrane amalgamation and accretion to the pre-Cordilleran continental margin

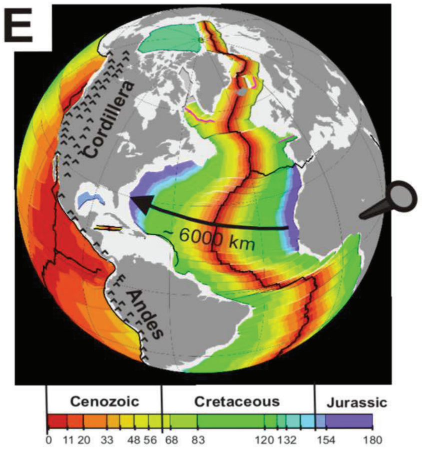


D **Modern convergent plate margins**

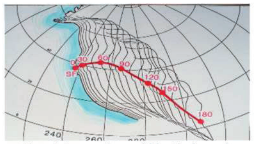


mod. fm. Hyndman, 1972; Uyeda and Kanamori, 1979

E

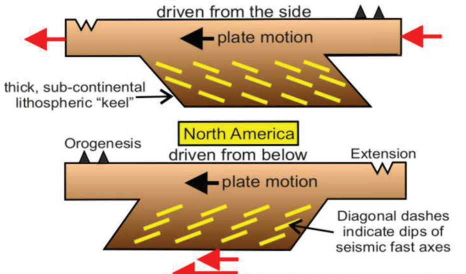


mod. fm. graphic by W. Roest



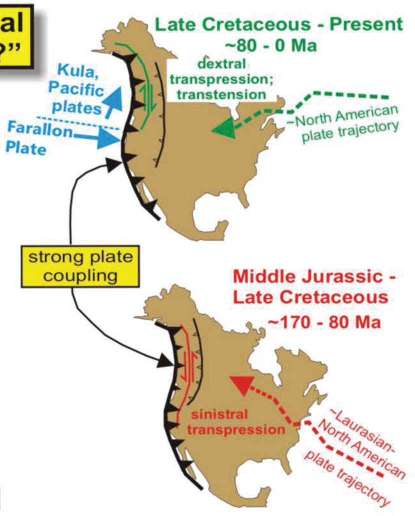
Absolute motion of North America (w.r. to hot spots) Engebretson, 1982

Plate driving forces and sense of shear



mod. fm. Bokelmann,2002

"Continental bulldozer?"



Growth of the North American Cordillera and Metallogenic Evolution along an Active Continental Margin

Goldfarb, Richard J., State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing 100083, P.R. China (rjgoldfarb@mac.com)

Hart, Craig J.R., Mineral Deposit Research Unit, University of British Columbia, Vancouver, B.C. V6T 1Z4, Canada

The North American Cordillera, a classic accretionary type orogen, is dominated by dozens of terranes added to the western North America margin between ca. 200 Ma and 50 Ma. Economic mineral deposits of the Cordillera include a complex association of pre-, syn-, and post-accretionary ores, and thus some ores that formed far from North America and long before Cordilleran orogeny. Prior to accretion, middle to late Paleozoic hydrothermal events in rifted continental margins were associated with formation of clastic-dominated (or SEDEX) Pb-Zn (e.g., Red Dog, Howards Pass) and polymetallic VMS (Arctic, Bonnifield, Finlayson Lake, Shasta) deposits. The subsequently accreted terranes were mainly Paleozoic and Mesozoic rocks of oceanic arcs and subduction-accretion complexes, some far-traveled and amalgamated into microcontinents more than 100 m.y. prior to accretion. In the northern part of the orogen, large Late Triassic VMS (Greens Creek, Windy Craggy) and Triassic-Jurassic porphyry (Schaft Creek, Galore Creek, Highland Valley) deposits formed distal to the continent and were added to the orogen in British Columbia and southeastern Alaska during mid-Mesozoic terrane docking. A subsequent major porphyry-forming event in mid-Cretaceous was syn-accretionary, with deposits (Orange Hill, Pebble) forming along the edge of a closing flysch basin and being rapidly translated hundreds of kilometers northward along the edge of North America to southern Alaska. Post-accretionary orogenic gold deposits formed along the length of the orogen, from Nome to central California, from 170 to 50 Ma, in fore-arc and back-arc positions relative to broadly coeval subduction-related batholiths, and during changes in far-field stresses. Inboard of the Cretaceous Sierra Nevada batholith in California, middle Tertiary extension, related to slab-rollback, was coeval with formation of the unique group of Carlin-type gold deposits in Nevada. Late Tertiary Basin and Range extension, likely related to outboard motion on the San Andreas fault system, led to world-class epithermal Au-Ag deposits. A thorough understanding of Cordilleran tectonics not only helps us better recognize areas of greatest favorability for specific mineral deposit types, but study of regional metallogeny can also help us better define major tectonic events.

Lower crust detachment and channel flow everywhere in the North American Cordillera: The crust moves independently of the mantle as ‘orogenic float’

Hyndman, Roy, Pacific Geoscience Centre, Geological Survey of Canada and SEOS, University of Victoria, roy.hyndman@canada.ca

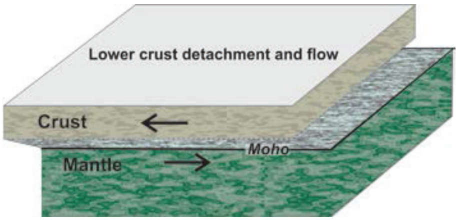


Figure 1. Cordillera-wide lower crust detachment

Lower crust detachment (*Figure 1*) with the crust moving independently of the upper mantle has previously been argued in a few special circumstances including Tibet, the high Andes, and the currently extending U.S. Basin and Range. Another example is the upper crust being driven 800 km westward from the coastal Yakutat terrane collision to the Mackenzie Mountains on the eastern Cordillera mountain front (Mazzotti and Hyndman, 2002). Oldow et al. (1990) showed how lower crustal detachment and upper crust orogenic float is required by tectonic continuity in many foreland thrust systems. I present the surprising conclusion that lower crust detachment and channel flow are occurring or recently have occurred in most of the North America Cordillera and in other continental backarcs. I first describe the evidence for detachment and flow and then the evidence for the high temperatures in the lower crust throughout most of the Cordillera such that that detachment and flow are expected.

A clear indication of detachment and flow comes from seismic structure data that show the Moho in most of the Cordillera is remarkably flat and has constant thickness of 33±3 km from Mexico to Alaska in spite of a complex history of extensional faulting, large shortening deformation, and terrane accretion. The flat Moho is evident over lateral distances of 10’s of km from multichannel seismic reflection and 100’s of km from seismic refraction, seismic tomography, and receiver functions. I argue that the constant crustal thickness and flat Moho result from lower crust flow associated with Cordillera-wide high temperatures (*Figure 2*). Numerical models show the Moho boundary may relax by lower crust flow to a nearly horizontal

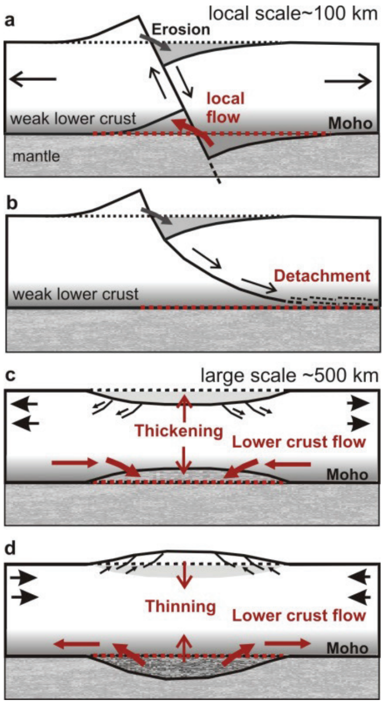


Figure 2. The lack of Moho topography indicates lower crust fault detachment and lower crust channel flow.

gravitational equipotential over a few 10s of m.y. Also, significant mountain belt elevations wider than the flexural wavelength of ~100 km in the Cordillera backarc last only a few 10's m.y. unless maintained by ongoing shortening (*Figure 3*).

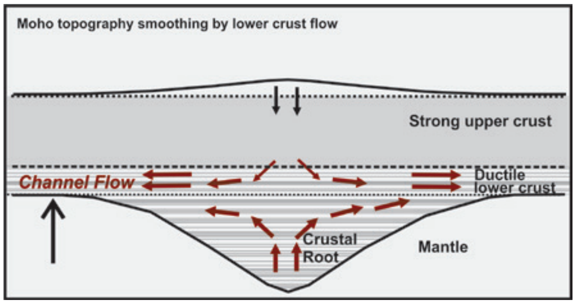


Figure 3. Any crustal root or other Moho topography is removed by lower crust flow in a few m.y. Corresponding isostatically supported topography also collapses.

Not just the volcanic arc but most of the Cordillera is surprisingly uniformly hot in common with other backarcs. Temperatures at the Moho are 800-850°C compared to 400-450°C in the adjacent craton from: heat flow measurements; upper mantle temperature-dependent seismic velocities; mantle xenoliths; receiver function lithosphere thicknesses; and thermal elevations (*Figure 4*). Similar high temperatures and a weak ductile lower crust are required for the effective elastic thickness Te of less than 20 km. These temperatures are high enough for viscosities of 10*19 Pa s in the lower ~10 km of the crust, allowing both detachment and ductile channel flow. Other indicators of lower crust shear and flow are: the common lower crust horizontal seismic reflectors in the bottom ~10 km of the crust that are interpreted to result from ductile horizontal shear; outcrops of former lower crust that show past horizontal shear at high temperatures; and areas where the former weak lower crust of the Cordillera has been extruded upward over the adjacent craton. Large-scale regional tectonic motions such as in oroclines seem to require that horizontal crust transport involves only the upper crust. The evidence for detachment indicates that upper crust structures and mineral deposits of mantle origin may not lie over their mantle source in the Cordillera.

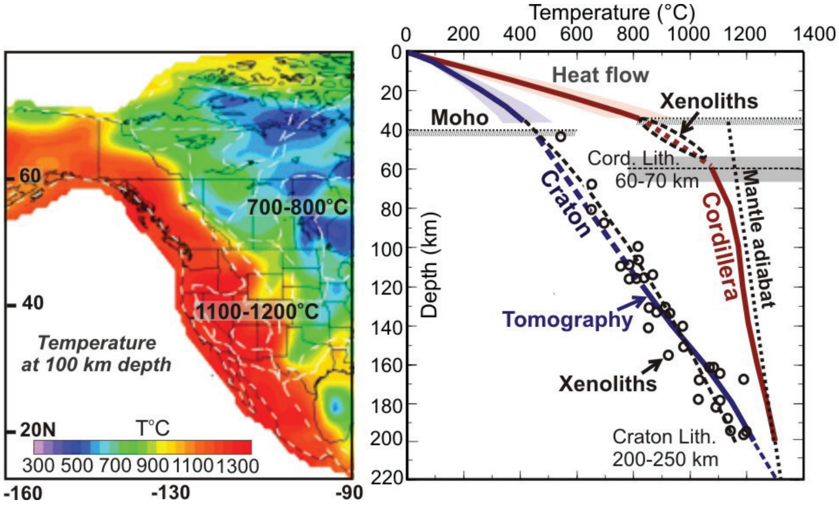


Figure 4. Left: Estimated temperature at 100 km depth from seismic tomography, showing bimodal Cordillera vs stable area thermal regimes. Right: Average temperature-depths for the Cordillera and adjacent craton.

The Canadian Cordillera Array is Coming Soon!

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The Canadian Cordillera Array is a bold initiative to install a Cordilleran-scale open data network with the ultimate goal of holistically examining entire Earth systems from the core to the magnetosphere. With the motivation of expanding upon the scientific momentum of other North American large Earth systems research and data collection initiatives (e.g. Lithoprobe (1984 to 2004) and EarthScope (2004 to 2018)), the vision for CCArray is to install a network of telemetered observatories (Figures 1 and 2), instrumented with a suite of sensors which would include one or more of the following sensors: broadband seismometers (including ocean bottom seismometers in the Beaufort Sea and eastern Pacific Ocean), Global Navigational Satellite System (GNSS, GPS) equipment, meteorological systems (including barometers), permafrost monitors, atmospheric gas sensors, shallow borehole temperature and moisture sensors, riometers, gravimeters and magnetometers. The CCArray represents the initial component of a planned future pan-Canadian Earth observation network. The CCArray is being undertaken first to take advantage of opportunities presented by EarthScope instrumentation currently in eastern Alaska and northwestern Canada. In the spirit of Lithoprobe, funding will be allocated to other supporting geosciences, with the intention of examining deep controlling processes and their connections between surface geology and the deep structures in the crust and upper mantle. While many of the stations will be in place for up to three years, the intention is to leave some stations in place permanently to enable long-term monitoring of Earth systems across Canada. This initial proposed Earth observation network will span the Canadian Cordillera from the Beaufort Sea to the US Pacific northwest. A recent workshop at Fall 2016 AGU explored broad science targets for CCArray, including imaging active and sequestered subducted slabs in the mantle, improving understanding of earthquake dynamics and tsunami hazards, extending critical

zone (region from tree canopy through the soil into bedrock – the portion of Earth critical for life), permafrost studies, the formation of auroras in the magnetosphere, and improving modeling of atmospheric gravity waves (important for enhancement of numerical weather modeling). Enhanced monitoring networks would contribute to studies of glacial isostatic adjustment – the ongoing response of the Earth to past ice mass change – and contribute to understanding of Earth rheology and structure. Potential climate-change targets include monitoring the response of the Earth to present-day ice-mass and hydrological change. In coastal regions, monitoring of vertical crustal motion, in concert with tide gauge installations, would improve the monitoring and projection of sea-level change. Here we will present a summary of some of the potential applications of such a network, expanding upon integrated research results that have emerged out of the US EarthScope program together with outcomes from a series of workshops and planning meetings held across Canada and the US over the past year.

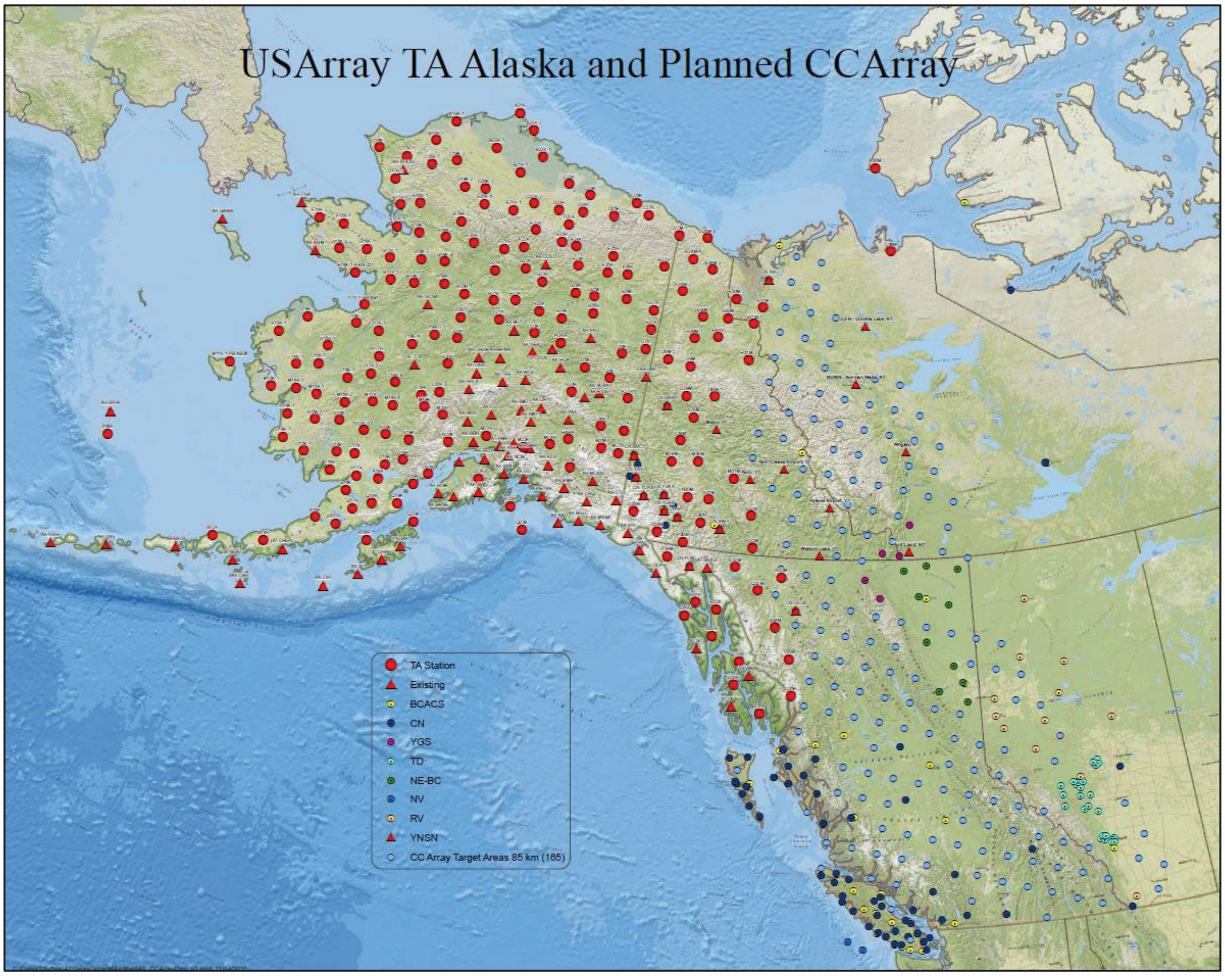

Figure 1: *Proposed distribution of seismometers for the CCArray (courtesy of S. Azevedo and B. Busby). The smaller light blue dots provide a schematic representation of a 165 broadband seismometer array at an 85km grid spacing. The larger red circles are current and planned USArray Transportable Array Stations; other symbols denote existing broadband seismometers installed by other groups. Ocean bottom seismometers would also be deployed in the Beaufort Sea and off the west coast of British Columbia.*

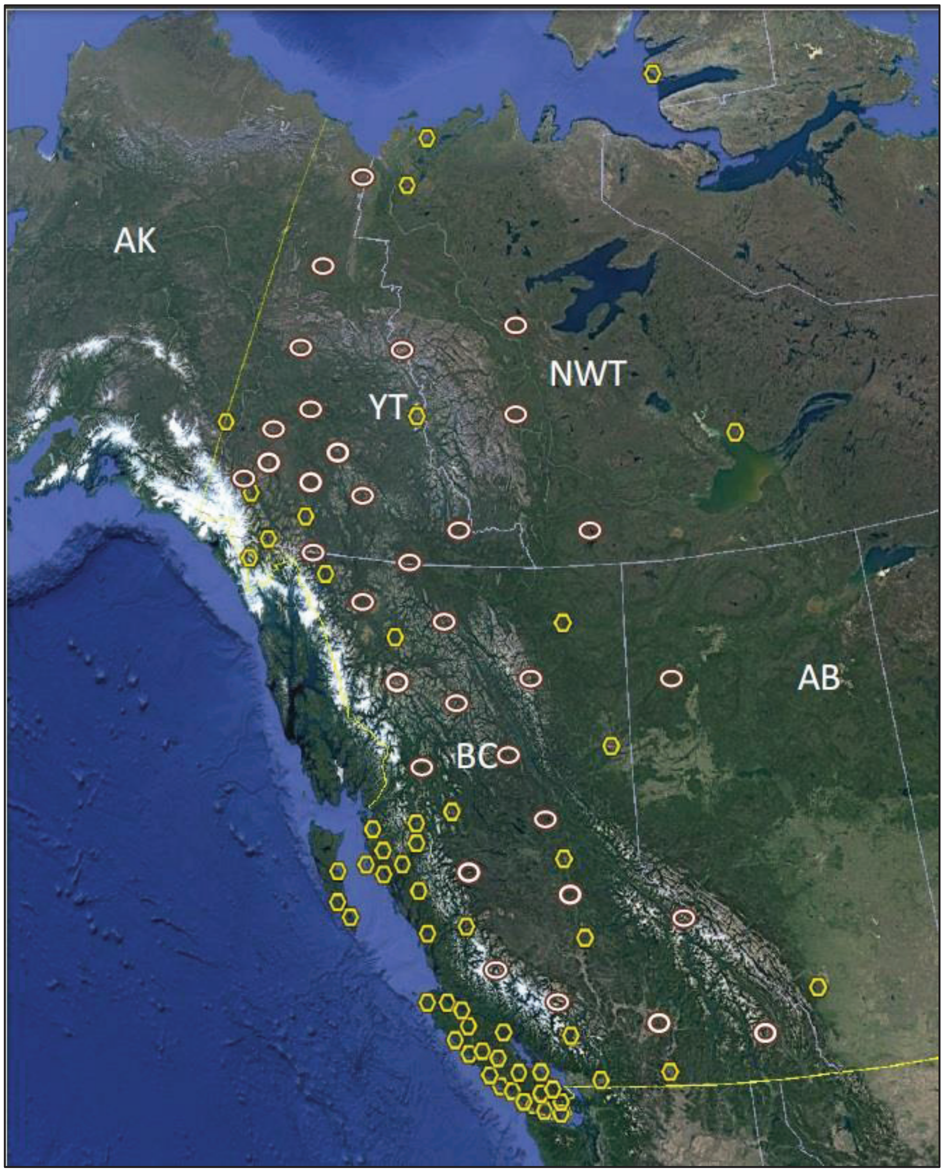

Figure 2: *Proposed distribution of GNSS (GPS) equipment for the CCArray (courtesy of M. Schmidt and J. Elliott). The pink ovals represent 35 proposed GNSS (GPS) equipment which would be co-located with some of the seismometers in Figure 1. The yellow hexagons represent installed GNSS (GPS) equipment from other sources.*

In-situ monazite dating of sediment-hosted stratiform Cu mineralization in the Redstone copperbelt, Northwest Territories, Canada: Cupriferous fluid flow late in the evolution of a Neoproterozoic sedimentary basin

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The 300 km-long Redstone copperbelt in the Mackenzie Mountains, Northwest Territories, Canada, comprises a series of sediment-hosted stratiform copper (SSC) deposits hosted in Neoproterozoic fault-bounded intracontinental rift basins. The Coates Lake deposit is the largest of these deposits. Mineralization at Coates Lake is concentrated in microbial laminite layers, in the Transition Zone between underlying continental redbeds (Redstone River Formation) and overlying marine carbonate (Coppercap Formation). The microbial laminate layers host disseminated cupriferous sulfide (chalcopyrite, bornite and chalcocite) that in association with dolomite, K-feldspar, albite, quartz, monazite and apatite, partially replaced detrital and early diagenetic minerals, including early calcite cements. Bornite (± minor chalcopyrite)-calcite-dolomite-quartz-K-feldspar-albite bedding-parallel veins are developed adjacent to mineralized microbial laminite layers in the lower part of the Transition Zone.

In this study, in-situ U-Th-Pb chemical dating of monazite was undertaken to determine the absolute timing of mineralization. Monazite from four mineralized samples have rounded Th-U-HREE-rich detrital cores surrounded by Th-U-poor, LREE-S-Sr-rich, rims that are part of the mineral association that accompanied growth of cupriferous sulfides. Analyses of eleven cores yielded dates between 1025 and 1843 Ma, i.e., older than the depositional age of the Transition Zone previously constrained to be within 775 and 732 Ma. Dates from ten rims range from 607 to 661 Ma and overlap at the 2σ level. A weighted average date of 635 ± 13 Ma suggests that SSC mineralization occurred about 100 Ma after deposition of the host rocks.

Stratigraphic reconstructions coupled with estimates of sediment compaction indicate that at 635 Ma the Transition Zone was buried by ~4 km of sediments, and overlay ~1.6 km of mainly red-bed sediments of the Redstone River Formation. By 635 Ma, mudstone and carbonate rich units above the Transition Zone acted as a low permeability cap that led to suprahydrostatic fluid pressures in the underlying sediments. Bedding-parallel veins indicate that fluid pressures transiently exceeded the lithostatic load. Following the establishment of suprahydrostatic fluid pressures, free convection initiated within the Transition Zone and underlying units. Mineralization formed as oxidized saline pore fluids circulated through the redbeds (± underlying basaltic flows and basal sedimentary detritus) carrying copper up into the Transition Zone. The salinity of the pore fluids might have originated from cryogenic brines generated by the Sturtian (720 to 660 Ma) and Marinoan (650 to 635 Ma) global glaciation events.

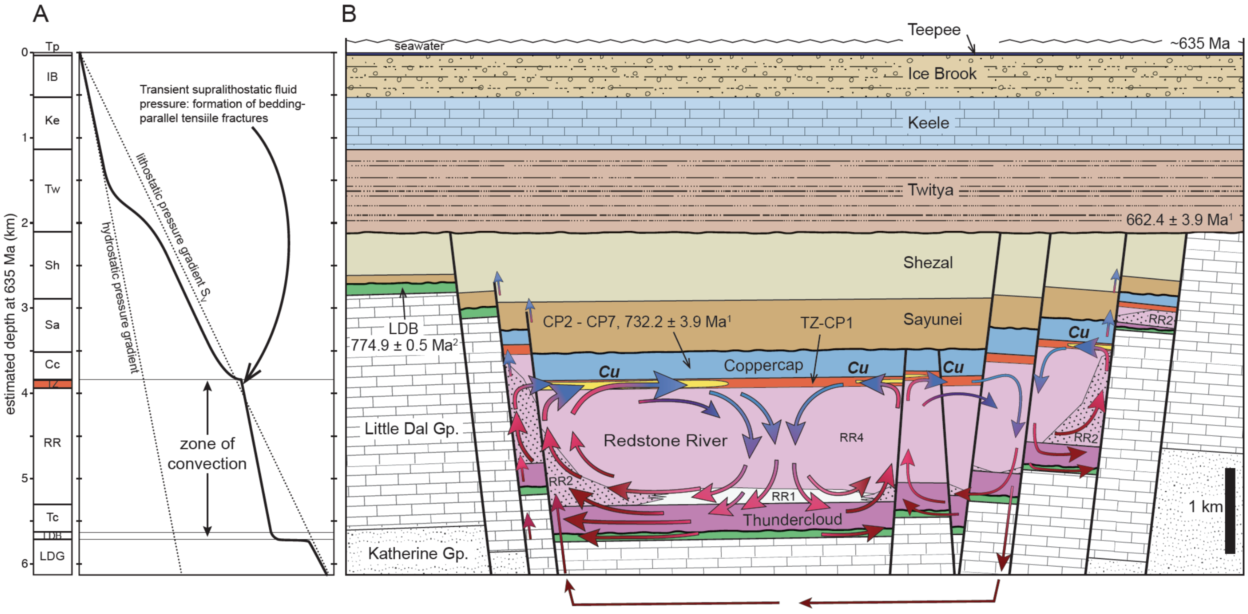

*Fig. 1. **A**. Schematic pore fluid pressure vs depth curve through the Coates Lake basin at ~635 Ma. **B**. Schematic cross-section showing the geological setting at 635 Ma during stratiform copper mineralization and convection in Coates Lake basin. The transition from localized rift sedimentation to areally extensive basins of the Twitya Formation resulted in the formation of lithological seals over pre-Twitya rift faults. "Cu" marks the formation of stratiform copper mineralization in the Transition Zone owing to the convection of mineralizing fluids through*

Coates Lake basin. Blue (cooler) to red (hotter) arrows show schematic heating-cooling pathways of mineralizing fluids during convection. [LDB, Little Dal Basalt; RR1, RR2, RR4, evaporite, fanglomerate, and distal alluvial fan flood-plain facies, respectively, of the Redstone River Formation; CP1 to 7 refers to members of the Coppercap Formation.]

Early Paleozoic volcanic rocks of the Kechika group, Pelly Mountains, Yukon: A record of post-breakup magmatism within the ancestral North American margin

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Passive margins result from continental breakup and are thought to represent a change in tectonic regime from active rifting to quiescence and subsidence. In simplistic models of continental breakup, magmatism is not expected within the passive margin following the initiation of seafloor spreading. Such models of continental breakup cannot explain the presence of post-breakup volcanic rocks within passive margin sequences, including those within the Cordilleran miogeocline of northwestern Canada. To understand the tectonic significance of post-breakup magmatism and its relationship to lithospheric-scale lineaments in the northern Cordillera, a field-based project was designed to characterize the physical stratigraphy, geochronology, and geochemistry of Upper Cambrian to Ordovician volcanic rocks of the Kechika group, central Pelly Mountains, south-central Yukon.

Latest Cambrian and Early Ordovician crystallisation ages are reported for Kechika group pyroxene gabbro stocks using chemical abrasion (CA-TIMS) zircon U-Pb geochronology. Observed lithofacies of dated and undated Kechika group rocks include pillow lava, sediment-matrix basalt breccia, and mafic sills, which are indicative of submarine volcanic centres and sediment-sill complexes. Chemically, all mafic rock samples have alkali basalt/foidite and ocean island basalt geochemical signatures. Whole-rock trace element and Nd-Hf isotope geochemical data for some of the mafic intrusive bodies indicate contamination by evolved crustal rocks.

The age, depositional setting, and geochemical signature of Kechika group strata is analogous to coeval mafic volcanic rocks within northwestern Canada, including the Menzie Creek formation within the Selwyn basin, and the Marmot Formation within the Misty Creek Embayment. Mafic volcanic rocks within the Menzie Creek formation, and Marmot Formation have been demonstrably linked to local extensional faulting. Field stratigraphic and analytical results suggest that magmatic rocks of the Kechika group were generated as a result of low-degree partial melting of an enriched mantle source during CambrianOrdovician extension and rifting along the Cordilleran margin. Previously proposed asymmetric rift models for continental margin evolution, including hyperextension, could explain the timing and geographic extent of post-breakup magmatism. Inferred transfer zones such as the Liard line that form at high angles to the rifted margin may have also controlled stratigraphic architecture and influenced regional tectonics, magmatism, and metal fertility. Potential analogues for Kechika group volcanism include syn- to post-breakup rocks associated with the Orphan, Fogo, and Newfoundland Seamounts in the Grand Banks area, offshore Newfoundland.

Lithotectonic associations of the Ladue River unit and new evidence of Permian (ca. 267–257 Ma) magmatism, deformation, and metamorphism in east-central Alaska

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Recent geologic mapping and U-Pb geochronology in the Tanacross and Eagle quadrangles of east-central Alaska provide a critical test of cross-border geologic correlations and reveal new evidence of Permian magmatism, deformation, and metamorphism in the region. Rocks of the informal Ladue River unit (LRu) were mapped by previous workers in the eastern Tanacross quadrangle along the Alaska-Yukon border and correlated with the Permian Klondike assemblage of western Yukon, Canada. The Klondike assemblage chiefly contains metavolcanic rocks and coeval plutons which have been metamorphosed to schist and orthogneiss. It is a well-characterized regional lithotectonic unit of the allochthonous Yukon-Tanana terrane (YTT). Limited, discontinuous LRu exposures include quartz-mica schist, locally pyritiferous Cr-rich chlorite schist, biotite schist, and amphibolite. Along the Alaska-Yukon border, LRu exposures are mostly quartz-mica schist and chlorite schist distinguished by abundant euhedral magnetite crystals up to 1 cm. New U-Pb zircon ages of ca. 267 and 261 Ma from quartz-mica schist and quartz-eye schist, respectively, are interpreted to represent crystallization ages of volcanic protoliths, supporting correlation of the easternmost LRu with the Klondike assemblage. Other LRu exposures are more lithologically heterogeneous than exposures in the Yukon border region and yield Late Devonian to Early Mississippian zircon ages. Thus, we interpret much of the remaining LRu to be correlative with the Fortymile River assemblage and not the Klondike assemblage.

We interpret LRu exposures to represent thin (up to a few hundred meters as exposed), structural panels of allochthonous YTT assemblages—both Fortymile River and Klondike. The panels are gently dipping, volumetrically small, and record predominately medium-temperature, ductile deformation and associated metamorphism. In contrast, panels of similar assemblages exposed in the Klondike district to the northeast exhibit lower-temperature (greenschist facies) assemblages. The structural panels of YTT assemblages in the eastern Tanacross quadrangle overlie broad areas of coarse-grained gneiss to K-feldspar-megacrystic augen orthogneiss with shallowly-dipping foliation. Several dated augen orthogneiss samples yield consistent Late Devonian U-Pb zircon crystallization ages, suggesting that they are part of the Lake George assemblage, which is part of the parautochthonous North America basement (NAb). The contacts between the YTT assemblages and underlying Late Devonian augen orthogneiss are generally low-angle. The low-angle boundaries, where exposed, are marked by pervasive mylonitic high-strain zones with complex kinematics recording multiple episodes and directions of movement. Complex folds, abundant layer-concordant quartz segregation veins up to a half meter thick, and a distinctive set of subvertical, layer-discordant, smaller quartz veins are also common within the high-strain zones. Our new Permian crystallization ages, combined with field observations of the relative timing of deformation, indicate that one or more episodes of penetrative deformation and associated metamorphism occurred after ca. 261 Ma.

In the northern Tanacross quadrangle, a concordant, meter-thick layer of felsic gneiss interlayered with quartzite, mica schist, and amphibolite of the Late Devonian to Mississippian Fortymile River assemblage also yielded a zircon crystallization age of ca. 262 Ma. The felsic gneiss appears to be concordant in outcrop, but its Permian age suggests that it is more likely a meta-intrusive body that was deformed at amphibolite-facies conditions after crystallization. Approximately 45 km to the north, the undeformed ca. 257 Ma Mt. Warbelow pluton cuts across the main foliation in rocks of the Fortymile River assemblage. These observations and age constraints bracket at least one episode of deformation and metamorphism between ca. 261 and 257 Ma, suggesting that the Late Permian Klondike orogeny extended from Yukon into eastern Alaska. Both the structural panel of ca. 267–261 Ma Klondike assemblage near the Yukon border and the ca. 262 Ma felsic gneiss are within a few kilometers of the Early Cretaceous extensional shear zone that separates the allochthonous YTT assemblages from the parautochthonous North American basement. Thus, we speculate that at least some of the deformation and metamorphism observed in the ca. 267–261 Ma rocks occurred after the Permian. Additional mapping, geochronology, and thermochronology are under way to better resolve the age, kinematics, and metamorphic conditions of Permian and younger tectonic events.

Composite pericratonic basement of west-central Stikinia and its influence on Jurassic magma conduits: Examples from the Terrace-Ecstall and Anyox areas

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The nature and affinity of the pre-mid-Paleozoic basement of Stikinia remains poorly known. However, this basement exerted a fundamental control on the location and distribution of intrusions and intrusion-related mineral deposits. A transect from west-central Stikinia near Terrace to the Ecstall belt (considered a possible correlative of the Yukon-Tanana terrane in the central Coast Mountains) indicates commonalities of basement; a comparison of detrital zircons from a Jurassic conglomerate (considered part of the Eskay rift) suggests that basement of central Stikinia differs from the Yukon-Tanana basement in the north.

Near Terrace, stratified upper Paleozoic and Mesozoic rocks of western Stikinia are cut by the Kleanza pluton, an ENE-elongate, multiphase Early Jurassic body. To the west, this section is juxtaposed with highly strained lower crustal rocks of the Central Gneiss Complex and Shames River intrusive complex (Early Jurassic) across the Shames River normal fault. Farther west, the Coast Shear zone marks the eastern boundary of the Ecstall belt, a mid-Paleozoic (in part Middle Devonian) magmatic arc complex cut by a Mississippian 'central diorite suite' and Early Jurassic plutons (Foch and Johnson). Geological continuity across the Terrace-Ecstall transect is demonstrated by similar igneous geochemical signatures of coeval Mississippian and Early Jurassic suites. Volcanic rocks of the Mt. Attree Formation and a small cogenetic pluton in the Terrace area are ca 323-325 Ma (U-Pb zircon), somewhat younger than, but within error of, a previously published Mississippian age (336.8±17.7 Ma) from a pluton in the Ecstall belt. Both suites are silica bimodal, showing strong subduction influence in felsic rocks and non-arc immobile element signatures in metabasalts. Early Jurassic intrusive phases from all three areas show a continuum on modified alkali-lime, aluminum saturation and Fe* vs silica plots, and generally increasing LREE/HREE and HREE/MREE with silica. Trace and major element chemistry show strong influence of plagioclase and hornblende fractionation. The Early Jurassic intrusions (ca 200-180 Ma) are interpreted as having evolved in related magma chambers in a structurally controlled permeability corridor corresponding to the Skeena arch, which trends across the terrane at a high angle.

Late Early to Middle Jurassic stratified rocks on Mt. Clashmore, west of the Anyox deposit at the southern end of the Eskay rift, consist of basalt, rhyolite, and sedimentary rocks including monomictic breccias and cherty argillites with tuffaceous laminae. They are correlated with the Iskut River Formation of the Eskay rift in the Iskut region. Evenchick and McNicoll (2002) reported non-northwest Laurentian detrital zircons (1058-517 Ma) from a conglomerate at Mt. Clashmore that may have been derived from a fragment of accreted exotic pericratonic basement that was exposed in a horst or rift shoulder adjacent to the Eskay rift in the mid-Jurassic.

Rocks of the Ecstall belt and the cryptic Precambrian source of detrital zircons at Mt. Clashmore are parts of the composite, pre-late Paleozoic basement of Stikinia. Major long-lived (Late Devonian to Recent) N-S and E-W fault corridors in the terrane cut across different basement components, suggesting that their precursors formed after amalgamation of its basement but before or coeval with the oldest units in the Stikine assemblage.

Triassic to Jurassic arc volcanism and porphyry prospectivity in northwestern British Columbia

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We present an updated regional model for the Triassic to Jurassic volcanic arc geometry and define five metallogenic epochs in northwestern British Columbia.

Several large (>1000 km^2) Late Triassic plutons define an arcuate belt that transects the northern part of Stikinia. They cut thick sections of mafic volcanic rocks of the Stuhini Group, and are interpreted to mark the approximate Late Triassic arc axis formed as a result of southward subduction (present coordinates). Several porphyry copper systems occur within the belt (e.g. Schaft Creek). Large plutons are absent further south, and here, Late Triassic rocks are both sedimentary and volcanic in nature.

During the latest Triassic, profound plate tectonic changes resulted in the changeover from Stuhini Group to Hazelton Group volcanism. An early metallogenic epoch formed the Galore Creek deposit; a late event resulted in the Red Chris and GJ deposit.

In the Early Jurassic, volcanic rocks of the lower part of the Hazelton Group were formed in the south. The volcanic rocks are attributed to subduction along the western and eastern margins of Stikinia. The volcanic rocks are associated with numerous porphyry and epithermal deposits, such as KSM, Red Mountain, Brucejack and Kemess. To the north, and along the Late Triassic arc axis proposed herein, the lower part of the Hazelton Group is absent. Instead Triassic rocks are overlain by a regional-scale sub-Toarcian unconformity, indicative of latest Triassic through Early Jurassic uplift and erosion.

The unconformity is overlain by late Early to Middle Jurassic volcanic rocks of the recently-defined Horn Mountain Formation (upper part of the Hazelton Group). The formation hosts several early-stage porphyry exploration projects that may represent a new Middle Jurassic metallogenic epoch within the Canadian Cordillera. The magmatism is interpreted to have resulted from remelting of subduction-modified lithosphere during collision of Stikinia with the other Intermontane terranes.

Late Triassic to Middle Jurassic magmatism in the Intermontane terranes of Yukon

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Patrick Sack, Yukon Geological Survey
Jim Crowley, Boise State University
Murray Allan, Mineral Deposit Research Unit, University of British Columbia

A series of Late Triassic to Early Jurassic granitoid plutons intrude the Intermontane terranes (Stikinia, Quesnellia, Yukon-Tanana) in southern Yukon. These are the northern continuation of two paired magmatic belts intruding Stikinia and Quesnellia in BC that converge in southern Yukon and peter out into eastern-central Alaska. In BC, these plutons are host to prolific Cu-Au porphyry deposits. The hairpin geometry of the Late Triassic-Early Jurassic magmatic belts form part of the argument that led to proposal of the oroclinal enclosure of the Cache Creek terrane.

In Yukon, the Late Triassic-Early Jurassic plutons define three magmatic suites: Stikine (216-206 Ma), Minto (204-194 Ma), and Long Lake (192-178 Ma) suites. Plutons of the Stikine suite are generally more mafic monzodiorite to quartz diorite, form small plutons and are restricted to Stikinia. They are inferred to represent upper crustal (4 kbar), subvolcanic intrusions to basaltic andesite of the Lewes River arc (Stikinia). The Minto suite straddles the northern apex of Stikinia/Quesnellia in central Yukon. It comprises variably deformed granodiorite that were emplaced at lower crustal depths (6-7 kbar) and host high-grade Cu-Au mineralization (Minto, Carmacks). These plutons were emplaced during accretion of the Intermontane terranes to western North America and onset of orogenesis in the northern Cordillera. The slightly younger Long Lake suite comprises granodiorite and granite that were emplaced at shallower crustal level (3-5 kbar) during development of the syncollisional Whitehorse trough, following regional exhumation. Trace element patterns for the Minto and Long Lake suites show decreasing subduction influence consistent with syncollisional emplacement.

Middle Jurassic plutons of the Bryde suite (172-168 Ma) are post-collisional and intrude Stikinia, Cache Creek terrane, and Whitehorse trough. These plutons have alkalic tendencies and range from monzonite to syenite to granite compositions. They locally host porphyry Cu mineralization (Mars) and may be product of slab break off. The youngest Jurassic intrusive in the Intermontane terranes of Yukon is the 163-161 Ma McGregor pluton. It has calc-alkalic to alkalic tendencies, ranges in composition from monzonite to granite, and was emplaced at mid-crustal levels (4-5 kbar).

Geochemical characterization of Triassic volcanic arc rocks of Stikinia in Yukon

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In south-central Yukon, volcanic arc rocks part of Stikinia are divided between the Middle Triassic Joe Mountain Formation and Upper Triassic Lewes River Group. Lithological, geochemical, and geochronological characterization of these rocks provides insights into the tectonic setting, evolution, nature and geometry of Cordilleran terranes during the Triassic. In the field, no contact has been formally mapped between the two groups; only an uncomformable stratigraphic relationship is inferred. Field distinction is based on geographic distribution, volcanic textures, and petrography. The Joe Mountain Formation comprises dominantly coherent, pillowed aphyric basalt. The Lewes River Group displays pyroxene-phyric basalt, but is dominated by volcaniclastic rocks. New geochronology constrains the age of the Joe Mountain Formation at ~245 Ma (Crowley, *pers. comm.,* 2016). The Upper Triassic age of the Lewes River Group is only defined by Late Carnian to Rhaetian fossils from the overlying carbonate sequence. Compiled lithogeochemistry and petrography data (Bordet, this study; Hart, 1997; Piercey, 2004; Sack, *pers. comm.* 2016) are used to characterize and compare these volcanic arc suites, identify regional geochemical patterns, and interpret of the evolution of one or multiple volcanic arcs within Stikinia during the Triassic.

Major elements, trace elements and REE trends for the Joe Mountain Formation and Lewes River Group volcanic rocks all overlap. Both are dominated by basalt and basaltic andesite, with increased trachyandesite to trachydacite for the Lewes River Group. Both suites display internal variations between tholeiitic, transitional and calc-alkaline basalt compositions, with tectonic settings ranging from MORB/BABB, IAT and CAB (Figure 1). The main observed difference is that the Joe Mountain Formation is almost exclusively characterized by tholeiitic and transitional basalt formed in MORB/BABB and IAT settings, whereas the Lewes River Group covers the whole spectrum of compositions and tectonic environments, with a larger amount of CAB. Therefore, the Joe Mountain Formation may represent a more juvenile end-member of the Triassic volcanic rocks sample suite, resulting from the onset of arc magmatism in the Middle Triassic. The Lewes River Group volcanic sequence is a temporal and spatial continuity of the Joe Mountain arc. Both suites likely originate from a same mantle source, and internal geochemical variations are attributed to mantle heterogeneities. As the arc became more mature and basalt compositions more calc-alkaline, the formation of volcaniclastic rocks became predominant over coherent lava.

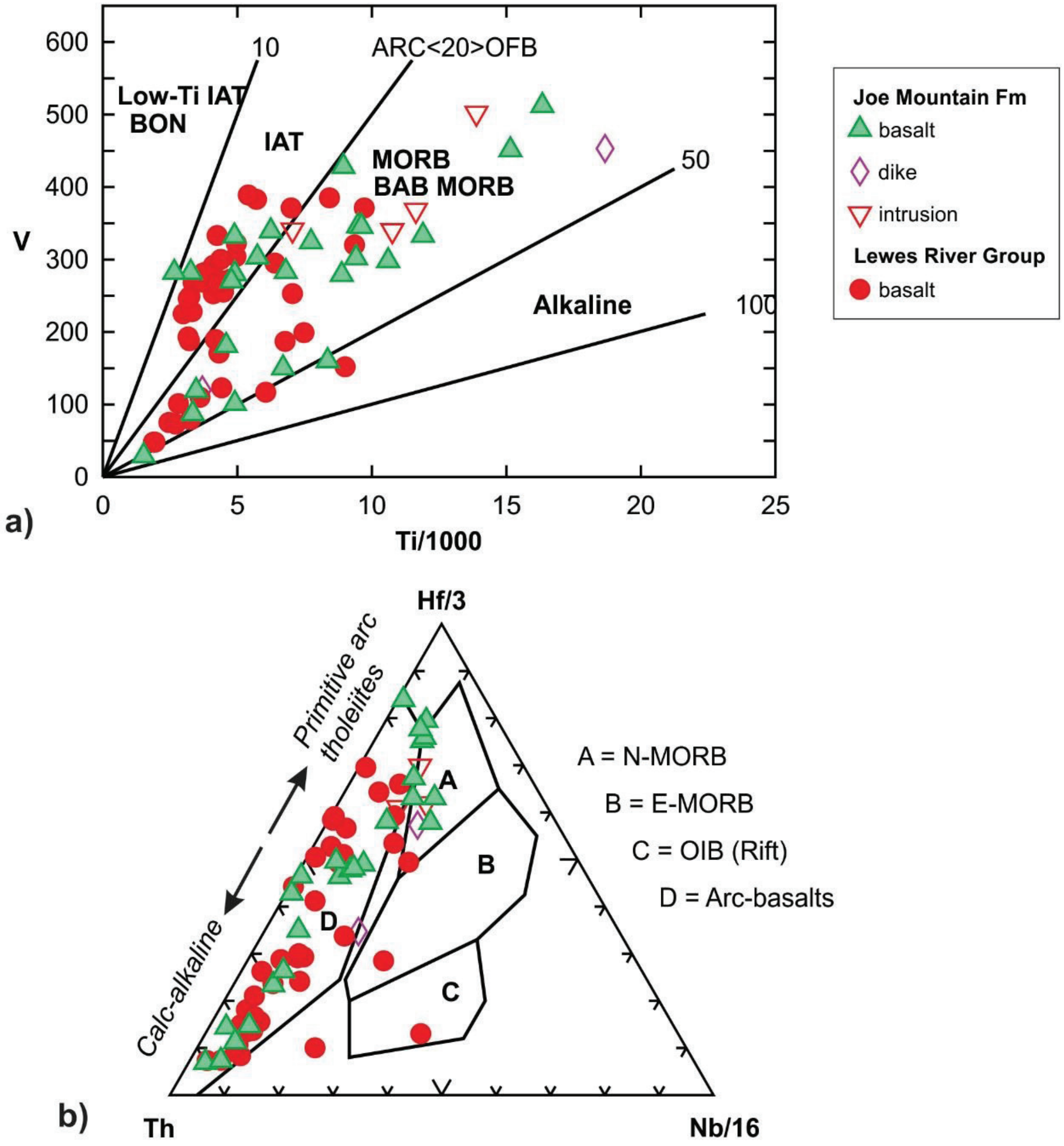

Figure 1. Tectonic discrimination trace element diagrams for the Joe Mountain Fm. and Lewes River Gp. basalts: a) Ti-V diagram of Shervais (1982); b) Th-Hf/3-Nb/16 diagram of Wood (1980)

Definitions: BABB = Back Arc Basin Basalt; CAB = Calc-Alkaline Basalt; IAT = Island Arc Tholeiite; MORB = Mid-Ocean Ridge Basalt; REE = Rare Earth Elements

From subduction to exhumation: the geological evolution of the Carmacks Copper deposit

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The Carmacks Copper belt is a northwest trending corridor of mineralization that includes the Carmacks Copper Cu-Au-Ag and Minto Cu-Au deposits, as well the Stu Cu-Ag prospect in west-central Yukon. These occurrences are distinctive in that they are metamorphosed and exhibit ductile deformation. The Carmacks Copper deposit is hosted in compositionally heterogeneous, foliated and folded, and variably migmatitic rocks, which occur as elongate, NNW-trending inliers in granitoid rocks of the Late Triassic to Early Jurassic Granite Mountain batholith. The metamorphic rocks are affected by an early foliation (S_1), which is dominantly NNW-striking and steeply dipping, and are subsequently intruded by undeformed plutonic phases. Hypogene copper mineralization is restricted to deformed host rocks, and occurs both as foliation-parallel chalcopyrite-dominant stringers in schistose rocks, and as net-textured bornite-chalcopyrite-dominant sulphides in migmatitic zones. Since mineralization hosted by schistose rocks is S_1-parallel, it is concluded that copper mineralization was introduced to the protolith prior to D_1 deformation.

We interpret that previously mineralized mafic igneous rocks were affected by ductile deformation (D_1) and amphibolite facies metamorphism such that sulphide minerals were dynamically remobilized into foliation-parallel blebs and stringers of sulphide, possibly in the Late Triassic in a W-dipping subduction zone that existed between the Lewes River Arc and Ancestral North America. Metamorphic rocks were then subsequently engulfed as inliers within Granite Mountain batholith ca. 199-197 Ma, resulting in the formation of migmatites from partial melting of schistose rocks. During this magmatic event, pre-existing sulphides were recycled via a sulphide melt phase into net-textured copper sulphides. At this stage, rocks of the Carmacks Copper deposit had been tectonically buried to a depth of at least 9 km, as indicated by plagioclase-hornblende thermobarometry.

A second phase of ductile deformation (D_2) post-dating magmatism preferentially affected rheologically incompetent metamorphic rocks and associated late dikes, whereas plutonic rocks of the Granite Mountain batholith remained largely unstrained. This event is correlated with mesoscopic folding of metamorphic rocks and late dikes that are locally dismembered as boudins along fold limbs or as rootless fold hinges. Preliminary high-precision U-Pb zircon ages of these late dikes indicated that they are younger than the massive phases of the GMB, which requires that D_2 deformation post-dates emplacement of the GMB and suggests that the deposit was still at deep-crustal levels by ~194 Ma. Previous Ar-Ar dating studies demonstrate that the GMB had taken approximately 10 million years to cool, with an average cooling rate of 40°C/m.y., implying relatively rapid exhumation. The deposit was exposed to erosion and supergene processes by the Late Cretaceous, as demonstrated by Late Cretaceous Carmacks Group volcanic rocks unconformably overlying rocks of the GMB.

The Carmacks Copper deposit is an unusual example of Cu-Au mineralization that has undergone a major tectonic cycle of ductile deformation, metamorphism, mid-crustal magmatism, and deep exhumation. This study provides insights into the nature and timing of Mesozoic Cu-Au mineralization and tectonic processes in the Yukon segment of the Cordilleran orogeny.

Cretaceous exhumation of the Aishihik batholith, central Yukon resolved through low temperature (U-Th)/He thermochronology

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The Aishihik batholith (ca. 190-180 Ma) is the largest within the main belt of late Jurassic plutons in the northern Cordillera, and is thought to stitch assemblages of the Yukon-Tanana terrane with those of Stikine terrane. Assessing the thermal history via zircon (ZHe) and apatite (AHe) (U-Th)/He thermochronology of samples from the Aishihik batholith with those of Paleozoic to Mesozoic host rocks can provide insight into the low-temperature (<200°C) window of Jurassic-Cretaceous tectonism and crustal exhumation. In particular, we are interested in the northwest margin of the batholith which has been purported to be a tectonic contact. We analyzed sixteen plutonic samples that exhibit ductile strain and possess a single population of zircon and apatite grains (demonstrated by typical igneous zoning and lacking metamorphic overgrowths). Single crystal zircon dates from individual samples show age dispersion by 200 m.y. with a positive to negative correlation as effective uranium (eU) concentration increases, as predicted by diffusion theory. Samples are grouped into three categories based on geographic location and rock type, and each set illustrates a differing thermal history. Within the first group, numerical modeling of the AHe and ZHe data in the southeast portion of the study area, within the Aishihik batholith, suggests relatively rapid (~10°C/m.y.) cooling immediately after emplacement of the batholith. Majority of the batholith cooled by the Late Cretaceous, coinciding with the Carmacks unconformity, however some data suggests that the centre of the batholith cooled earlier (Early Cretaceous), which overlaps with the Mount Nansen unconformity. Comparatively, adjacent Yukon-Tanana terrane rocks exhibits slower (~2°C/m.y.) cooling from the Permian to the Early Cretaceous followed by very rapid (~15°C/m.y.) cooling in the Late Cretaceous. Both the second group in the central study area and third group in the northwest seem to exhibit this similar cooling history with slow (~2°C/m.y.) cooling until the Early Cretaceous proceeded by rapid (~15°C/m.y.) cooling in the Late Cretaceous. Recent mapping suggests that the northwestern margin of the Aishihik batholith is an intrusive contact, which has implications for the level of crust that is preserved from Jurassic time. This research adds to the network of thermochronologic data in exploring Cretaceous crustal exhumation and tectonism of the Yukon portion of the Cordillera compared to the Alaskan and British Columbia

Cordilleran, which recorded Eocene exhumation signature. Increased recognition and understanding of low-temperature tectonothermal history can allow for better understanding of shallow crustal processes and their relationships to adjacent metal-bearing regions.

Geologic setting of the Granite Mountain batholith, host to the Gibraltar porphyry Cu-Mo deposit, south-central British Columbia

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The Gibraltar porphyry Cu-Mo deposit was considered unusual because ore zones are associated with ductile contractional fault zones, and the host Granite Mountain batholith (Late Triassic) was thought to be in oceanic Cache Creek terrane. A contrary view (Ash et al., 1999) held that the batholith is part of the Quesnel arc terrane, host to numerous other porphyry deposits, and had been faulted into Cache Creek terrane. Mapping in 2013 and 2014 was implemented to clarify the contact relationships and terrane affinity of the batholith.

The Granite Mountain batholith is included in Quesnel terrane because, on its northeast margin, it intrudes the slightly older Burgess Creek stock, which itself intrudes an assemblage of Upper Triassic sedimentary and volcanic rocks correlated with the Nicola Group, the defining stratigraphic unit of Quesnel terrane. These Nicola rocks consist mainly of volcanogenic sandstone (locally gritty to pebbly), intercalated with conglomerate, mafic and felsic volcanic breccia, siltstone, limestone and basalt. The Nicola rocks, and possibly the northern part of the Granite Mountain batholith, are overlain by a younger assemblage that includes slate, siltstone, sandstone and conglomerate, and is correlated with the Dragon Mountain succession (Lower to Middle Jurassic), another characteristic element of Quesnel terrane. A narrow belt of rocks along the southwest margin of the Granite Mountain batholith is assigned to the Cuisson Lake unit. It consists mainly of chlorite schist, foliated limestone and skarn, and was derived from a succession of feldspathic volcaniclastic ±volcanic rocks intercalated with limestone. These rocks were previously included in the Cache Creek Complex, but herein are correlated with the Nicola Group. The Granite Mountain batholith, and rocks of the Nicola Group, Cuisson Lake unit, Burgess Creek stock, and Dragon Mountain succession, form a panel of Quesnel rocks that is bounded to the east and south by rocks of Cache Creek terrane. The eastern boundary is an unexposed north-northwest striking fault that may record more than 20 km of sinistral strike slip. The southern boundary of the Quensel panel is an east-trending fault that juxtaposes the Cuisson Lake unit against Early Cretaceous tonalite of the Sheridan Creek stock, which apparently intrudes Cache Creek rocks farther south. This structure is inferred to be a south-dipping thrust or reverse fault that formed in conjunction with greenschist facies metamorphism and the development of south-dipping foliations in the Sheridan Creek stock, the Cuisson Lake unit, and the southern part of the Granite Mountain batholith.

Structural geology and timing of deformation at the Gibraltar Cu-Mo porphyry deposit.

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**speaker*

The Gibraltar Cu-Mo porphyry deposit, located near Williams Lake in south-central BC, is hosted in the Late Triassic Granite Mountain Batholith. The main ore zone, hosted with the Mine Phase tonalite, is variably, ductiley deformed and structurally dismembered. Past interpretations have suggested that ductile deformation occurred during pluton emplacement. Here, deformation structures are divided into two deformation events: D_1 and D_2. A variably developed, tectonic foliation (S_1) that is folded into gentle to open folds is associated with D_1. S_1 is associated with shallowly to moderately south-southwest dipping ductile thrust faults and smaller –scale imbricate ductile thrusts. The ductile thrusts, have quartz-chlorite and ankerite-quartz alteration and typically host – or bound the ore. D_2 resulted in the formation of northwest-to north-northeast trending dextral, normal faults, N-S striking normal faults and variably striking low-angle normal faults that offset and rotate D_1 structures and mineralization. Late, shallowly SE plunging intersection lineations and fold axes (F_2) are associated with a sub horizontal crenulation cleavage that likely formed during extension. The Mine Phase tonalite yields a U-Pb (zircon) crystallization age of ca. 216.17 ± 0.24 Ma (CA-TIMS). In contrast, Ar-Ar (white mica) minimum cooling ages ranged from 54-36.5 Ma for mica collected from S_1, ductile thrust faults, and N-S striking, dextral normal faults. It is proposed that *both* D_1 and D_2 are associated with movement along regional Paleocene –Eocene, dextral strike-slip faults, and ductile deformation significantly post-dates porphyry emplacement. This interpretation is consistent with deformation microstructures in quartz and plagioclase that constrain the temperatures during deformation to be less than ~ 450°C; likely too low to be contemporaneous with pluton emplacement.

Mesozoic Orogenic Gold Systems of British Columbia: Structural Setting and Tectonic Implications

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Orogenic gold deposits remain an attractive global exploration target due to their typically high grades. In general, Phanerozoic belts have received less modern exploration interest for orogenic gold relative to Archean districts such as Western Australia and West Africa. However, a revival of exploration activity in the Cariboo district of BC – which historically produced 3.2 Moz from placer creeks and 1.3 Moz from lode souces – highlights the potential for similar systems in BC and elsewhere in the Cordillera. This study examines structural controls on orogenic gold in the Cariboo and similar settings in the Cassiar and Sheep Creek districts, in order to assess the timing and kinematic controls on mineralization, as a function of tectonic processes (Figure 1).

Late Jurassic to Early Cretaceous gold-bearing quartz veins of the Cariboo and Sheep Creek districts formed inboard (east) of the suture between the Quesnellia arc terrane and North American passive margin sediments of Upper Proterozoic to Lower Paleozoic age. Vein-hosted gold mineralization in the Cassiar district is similarly situated east of the Quesnellia margin, but is hosted mainly in metabasaltic rocks of the Slide Mountain terrane (Sylvester allochthon), which structurally overlies platformal North American strata. Previous Ar-Ar dating studies indicates that the timing of mineralization was broadly similar in the Cariboo (148 – 139 Ma) and Cassiar (135 – 133 Ma) districts. The age of mineralization in the Sheep Creek district is loosely bracketed by Middle Jurassic, pre- to syn-tectonic granitoids and Early Cretaceous intrusions that post-date regional deformation (i.e., 161 – 118 Ma). Magmatism that is either contemporaneous with, or genetically related to, mineralization has been suggested by numerous workers, but has yet to be demonstrated in any of the districts.

In all three orogenic gold districts, penetrative strain fabrics of the host rock sequence imply orogen-normal shortening and simultaneous orogen-parallel, longitudinal extension. This lateral escape tectonic style appears to have been accompanied by N-directed transport of the Slide Mountain terrane, as demonstrated by mylonitic shear fabrics along the Pundata thrust in the Cariboo, and shear and vein geometries in the Table Mountain area of the Cassiar district. Quartz vein geometries and shear sense indicators are kinematically compatible with coaxial progressive shortening under the same general stress regime responsible for early, thin-skinned fold-and-thrust style deformation. Gold mineralization associated with the late, low-strain stage of this deformation thus signals the transition from penetrative thick-skinned deformation in the Jurassic, to the partitioning of strain into orogen-parallel strike-slip fault systems and the onset of voluminous magmatism in the Early to mid-Cretaceous.

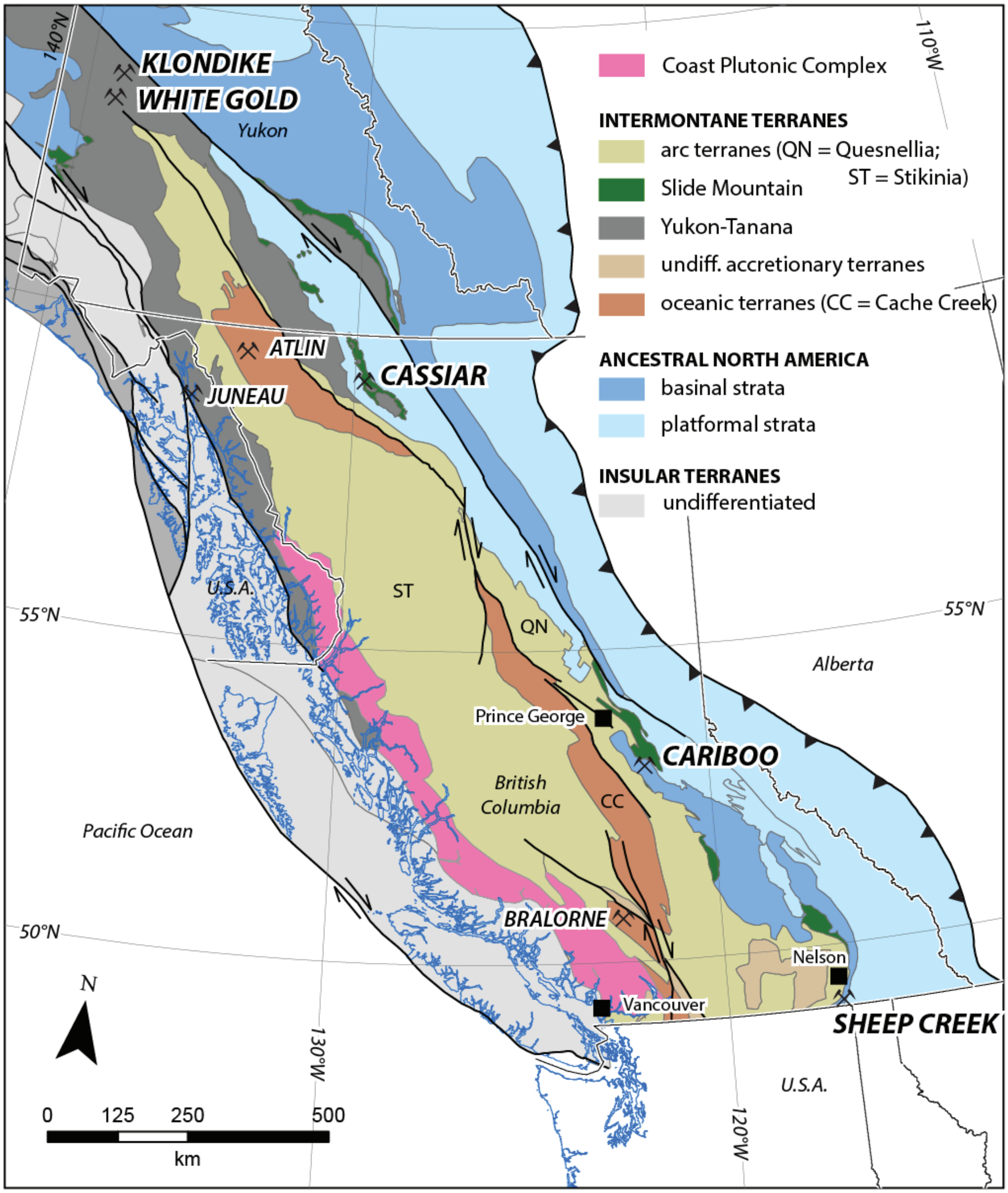

Figure 1. Location of Phanerozoic orogenic gold districts of the Canadian Cordillera.

Preliminary Structural Constraints on the Geometry of Selwyn Basin from Summit Lake to Howard's Pass, Nahanni Map Sheet (NTS 105I), NWT

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Mesozoic crustal shortening related to the Cordilleran Orogeny is well documented throughout Yukon and Northwest Territories. The Mackenzie foreland fold and thrust belt (FFTB) is characterized by thrust systems having long flats, discrete zones of imbricate fans, and box-shaped detachment antiforms that deform platform facies carbonate rocks. Metamorphic grade is sub-greenschist and internal deformation of thrust sheets is limited to localized cleavage development and minor parasitic folding. Southwest, towards the hinterland, rocks of the southern Selwyn FFTB are characterised by shortening that induced multigenerational folding, penetrative foliations, and widely spaced thrusts in deep-water facies siliciclastic rocks. Compared to the Mackenzie FFTB, the geometry and kinematic history of shortening in southern Selwyn FFTB is not well understood. Two distinct structural models have been recently proposed, based on regional mapping in the Nahanni area of the Selwyn FFTB; the fundamental discrepancy between the two models is whether discreet thrusts with internal deformation, or macroscopic folds and associated penetrative foliations, are the dominant mechanism for accommodating regional contraction. However, no detailed structural mapping has been done to resolve deformation geometry and history. From the perspective of regional geoscience, complete sections across the northern Cordilleran foreland currently lack important structural detail in the Nahanni region and models of the geometry and kinematic evolution of the FFAT belt are not fully constrained. From the perspective of regional mineral exploration, such as at the Howard's Pass Pb-Zn district along the NWT-YT border, important structural context for ore deposit deformation in the inner FFAT belt is lacking.

The goals of my thesis are to generate a detailed model for deformation in the Nahanni region of the Selwyn FFTB, to test the validity of the two recently proposed regional models of deformation in Nahanni, and to propose an updated model for belt-scale deformation in the northern Canadian Cordilleran Orogen. My thesis will accomplish these goals through (i) detailed structural transect mapping and construction of structural cross-sections across the Nahanni region; (ii) analysis of microscopic and macroscopic structures to determine the kinematic history and processes of deformation; (iii) thermobarometric analysis of metamorphic minerals to determine the conditions of peak metamorphism; (iv) analysis of deformation timing relative to metamorphism; and (v) absolute timing constraints on deformation by in-situ laser ablation dating of structurally constrained radiogenic mineral phases (if present). To date, structural mapping at 1:7500 scale has been conducted along ca. 35 km of staggered transects oriented perpendicular to regional structural trends. Mapping focused on defining fold geometry, resolving overprinting foliation relationships, relating foliations to fold structures in bedding, and constraining the distribution of penetrative deformation across the belt and down through stratigraphy.

Preliminary analysis of map data and oriented samples has identified three structural-lithostratigraphic domains across the study area. The two northernmost domains share a common steeply dipping, NW-SE striking penetrative marker foliation that is axial planar to subhorizontally plunging mesoscopic folds. The southernmost domain shows four foliations overprinting bedding and two fold generations that are not yet correlated with the other two domains. Foliations and parasitic folds in all domains are evenly distributed across lithostratigraphic units. Apparent offset along a previously recognized regional thrust (March Fault) is instead proposed to be a function of structural thinning along the limb of a regional anticlinal fold. No evidence for significant thrust displacement is observed. Preliminary results indicate that regional folding and development of penetrative foliations accommodated the bulk of orogenic contraction in the Nahanni region of southern Selwyn FFTB.

Integrating basement structure, “Antler” foreland events and Cretaceous deformation and diagenesis for economic success in the Alberta foreland basin

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The main goals of this presentation are to use a case study to emphasize the fact that Cordilleran deformation does not stop at the eastern thrust front, and that understanding linkages between events in and beneath both the Cordillera and the foreland basin can be useful for identifying new commercial opportunities in the basin.

EnCana’s natural gas discovery at Ferrier, Alberta, in lower Mississippian Banff Formation dolomitized grainstone, was a significant new pool discovery and new play concept in a long-active, competitive and production-mature part of the basin. Most drilling east of the foothills in western Canada pursues stratigraphic plays. Earlier Mississippian drilling in the Ferrier area focussed on traditional subcrop plays in younger carbonates above the Banff Fm., and on overlying Mesozoic clastic plays. A few previous, deeper wells had encountered reservoir-quality dolomite porosity in the usually finer-grained, non-prospective Banff formation, and significantly down-dip from its subcrop edge. These mostly serendipitous finds culminated in local development of three modest gas pools in the 1990s, but there was little geological context and no workable exploration model. Additional exploration drilling, even after identifying “look-alike” seismic anomalies, encountered only water-filled dolomite porosity, impermeable limestone or shale.

We used a regional, interdisciplinary exploration approach to build a stratigraphic and structural context for the cryptic Banff porosity and to high-grade the most prospective play trends. We worked to identify favourably overlapping and oriented trends in coarse-grained carbonate facies belts, Mississippian and Cretaceous flexural extensional faulting, and deep basement structure and hydrothermal dolomitization pathways. We then focused on using intersecting reservoir facies, diagenetic and trapping fairways in order to locate 3-D seismic surveys to best image the Banff porosity and to identify drillable prospects. Our strategy resulted in a larger new pool discovery well down-dip from previous pools, and several follow-up opportunities. A revised regional sequence stratigraphic model, coupled with specialized seismic processing, have been critical in distinguishing Banff Formation shales and tight limestones from porous grainstone reservoir facies, and thus dramatically reducing the initially high reservoir risk on this play. We also identified other parts of the foreland basin with similar favourable tectonic and depositional elements.

The gross depositional fairway is associated with “Antler” foreland basin (or back-arc) NW-SE extensional faulting that localized the transition from shallow to deep water on the prograding carbonate ramp. Another key component of this play is proximity to long-lived, primarily NE-

SW structural boundaries within the Paleoproterozoic basement. The Banff gas accumulations at Ferrier are apparently associated with the so-called Snowbird Tectonic Zone. Similar basement features include the Hay River Fault Zone and the Great Slave Lake Shear Zone, associated with the MVT Pb-Zn deposit at Pine Point, NWT. Reactivation of the Snowbird Tectonic Zone may have helped to localize both important high-energy Mississippian depositional facies as well as conduits for high-temperature dolomitizing fluids. Cretaceous flexural extensional faulting east of the thrust front may have helped to isolate structurally and trap hydrocarbons down-dip from other porous trends, and/or provided additional conduits for hydrothermal fluids.

Finally, recognizing Late Cretaceous to Paleocene thin-skinned fold-thrust structures in the subsurface east of the foothills highlights shallow structural trap potential beyond known Cretaceous stratigraphic plays.

The evolution of “mid” Cretaceous Omineca Magmatic Belt granites in the Northern Canadian Cordillera: A product of mantle lithosphere delamination.

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“Mid” Cretaceous (mid-K) plutonism in the Omineca Magmatic Belt (OMB) is associated with some of the largest known mineral resources in the Northern Canadian Cordillera (NCC). However, the tectonic setting of these plutons remains controversial. Previous attempts to model mid-K plutonism in the NCC have been constrained by two assumptions: 1. OMB plutons collectively define continent margin parallel bands, and 2. These bands systematically young inboard to the east. We demonstrate, based on detailed mapping combined with geochemical and geochronological studies of OMB plutons in the Tay River district, Yukon, that neither of these assumptions are valid in this area. Plutonism in the Tay River district was continuous over a 20 Myr interval from 110Ma to 90Ma and shows no inboard migration. The oldest plutons are S-type granites that record post-orogenic upper crustal melting in a thickened crust undergoing exhumation. At 100Ma there was a significant change to I-type plutonism, which was derived from lower crustal melting. This plutonism is coeval with voluminous explosive volcanism. We postulate that the I-type magmatism is generated due to external mantle heat delivered to the lower crust during regional exhumation and extension. Plutonism, extension and exhumation in the Tay River district terminated at 90Ma. This magmatic and structural evolution can be shown to characterize the OMB on a regional scale. We hypothesis that, the oldest S-type plutons occur only in regions characterized by over-thickened, ‘fertile’, crust. Subsequent I-type plutonism defines an arcuate, north-closing band that parallels the peripheries of the Yukon-Tanana terrane. Finally 96-90 Ma plutonism occurred across the whole of the NCC. To explain the distribution of mid-K magmatism in the Tay River district, and, more broadly, the entire OMB, we propose a model of collapse of thickened crust and related lithospheric mantle delamination.

Mid-Cretaceous gold-bearing veins in the Dawson Range, Yukon

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Mid-Cretaceous (115 - 99 Ma) plutonic rocks of the Dawson Range, Yukon are cut by similarly aged intermediate andesite and diorite dikes, which in turn are cut by faults and a variety of gold-mineralized quartz veins, breccias, and shear zones (Fig. 1). Mineralization is interpreted to be structurally controlled by dextral faults and shear zones that dissect the Dawson Range. Mineralization has a strong regional Au-As-Sb element association and includes quartz-carbonate-sulphide veins ± native gold with arsenian pyrite and arsenopryite as the main traps for solid solution gold, as well as quartz-absent structures dominated by disseminated auriferous arsenian pyrite and arsenopyrite.

The Coffee deposit, a gold system hosted by steep structures related to the dextral strike-slip Coffee Creek fault, is characterized primarily by disseminated arsenian pyrite, with gold liberated from solid solution through intense surface oxidation. The nearby Boulevard (ca. 96 Ma, ^{40}Ar/^{39}Ar) gold prospect is a series of quartz-carbonate-sulphide veins with gold occurring both as free gold and trapped in solid solution in arsenian pyrite. Boulevard is spatially and temporally associated with Toni Tiger (ca. 95 Ma, ^{187}Re/^{187}Os molybednite), a quartz-molybdenite vein system which also shares carbon dioxide rich, low salinity fluid inclusions. Boulevard and Toni Tiger have previously been classified as orogenic veins, however the presence of molybdenite may alternatively be explained by a magmatic input. Sugar, a gold prospect 20 km east of the Coffee gold deposit, shares similarities in veining style, ore and gangue mineralogy, structure, and paleo-fluid composition with Boulevard. Petrographic and field observations show that both Boulevard and Sugar veins may have a strong component of shear. The systems above have similar Au-As-Sb element associations, paleo-fluid composition, as well as ore and gangue mineralogy to the Moosehorn (Longline) deposit (92-93 Ma ^{40}Ar/^{39}Ar), a past orogenic gold producer located at the NW end of the Dawson Range (Fig. 1).

Mineralized structures at Coffee, Sugar, Boulevard, and Moosehorn are all formed in a structural setting dominated by dextral shear within, and along the northern margin of, the Dawson Range batholith. The gold systems of the Dawson Range all formed from low-salinity CO_2 bearing fluids (Figure 2), however this fluid composition is not diagnostic of a particular deposit model. These systems provide a valuable opportunity to understand the mid-Cretaceous tectonic and metallogenic history of the Dawson Range.

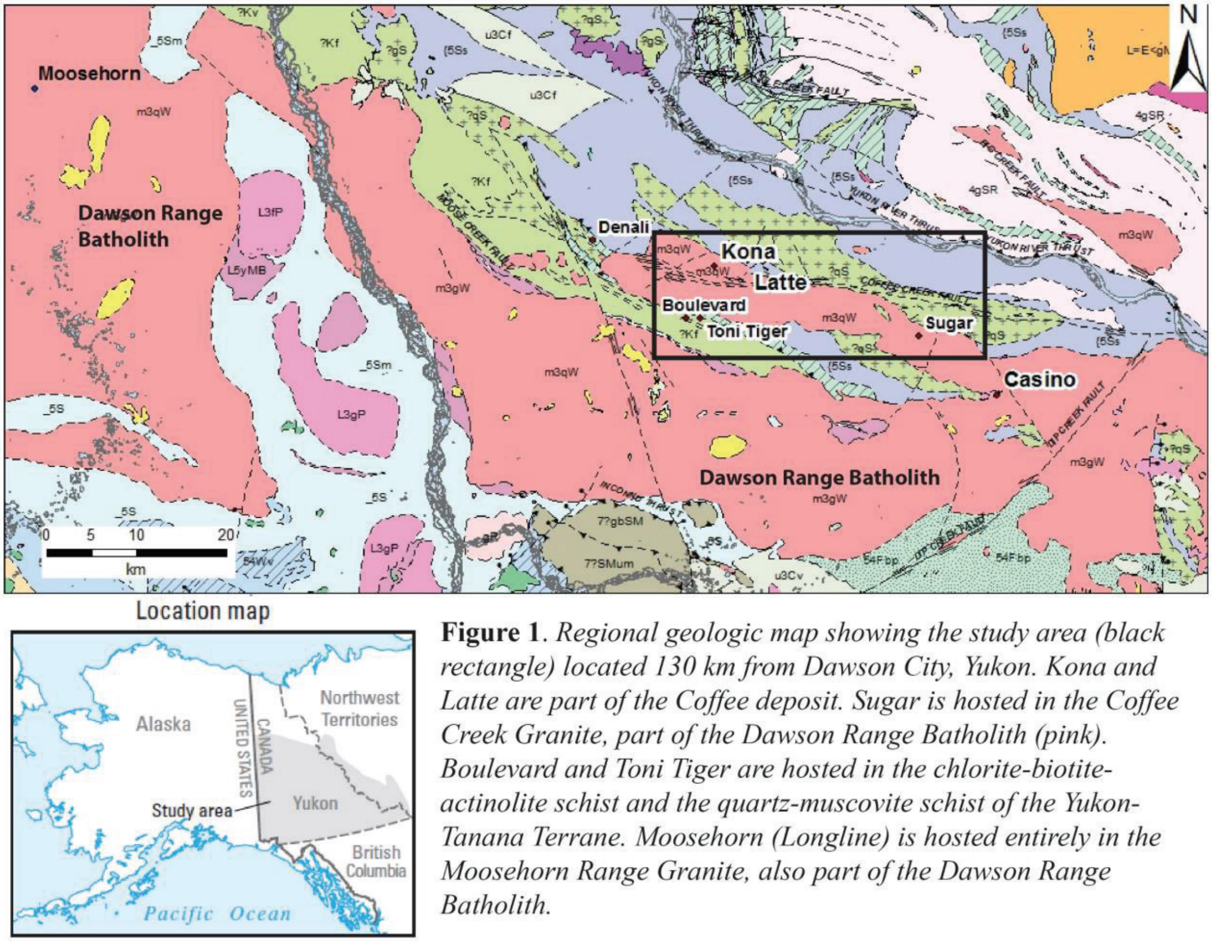
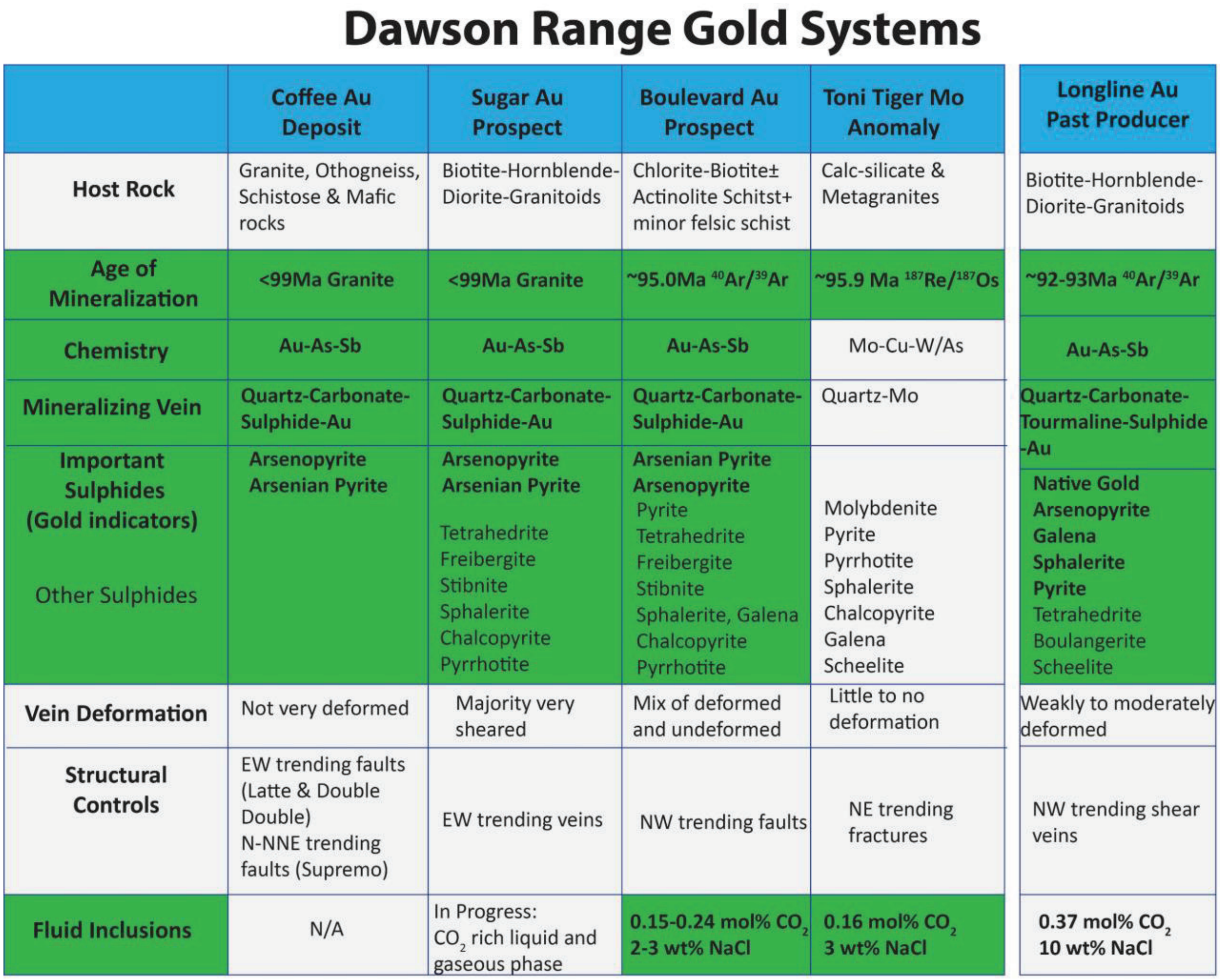


Figure 1. *Regional geologic map showing the study area (black rectangle) located 130 km from Dawson City, Yukon. Kona and Latte are part of the Coffee deposit. Sugar is hosted in the Coffee Creek Granite, part of the Dawson Range Batholith (pink). Boulevard and Toni Tiger are hosted in the chlorite-biotite-actinolite schist and the quartz-muscovite schist of the Yukon-Tanana Terrane. Moosehorn (Longline) is hosted entirely in the Moosehorn Range Granite, also part of the Dawson Range Batholith.*



Dawson Range Gold Systems

	Coffee Au Deposit	Sugar Au Prospect	Boulevard Au Prospect	Toni Tiger Mo Anomaly	Longline Au Past Producer
Host Rock	Granite, Othogneiss, Schistose & Mafic rocks	Biotite-Hornblende-Diorite-Granitoids	Chlorite-Biotite± Actinolite Schist+ minor felsic schist	Calc-silicate & Metagranites	Biotite-Hornblende-Diorite-Granitoids
Age of Mineralization	**<99Ma Granite**	**<99Ma Granite**	**~95.0Ma ^{40}Ar/^{39}Ar**	**~95.9 Ma ^{187}Re/^{187}Os**	**~92-93Ma ^{40}Ar/^{39}Ar**
Chemistry	**Au-As-Sb**	**Au-As-Sb**	**Au-As-Sb**	Mo-Cu-W/As	**Au-As-Sb**
Mineralizing Vein	**Quartz-Carbonate-Sulphide-Au**	**Quartz-Carbonate-Sulphide-Au**	**Quartz-Carbonate-Sulphide-Au**	Quartz-Mo	**Quartz-Carbonate-Tourmaline-Sulphide-Au**
Important Sulphides (Gold indicators) Other Sulphides	**Arsenopyrite** **Arsenian Pyrite**	**Arsenopyrite** **Arsenian Pyrite** Tetrahedrite Freibergite Stibnite Sphalerite Chalcopyrite Pyrrhotite	**Arsenian Pyrite** **Arsenopyrite** Pyrite Tetrahedrite Freibergite Stibnite Sphalerite, Galena Chalcopyrite Pyrrhotite	Molybdenite Pyrite Pyrrhotite Sphalerite Chalcopyrite Galena Scheelite	**Native Gold** **Arsenopyrite** **Galena** **Sphalerite** **Pyrite** Tetrahedrite Boulangerite Scheelite
Vein Deformation	Not very deformed	Majority very sheared	Mix of deformed and undeformed	Little to no deformation	Weakly to moderately deformed
Structural Controls	EW trending faults (Latte & Double Double) N-NNE trending faults (Supremo)	EW trending veins	NW trending faults	NE trending fractures	NW trending shear veins
Fluid Inclusions	N/A	In Progress: CO_2 rich liquid and gaseous phase	**0.15-0.24 mol% CO_2** **2-3 wt% NaCl**	**0.16 mol% CO_2** **3 wt% NaCl**	**0.37 mol% CO_2** **10 wt% NaCl**

Figure 2. *A summary table comparing gold-bearing vein systems in the Dawson Range. Boxes in green display characteristics two or more of these systems share in common. Characteristics in these boxes could potentially be used to locate gold systems in the Dawson Range.*

Structural Framework and Magmatic Constraints on Mineralized Porphyry Systems in the Western Skeena Arch

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The Skeena Arch in central British Columbia is a north-easterly (arc-transverse) paleotopographic high that extends across the width of the Stikine terrane. It hosts porphyry and related mineralization, which is predominantly interpreted to be genetically associated with Late Cretaceous and Eocene intrusive suites. To better understand the distribution of porphyry and related mineralization in the Skeena Arch, as well as its tectonic significance, the structural framework of the western Skeena Arch and magmatic events within it, were investigated through aeromagnetic interpretation, targeted mapping, geochronology and geochemistry.

East-northeasterly structures underlying the Skeena Arch have a protracted deformation history. An early phase of deformation with a north-easterly-trending foliation is locally crosscut by Late Triassic intrusions. Early Cretaceous Skeena Group sediments are affected by northeast-trending folds. The structural anisotropy underpinning the northeast-trending Skeena Arch helped to localize the emplacement of Late Triassic to Eocene intrusive suites. At a regional scale, the Kleanza and Topley (latest Triassic to Early Cretaceous), Bulkley, Babine and Nanika suites are broadly coincident with the Skeena arch (Figure 1). At a smaller scale, individual intrusions and trends of intrusions exhibit a strong north-easterly preferred orientation.

New zircon geochronology and lithogeochemistry confirms the presence of distinct Late Triassic, Early Jurassic, Late Cretaceous and Eocene intrusive suites in the western Skeena Arch. Geochemical characteristics suggest fractionation under high water content conditions that support the previously identified high porphyry prospectivity of Late Cretaceous and Eocene intrusions. Identification of intermediate sulfidation epithermal mineralization, apparently associated with Early Jurassic magmatism, suggests that prospectivity may not be limited to the Late Cretaceous and younger intrusions.

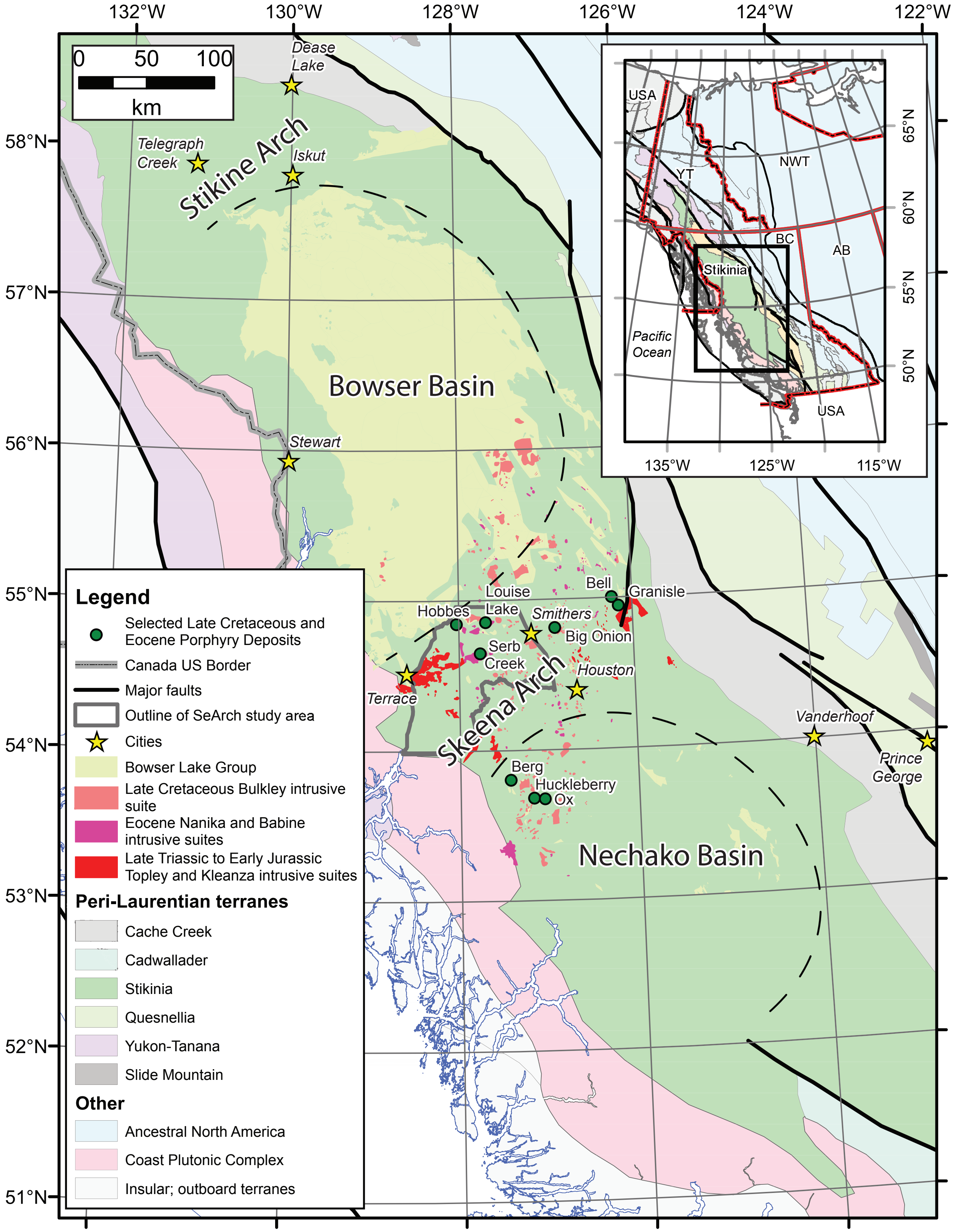

Figure 1. Location of the Skeena Arch and associated intrusive suites in the context of the terranes of the North American Cordillera.

Early Tertiary tectonic and magmatic evolution of southwest Yukon

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The early Tertiary (Paleocene – Eocene) was a time of complex interactions between large-scale tectonic and magmatic events throughout the Northern Cordillera. A voluminous amount of igneous material was intruded along a northwest axis from southern British Columbia into southwest Yukon, during a period of dextral transpression that was closely followed by dextral transtension and exhumation of lower and middle crustal rocks.

In Yukon, the continuation of the early Tertiary magmatic rocks is represented by the spatially large Ruby Range suite that includes the Ruby Range and Annie Ned batholiths. The suite is composed of a variety of granitoid compositions including quartz diorite, granodiorite, tonalite, granite and minor diorite and gabbroic phases. Ages range from ca. 64 Ma to 54 Ma for the main intrusive bodies. Some smaller plutons and dikes are as young as ca. 51 Ma. The character of the suite changes through time, with older phases generally located near the base of the intrusion where they are often weakly to strongly foliated. Progressively younger phases intrude the older phases and show evidence for shallower depth of intrusion such as miarolitic cavities and porphyritic phases. At the highest crustal levels the plutonic rocks intrude into their own volcanic cover where andesite, rhyolite and rare basalt are preserved in the Rhyolite Creek volcanoplutonic complex.

The suite intrudes along the tectonic boundary between Proterozoic to Paleozoic metamorphic rocks of the Yukon-Tanana terrane and Jurassic (?) to Cretaceous metasedimentary rocks of the Kluane schist and the Blanchard River assemblage. This tectonic boundary is nowhere exposed but is assumed to be a northeast-dipping thrust contact. The strongly foliated nature of the oldest and structurally lowest part of the Ruby Range suite suggests this thrust contact may have been active into the earliest Paleocene (~64 Ma). Younger phases of the suite cross-cut the foliation and are predominantly found within the Yukon-Tanana terrane in the hangingwall.

A period of exhumation after ~64 Ma is suggested by the observation that younger magmatic bodies that were emplaced at shallow crustal levels intrude older, deformed parts of the batholith that were emplaced at deeper levels. This is corroborated by ca. 55-53 Ma biotite cooling ages from metamorphic rocks in the Kluane schist. The exhumation mechanism is not well established but may be related to an extensional reactivation of the initial thrust contact between the Yukon-Tanana terrane and the Kluane schist, or to a series of poorly characterized faults that may be kinematically linked to regionally significant dextral transcurrent faults such as the Denali fault.

Paleocene magmatic and structural evolution is important for regional metallogenic considerations. Several intrusion-related mineral occurrences and deposits are directly associated with the Ruby Range suite. These include the structurally controlled Mt. Skukum epithermal gold deposit in southern Yukon and several porphyry and epithermal showings east of Kluane Lake. Vein-hosted gold occurrences within the Kluane schist show some similarity with orogenic gold deposits found near Juneau, Alaska, including their age (ca. 57 Ma) and tectonic setting.

New insights into the Mesozoic to Paleocene tectono-metamorphic evolution of the Kluhini and Takhanne River map areas of southwestern Yukon

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The tectono-metamorphic evolution of southwestern Yukon records a complicated history related to the Mesozoic-Paleocene reorganization of the western edge of the northern Cordillera. However, a detailed understanding of the geologic evolution of this region has yet to be resolved. This study focuses on the recently recognized Blanchard River assemblage located south of Haines Junction, Yukon. This assemblage is thought to belong to a series of Jura-Cretaceous basinal and arc assemblages deposited between the Yukon-Tanana terrane of the Intermontane terranes and Wrangellia and the Alexander terrane of the Insular terranes. Along with the Blanchard River assemblage, these assemblages include: the Jurassic to Cretaceous Dezadeash Formation, the Late Triassic to Middle Jurassic Bear Creek assemblage and the Cretaceous Kluane schist. Detrital zircon analyses from the Blanchard River assemblage suggests that it was sourced from exhumed Yukon-Tanana terrane and plutons found therein. The youngest detrital ages indicate an Early Cretaceous upper age limit for the assemblage.

Detailed mapping has demonstrated that the Blanchard River assemblage structurally underlies Proterozoic to Devonian meta-siliciclastic rocks of the Yukon-Tanana terrane, a contact that is somewhat obscured by the intrusion of the Paleocene Ruby Range suite. Near the contact between the Blanchard River assemblage and the overlying Yukon Tanana terrane, rocks in both packages preserve amphibolite facies metamorphic assemblages that include kyanite, garnet, staurolite, muscovite and biotite. Away from the contact, within the southern Blanchard River assemblage immediately north of the BC border, it appears that contact metamorphism related to Paleocene plutonism overprints the earlier high-grade metamorphic event. The overprinting of amphibolite-facies metamorphism by low-pressure minerals such as andalusite, spinel, cordierite and sillimanite puts an upper age constraint on an older, more complicated metamorphic and structural history that may be related to structural stacking observed to the north. It is suspected that contractional structures affecting assemblages in the study area were developed during the Late-Cretaceous, marking the closure of the Jura-Cretaceous basinal arc assemblage between the Intermontane and Insular terranes. The contact metamorphism that has overprinted the regional Barrovian amphibolite facies metamorphism is interpreted to be related to the Paleocene (ca. 64-57 Ma) intrusion of the Ruby Range suite.

At least two phases of deformation and metamorphism can be identified in the area that characterize the complicated geologic evolution of this region. Structurally, foliation within the Blanchard River assemblage exhibits a primary northwest strike with moderate dip to the northeast, parallel to that found within the Yukon-Tanana terrane. Although the Blanchard River assemblage reached amphibolite facies metamorphic conditions, it is possible to see primary sedimentary features (S_0) that have been isoclinally folded (F_1) and then refolded (F_2). Unlike the Yukon-Tanana terrane in the region, it does not appear that the Blanchard River assemblage has been completely transposed. This indicates an additional, more penetrative tectonic history preserved within the Yukon-Tanana terrane rocks that is at least Latest Triassic to Earliest Jurassic in age. Timing constraints for the tectonic evolution of this region are based primarily on relative geologic relationships such as cross-cutting plutons. To provide a more complete understanding of the tectono-metamorphic history of this part of the northern Cordillera, the determination of precise ages of the metamorphic and deformation events preserved in this region is underway using *in-situ* U-Th-Pb dating of monazite and zircon using split stream LA-ICPMS of which the preliminary results will be discussed.

Glaciovolcanism in the Northern Cascade Volcanic Arc: Terrestrial Paleo-environment Reconstruction.

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Glaciovolcanism encompasses the interaction of volcanism and ice in all of its forms. Glaciovolcanoes are increasingly recognised as agents and recorders of global climate variability. By preserving unique edifice morphologies and a distinctive set of lithofacies, these volcanoes have the unique ability to inform on: i) the spatial-temporal distribution(s) and thicknesses of paleo-ice sheets, ii) terrestrial (i.e. non-marine) paleo-environments and paleo-climates, and iii) processes (re-) shaping planetary surfaces. The Garibaldi Volcanic Belt (GVB) of southwest British Columbia (SW BC) is host to over 70 individual Quaternary glaciovolcanic edifices that range widely in composition from calc-alkaline basalt, andesite and dacite to alkaline basalt. The area also features a complex history of advancing and retreating cordilleran ice sheets, and thus offers an exceptional natural laboratory in which to characterise and explore a diverse array of glaciovolcanic interactions.

Here, we present and array of detailed volcanological maps (1:10,000) that document and characterise a selection of glaciovolcanic interactions within the GVB. We demonstrate forensic volcanological field techniques that, combined with petrological and geochemical modelling, allow us to decipher the paleo-presence of ice and the elevation (thickness) of the paleo-ice sheet(s). We use these data in conjunction with new and existing Ar^{40}/Ar^{39} and K/Ar radiometric dating to build a 4-dimentional database (x, y, z & time) of Quaternary glaciovolcanic and non-glaciovolcanic deposits throughout SW BC. We then compare this database to the existing O^{18} Marine Isotopic Stage (MIS) record and establish a number of correlations and discrepancies. We highlight the unique ability of glaciovolcanoes to: i) expand and develop the MIS-based paleo-climate reconstruction model, ii) shed light on global paleo-ice distributions, and iii) build a detailed picture of SW BC's glacial episodes that stretches well beyond the last glaciation.

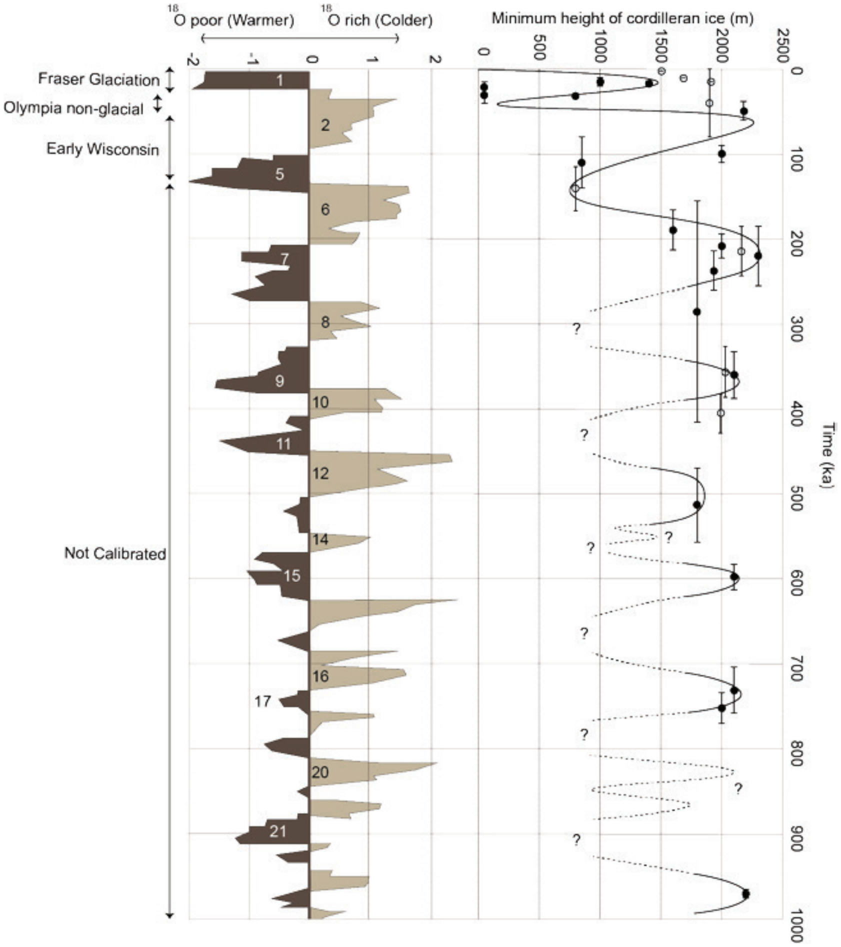

Figure 1: O^{18} isotopic record displaying the MIS stages for last 1.5 Ma. MIS data are used as a proxy for global sea temperature, thus representing the waxing (colder) and waning (warmer) of continental ice sheets. Known ages for glaciovolcanic (black dots) and non-glaciovolcanic edifices (grey dots) from the GVB are show. The model line (black) represents an independent paleo-environment reconstruction, recording the minimum height of cordilleran ice based on dated and mapped glaciovolcanic edifices alone.

Mid-Paleozoic magmatism and timing of VMS mineralization in the Pelly Mountains, Yukon: Implications for Cordilleran tectonics and metallogeny

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Felsic volcanic and volcaniclastic rocks of the Devonian-Mississippian Seagull group (informal) are recognized hosts to polymetallic (Zn-Pb-Cu-Ag) volcanogenic massive sulphide (VMS) mineralization in the Cassiar terrane, south-central Yukon. Despite abundant evidence for mid-Paleozoic magmatism and hydrothermal activity along the Cordilleran margin of western Canada, many fundamental questions remain about the precise age of the Seagull group and its genetic relationship with rift-related units of the Yukon-Tanana terrane, Slide Mountain terrane, and ancestral North America. To investigate these questions, we initiated a project to constrain the timing and tectonic setting of Seagull group magmatism in the central Pelly Mountains.

At one locality near the headwaters of the McConnell River, Upper Devonian(?) black to tuffaceous shale and lithic sandstone units at the base of the Seagull group conformably grade upwards into Lower Mississippian(?) lapilli tuff and rhyolite flows. Volcanic rocks at this and other localities yield both non-arc and arc-like trace element signatures that together are consistent with high-temperature felsic magmatism in a continental rift setting. Rhyolite lavas at the Wolf VMS deposit in the Finlayson Lake map area (Yukon MINFILE 105F127) are geochemically similar to other non-arc felsic rocks in the Pelly Mountains, including those with Nd-Hf isotope signatures that indicate the sampling of old crustal material during regional magmatism. Notably, this non-arc geochemical fingerprint is also recognized within gossanous, Tournaisian felsic volcaniclastic rocks in the Quiet Lake map area that we recently analyzed by chemical abrasion (CA-TIMS) zircon U-Pb geochronology.

The available geochemical evidence is consistent with the idea that some VMS-associated Mississippian rhyolites in the Canadian Cordillera are the result of crustal melting processes. Our working hypothesis is that Upper Devonian strata of the Seagull group likely comprised part of a turbidite basin that developed during regional extension and initial felsic volcanism, whereas Lower Mississippian strata were deposited in a metalliferous volcanic rift basin that was located behind the Yukon-Tanana continental arc-rift system, along what would become the passive margin side of the Slide Mountain Ocean.

Implications of a sharp craton edge: Conditions for extrusion of the cratonic lithosphere

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Mobile belts surrounding cratons are thought to have shielded them from erosion contributing to their longevity (Lendardic et al., 2000), but can lithospheric instabilities within the mobile belt induce cratonic deformation?

In the southern Canadian Cordillera, a profound east-west transition from cold, thick lithosphere beneath the North American craton to hot, thin lithosphere in the Cordilleran backarc environment is inferred to be roughly coincident with the physiographically defined Rocky Mountain trench. This step-like boundary also juxtaposes domains of contrasting rheologic strength, heatflow and buoyancy. Geodynamic models of this transition have shown vigorous edge driven convection can erode the craton boundary (Hardebol et al., 2012). However, recent work has shown that in some cases this lateral boundary can result in the flow of the cratonic mantle lithosphere towards the mobile belt (Currie and van Wijk, 2016). Sesimic tomography seems to support this and shows cratonic mantle lithosphere dipping toward the mobile belt (Schaeffer and Lebedev, 2014) (figure 1).

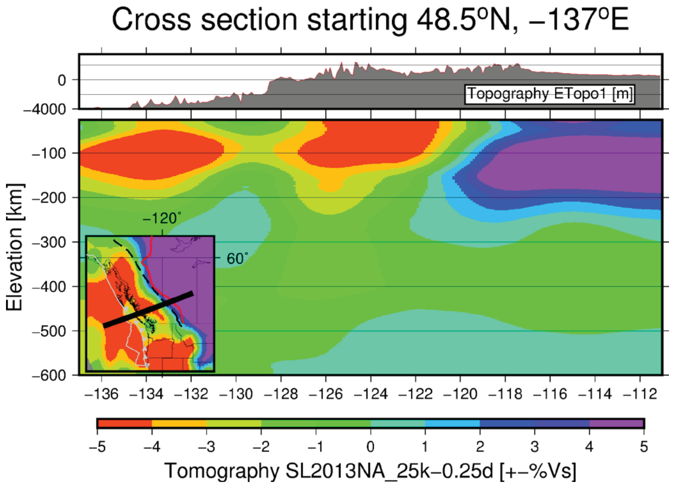

Figure 1: Cross section through tomography model (Schaeffer and Lebedev, 2014) showing dipping craton (right fast velocity perturbation) towards the mobile belt. Inset is a depth section at 100 km showing the dramatic velocity change from east to west

There is strong evidence that autochthonous mantle lithosphere beneath the former Proterozoic passive margin underwent some form of convective removal to create the present-day Cordilleran backarc (mobile belt). This has been geodynamically modeled and tied to heatflow and uplift observations (Currie et al., 2008, Hardebol et al., 2012, Bao et al., 2014). Any proposed mechanism for mantle lithosphere thinning would reduce the integrated strength of the mobile belt mantle lithosphere and change its resistance to lateral flow. Here we build on the concept of lateral density contrasts driving flow (Faccenna et al., 1999, Goren et al., 2008, Mart et al., 2005, Nikolaeva et al., 2011, England and McKenzie, 1982) and use visco-plastic thermo-mechanical numerical models to evaluate the implications of the removal of the mobile belt mantle lithosphere on the cratonic keel. We find that when the cratonic keel is buoyant, instabilities in the adjacent lithosphere allow the craton to advance (figure: 2).

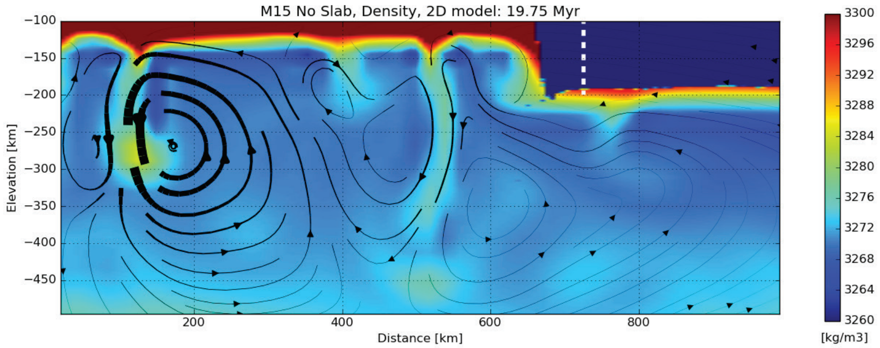

Figure 2: Snapshot from a thermo-mechanical model showing the development of instabilities within the mantle lithosphere beneath the mobile belt and the subsequent advance of the craton mantle lithosphere. White dashed line delimits the initial eastern extent of the craton lithosphere.

Cratons are thick (200km) and cold but they are also chemically depleted (Jordan, 1978) which may leave them buoyant (Sleep, 2005, Kelly et al., 2003) relative to the surrounding mantle. Xenolith and residual gravity studies suggest that cratonic mantle lithosphere may be 50-80 kg/m^3 or 1.5 - 2.5% less dense than asthenosphere at the same temperature (Djomani et al., 2001). In southwestern Canada, proterozoic arc and orogenic terranes and highly depleted Archean terranes lie to the east of the mobile belt. Compositional density anomalies for the mantle lithosphere adjacent to the mobile belt in southwestern Canada are modeled to be -20 kg/m^3 (Kaban et al., 2015). Thermo-mechanical models using typical (temperature and strain-rate dependent viscosity) show this density deficit may be sufficient to produce lateral extrusion of the cratonic mantle lithosphere following a lithospheric instability.

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Cretaceous exhumation of the Yukon Tanana Terrane, northern Canadian Cordillera: insights from low-temperature (U-Th)/He thermochronology

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Despite the relatively high elevation of the northern Canadian Cordillera, the lithosphere is about 150 km thinner than the adjacent craton, reflecting the contrast in thermal regime and crustal exhumation history between the craton and mountainous Cordilleran region. The models commonly used to explain the present-day lithospheric structure of the cordillera are down-welling and delamination of the lower lithosphere. To better resolve the model for the northern Canadian Cordillera, the exhumation history and thermal structure within the Yukon Tanana Terrane will be elucidated, from which lithospheric strength profiles may be evaluated. The first phase of this study is determining the timing and rate of exhumation of different crustal blocks within this area of the cordillera using low-temperature (U-Th)/He thermochronology. Five crustal blocks spanning between 50 and 150 km wide have been defined using magnetic anomaly data and previously published structural and geochronological data. Numerical modeling of the zircon and apatite thermochronology data indicates rapid cooling (~10°C/m.y.) during the middle to late Cretaceous for the crustal block south of the Yukon River Thrust Fault and east of Yukon River, reaching surface temperatures at c. 70 Ma. To the northwest, the adjacent Permian tectono-metamorphic domain exhumed rapidly to mid-crustal depths by the early Cretaceous, followed by a 70 m.y. period of monotonic (~1°C/m.y.) cooling. The models require the Permian domain to quickly reach surface conditions between c. 80 and 90 Ma, preceding the exhumation to shallow depths of the mid-Cretaceous metamorphic core complex in western Yukon. In this portion of the cordillera, most of the tectonic activity in the shallow crust abates by the late Cretaceous. These results mark an older exhumation history compared to the Alaskan and southern Canadian Cordillera, which define a dominant Eocene signature. Understanding the different processes governing orogenic plateau formation in the northern and southern Canadian Cordillera is significant for understanding the evolution of craton margins.

Current deformation of the Olympic Orocline: a model for crustal fault activity in the Cascadia forearc.

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Paleomagnetic vectors from Eocene-age rocks of the Crescent-Siletz Terrane – a geological unit within the Cascadia forearc – are consistently parallel to the curving strike of the unit on the Olympic Peninsula and southern Vancouver Island. The paleomagnetic data imply that the terrane was previously straight, and subsequently bent around a vertical axis to form an orocline. This suggests that at least some deformation in the Cascadia forearc is inelastic, and may be accommodated permanently on crustal faults, rather than being entirely restored during the next megathrust earthquake. Paleoseismic investigations have shown that many faults in the forearc (e.g., Seattle, Southern Whidbey Island, Darrington-Devil's Mountain, and Leech River Faults) are indeed active and pose a significant hazard to the region. However, the faults are arranged in a complex network with variable slip senses, and the patterns of deformation are not well understood. In this study, we compare contemporary rotation rates derived from geodetic networks to those inferred from paleomagnetic vectors, and find a close spatial correlation between the two, with an axis of rotation centred on the Olympic Peninsula. We suggest that the "Olympic Orocline" is bending in real-time, and that movement on crustal faults in the region might be better understood when placed in this conceptual framework. The paleomagnetic data indicate rotation rates of approximately 0.5°/Myr on each limb of the orocline, while the GPS rates are slightly higher. This disparity could be due to the fact that the GPS stations also record elastic deformation in the forearc. At 48°N, the continental margin deflects 45° to the northwest, and the obliquity of relative movement between the Juan De Fuca and North American Plates is reversed; the result is margin-parallel convergence of the forearc at the Olympic Peninsula, thereby driving active deformation of the orocline. Anomalously high exhumation rates are also observed in the Olympic Mountains, which supports the notion of convergence. We suggest that strike-slip motion on faults that follow the perimeter of the Olympic Orocline (e.g., Leech River Fault, Darrington-Devil's Mountain Fault) is due to flexural slip between crustal blocks, while reverse slip on faults that strike at high angles to the continental margin (e.g., Seattle Fault) is caused by north-south compression. The results of this study have broader implications for the assembly of the Canadian Cordillera, where it has been proposed that the exotic Cache Creek Terrane was enveloped by the Stikine and Quesnel Terranes via oroclinal bending. The Olympic Orocline may provide a modern analog of how this could occur at a continental margin.

Field Relationships and Structure of Silver-rich Veins, Cariboo Gold District, British Columbia

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The Cariboo Gold District (CGD) in east-central British Columbia is a hotbed for gold exploration and production. The Cariboo gold rush began in the late 1850s with the discovery of placer-gold in streams near Likely and the Wells-Barkerville area, and lode-gold was discovered not long after. To date, the CGD has yielded an estimated 118 - 134 tonnes of gold (Levson and Giles, 1993). Although structural controls appear to be similar throughout the CGD, not all mineralized veins are gold-bearing; a cluster of argentiferous quartz veins, located 23 km southeast of Barkerville Gold Mines' Cow Mountain deposit, are dominated by silver, copper, lead, zinc and tungsten minerals with little to no gold mineralization. Relatively fresh lamprophyre dikes, some containing xenoliths of quartz vein fragments, intrude close to and apparently cross-cut these veins. Silver Mine, Penny Creek, and Cariboo Hudson are examples of such occurrences. Silver Mine, a past-producer and the most prominent vein in this cluster, is the focal point of this study. Outcrop maps and field observations produced in the summer of 2016 are presented, as well as preliminary results from structural analysis.

Tracking detrital zircon lineages across time-tectonic elements of the allochthonous Yukon-Tanana terrane and parautochthonous North American basement, eastern Alaska and western Yukon

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There are several factors that impact the detrital zircon age signature of sedimentary rocks throughout the rock record. These include tectonic and sedimentary processes (e.g. local basement types and ages, accretionary terranes and terrane docking, transport of detritus, and recycling). Each of process imparts its own detrital zircon age distribution, herein referred to as a lineage, on the detrital zircon age spectrum of tectonostratigraphic assemblages. Here we leverage distinct craton, basin, and terrane specific lineages of the northern Cordillera to infer time-tectonic pathways of tectonostratigraphic units of the Yukon Tanana uplands in eastern Alaska-western Yukon.

The allochthonous Yukon-Tanana terrane (YTT) and parautochthonous North American basement (NAB) in eastern Alaska and western Yukon contain multiple Neoproterozoic through Paleozoic metasedimentary successions. Basement successions are largely Laurentia-derived and can be correlated across the Tintina fault to the Selwyn basin and cratonic sources farther into North America. However, detrital zircon (DZ) age spectra for metasedimentary rocks throughout the Yukon Tanana upland indicate multiple North American lineages, with regional implications for sediment transport pathways and recycling histories. For example, the Neoproterozoic-Cambrian Wickersham unit contains 2.8-2.5 Ga and 2.0-1.7 Ga detrital zircons. This likely reflects the craton-derived lineage of the northern Cordillera. The Fairbanks Schist is distinct from the Wickersham unit because it contains additional younger DZ age populations between 1.6-0.9 Ga. This population likely reflects incorporation of long-distance sedimentary transport ± recycling of zircons, which are not part of the regional craton DZ lineage. The Devono-Mississippian Chatanika assemblage contains DZ age peaks spanning 2.7-0.9 Ga, thus suggesting a mixture of the Wickersham and Fairbanks DZ lineages. The younger assemblages reflect the hybridization of distinct DZ lineages.

Systematic DZ age determinations in metasedimentary rocks throughout the Yukon-Tanana upland are essential to determine regional provenance patterns and to discriminate between allochthonous and parauthochthonous parts of the YTT tectonic collage; most litho-tectonic assemblages in the region contain similar lithologies, were multiply deformed and metamorphosed, and were intruded during protracted Mesozoic-early Cenozoic magmatism. In the central Tanacross quadrangle, schist and quartzite yielded only Precambrian DZ ages, with distinctive populations between 2.6-1.8 Ga. We interpret these rocks as part of the Wickersham unit regionally and, locally, as part of the Lake George assemblage of NAB. Other samples, which are structurally separated from the Lake George assemblage by shallow-dipping high-strain zones, have distinct 360-350 Ma DZ age populations in addition to secondary peaks at 2.8-2.5 Ga and 2.0-1.7 Ga. Because the presence of 360-350 Ma DZ age populations is a distinctive characteristic of rocks in Late Devonian-Early Mississippian assemblages of the allochthonous YTT, we interpret these rocks to belong to the same marginal basin to the Slide Mountain Ocean as the regionally extensive Fortymile River assemblage. The bimodal Precambrian DZ age distributions are similar to the Wickersham unit DZ signature found in the Lake George assemblage, suggesting that allochthonous and autochthonous assemblages share similar lineages because 1) both are derived from the same Laurentian sources and/or 2) autochthonous basement assemblages were recycled into younger allochthonous successions during rifting of the YTT from northwestern Laurentia.

Tracking of DZ lineages is a powerful tool in understanding the tectonic history of the YTT. The DZ signature in all the YTT metasedimentary units and its overlap assemblages contain the northern Cordillera cratonal lineage. Through time, the proportion of the craton signature varies. It decays due to recycling of DZ or is diluted by the addition of other DZ lineages. DZ signatures of the metasedimentary rocks of the YTT along the eastern Alaska-Yukon border have allowed us to differentiate lithologically similar units into allochthonous (Fortymile assemblage) and parautochthonous (Lake George assemblage) terranes, while also deducing that they shared a similar DZ lineage/basinal history prior to rifting.

Uniformly hot backarcs prior to orogenic collision as an explanation of regional high temperature metamorphism; there is no heat of orogeny

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The origin of the regional high temperature Barrovian metamorphism exposed in orogenic belts, up to ~800C, is an unresolved problem. What generates such high temperatures? (e.g., Jamieson et al., 1998). Orogenic crustal thickening should reduce vertical temperature gradients not increase them. Most collision models use a standard cool initial crust, ~450C at the base of the crust, as is estimated for stable continental areas. With this initial condition, two mechanisms have been proposed to produce sufficiently high metamorphic temperatures in orogenic belts; (1) the special condition of upper crust high radioactive heat generation being distributed downward within the deforming orogen, or (2) substantial viscous heating. Although possible, both mechanisms have serious difficulties. I summarize an alternative explanation, that most orogens involve a pre-collision subduction backarc that was uniformly hot. High temperature Barrovian conditions were already present on one side of the closing ocean. The former backarc makes up the main part of the subsequent orogeny because it is hot and deforms readily (**Figure 1**) in contrast to the opposite side of the closing ocean that generally is a cool rifted margin where the crust is strong. A compilation by Currie and Hyndman (2006) showed that continental backarcs, commonly at least several 100 km wide, are uniformly hot globally with the exception of infrequent flat slab subduction. It is important to recognize that recent crustal extension is not required for the backarc high temperatures. In backarcs, shallow small-scale asthenosphere convection is inferred below a 60-70 km thick lithosphere, in contrast to ~200 km for stable areas. In all 10 backarcs studied, the heat flows are high, ~75 mW/m2, there are low seismic velocities in the upper mantle characteristic of high temperatures, and volcanic xenoliths from the lower crust and upper mantle indicate high temperatures. Sporadic backarc basaltic volcanism is also

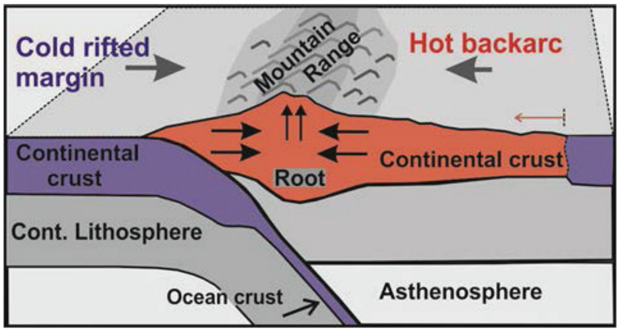

Figure 1. Collision of cold rifted margin and former hot backarc. Deformation is primarily in weak former backarc.

common. The estimated Moho temperatures in the backarcs are 800-900C. They also estimated a 300 m.y time constant for backarc cooling after subduction stops, so for example, the areas of the North America Cordillera where subduction has been cut off by the Queen Charlotte and San Andreas Fault zones are still hot. These high temperatures represent the thermal regime on one side of the closing ocean prior to collision. Crust with these high temperatures becomes incorporated in the subsequent orogenic belt. For the best studied current hot backarc, the North American Cordillera, I have carried out a new thermal review of the five principal constraints of deep temperatures. Regional temperatures at the Moho are surprisingly constant from Mexico to Alaska, 800-850C, compared to 400-450C for the adjacent craton, with temperatures in the lower 10 km crust of 700-850C, i.e., within the Barrovian P-T field (**Figure 2**). The high temperatures in the collisional former backarc also explain why deformation is concentrated on one side of orogens, for example, most deformation is in Tibet, the former hot backarc side of the India-Asia collision rather than in India. The former hot weak backarc includes the area to the east and west of Tibet into which the crust is now laterally extruding. At the time of deformation, similar high temperatures were likely present on one side of the Grenville, Appalachian, and most other orogens prior to deformation, providing an explanation for the observed Barrovian metamorphism, and for the bimodal distribution of metamorphism. I emphasize that understanding the origin of metamorphism in orogenic belts requires knowledge of the temperature distributions of the two converging continental margins before collision. Orogenic processes do not generate heat, orogeny simply exhumes already hot deep crust.

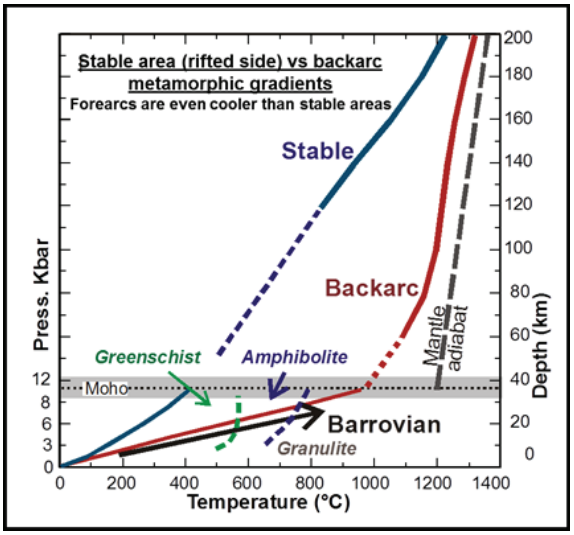

Figure 2. Comparison of Barrovian metamorphic temperatures and temperatures in most hot backarcs prior to collision.

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New U-Pb age constraints and lithogeochemical classification for Late Cretaceous volcanics in the TREK project area, central British Columbia

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Prospectivity in the Late Cretaceous Kasalka Group in the Interior Plateau has been spurred by the discovery and development of the ~10Moz Blackwater Au-Ag intermediate sulfidation epithermal deposit. However, this group of rocks is poorly documented and understood in this region due to limited outcrop exposure and subsequently limited availability of data. Recent regional bedrock mapping in the Nechako Plateau with Geoscience BC's TREK project has revisited and sampled previously mapped areas and in addition has helped identify new exposures of Late Cretaceous volcanic rocks. Major and trace element lithogeochemistry show that the Kasalka Group rocks are high-K calc-alkaline to alkaline trachyandesites to rhyolites, following a separate trend from Jurassic Hazelton subalkalic andesitic to basaltic andesite arc rocks. A slight to strongly peraluminous trend in some Kasalka Group rhyolite samples may also be a distinguishing feature when compared to Eocene Ootsa Lake Group rhyolites. Petrographic investigation has identified the presence of andalusite phenocrysts supporting this primary peraluminous geochemistry. New U-Pb zircon geochronology ages of 68- 82 Ma indicate a contrast between ~80 Ma volcanic rocks to the west at the Kasalka Group type section and 75-68 Ma volcanic rocks farther east near Blackwater.

New insights into the tectonic evolution and continental affinity of the Qilian Block: Evidence from zircon U–Pb and Lu–Hf isotopes for metasupracrustal rocks in the North Wulan terrane

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The Qilian Block is one of several Precambrian micro-continents among the Phanerozoic Qinling-Qilian-Kunlun orogenic systems in NW China. The North Wulan terrane, located in the southern Qilian, can provide important keys for understanding the origin of the Qilian Block. The metasupracrustal rocks in the North Wulan terrane is divisible into three sub-units with ages of early Mesoproterozoic, late Meso- to early Neoproterozoic and early Paleozoic, respectively. An investigation into the zircon U–Pb and Lu–Hf isotopic analyses for metasupracrustal rocks from the two Precambrian units is conducted to provide constraints on their age, provenance and tectonic setting and insights into the crustal evolution and tectonic affinity of the Qilian Block.

The early Mesoproterozoic unit is dominated by Al-rich rocks as well as felsic gneiss, arkosite, leptynite and minor calc-silicate rock, that are together interpreted as a record of development of a continental rift basin. Detrital zircons from this unit show two main populations of 1761–2098 Ma and 2276–2685 Ma with prominent age peaks at ~1.94 Ga, 2.32 Ga, 2.48 Ga and 2.57 Ga. These zircons exhibit predominantly negative εHf(t) values with some in the slightly positive field (–14.0 to 3.6). This unit is well constrained to have formed during ca. 1.67–1.52 Ga by the youngest age peak of detrital zircons and by ca. 1.52–1.50 Ga anorogenic intrusions. Because Archean to Paleoproterozoic source materials are absent in the Qilian Block, an exotic continental crustal domain is required as the probable sedimentary provenance. Considering the potential source areas around the Qilian Block, we suggest the Tarim Craton is most likely the provenance to supply detritus and that the Qilian Block was probably once a part of Tarim Craton before it rifted off at ca. 1.52–1.50 Ga during the breakup of Columbia. These early Mesoproterozoic metasedimentary rocks represent the oldest rocks that have ever been found in the Qilian Block. The late Meso- to early Neoproterozoic rocks mainly consist of felsic gneiss, quartzite, calc-silicate rock, marble and felsic metavolcanic rock, and are widely distributed in the Qilian Block. Three metasedimentary rocks from this unit have detrital zircons clustering from 899 to 1809 Ma with peak ages of 942 Ma, 1139–1161 Ma, 1255–1315 Ma, 1433 Ma and 1636 Ma. εHf(t) values for these rocks are mostly positive ranging from –7.1 to +9.7. One felsic metavolcanic rock yielded a syn-depositional age of ca. 1110 Ma with positive εHf(t) values ranging from +6.5 to +9.1. The depositional age of this unit is constrained to ~1.1–0.9 Ga. There is a shift of the provenance in the late Mesoproterozoic to Neoproterozoic as the Qilian Block began to be incorporated into the Rodinia supercontinent. We consider the source sediments to have been deposited within an active continental margin. The Qilian Block has affinities with other micro-continents in the Qinling-Qilian-Kunlun Orogens as well as surrounding Alxa Block, Altyn Block and Chinese Central Tianshan terrane.

Acknowledgement

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Constraining Rodinian rifting and magmatism from U-Th-Pb detrital zircon ages

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Samples of early Cambrian quartzites from the western margin of Laurentia have yielded zircons with U-Th-Pb ages from the Neoproterozoic through Cambrian (Figure 1a). These ages coincide with Rodinian rifting preceding the formation of the Laurentian passive margin. For each of 13 samples, a large number of grains (n≈660) were analyzed with short ablation periods to identify the youngest zircon grains. Grains of magmatic origin yielding U-Th-Pb ages less than 800Ma were re-ablated over longer periods to obtain higher-precision ages with the aim of improving constraints on the timing of rift magmatism.

Preliminary results show general trends of older magmatic events in the north (Alberta-British Columbia) and younger events in the south (Southern California-Arizona), suggesting a southward propagation of Rodinian rifting (Figure 1b). Northern samples are dominated by dispersed Cryogenian ages, which are likely sourced from Windermere Supergroup volcanics and central Idaho plutons and volcanics. Samples from the Canadian Rocky Mountains have smaller populations of latest Neoproterozoic to early Cambrian grains than samples from the Columbia Mountains to the west. These westerly samples are proximal to known synrift volcanics, such as Hamill Volcanics and Fish Lake Volcanics, which are proof of renewed magmatism north of the Idaho suite. The southern samples yield ages early Cambrian ages with a weighted average of 508±19 and lack significant Proterozoic populations with many samples completely devoid of Cryogenian ages. From these results, two periods of rift magmatism can be deduced: (1) volcanism throughout the Neoproterozoic along the Laurentian margin, (2) southward propagation of rifting with renewed magmatism in the north.

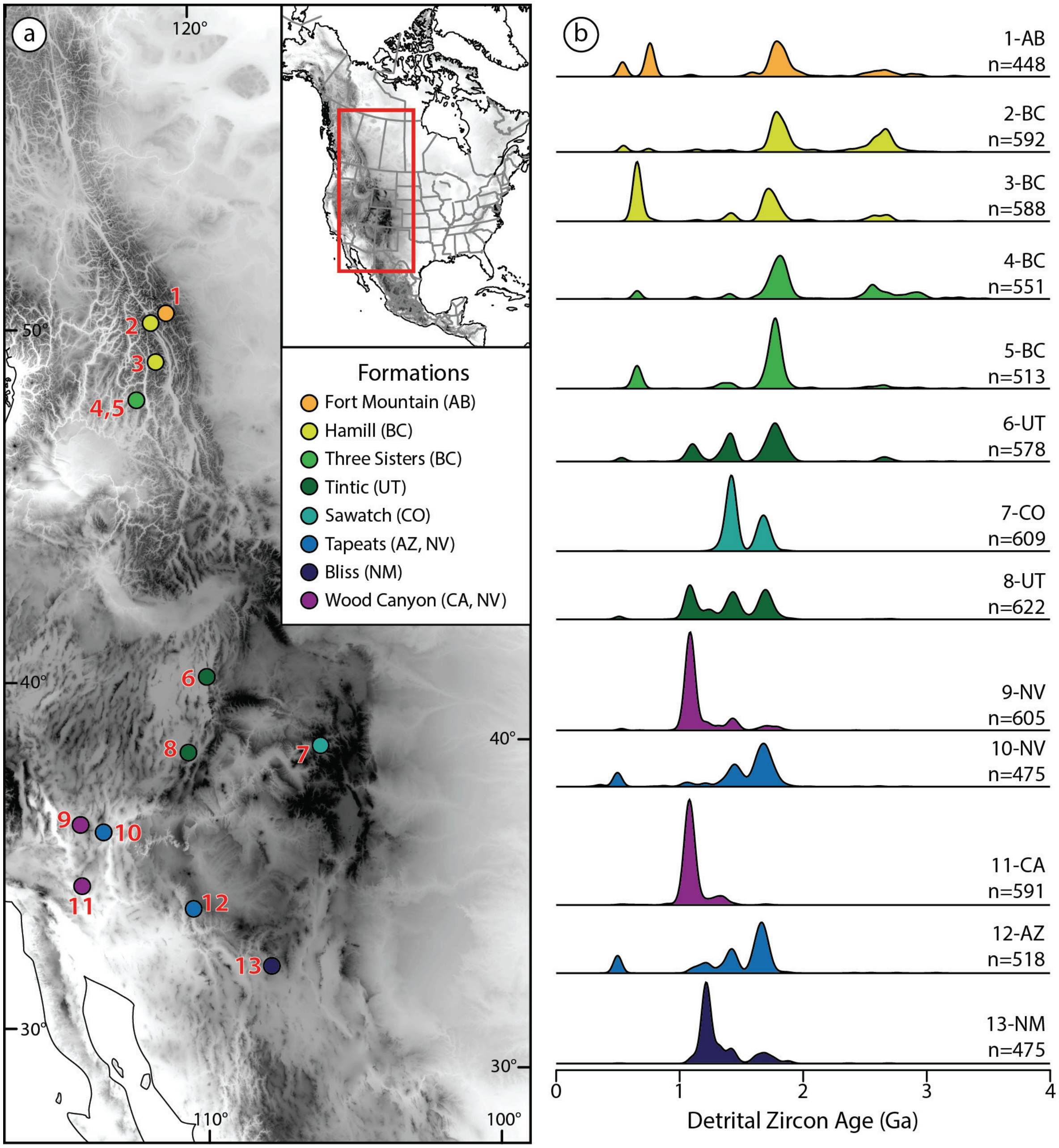

Figure 1. (a) Study area showing sample locations and formations with sample numbers in red. (b) Normalized kernel density plots from the screening round of ablations with number of concordant analyses listed for each sample (n).

Convergent Margin Ni-Cu-PGE: Giant Mascot Mine, Hope, British Columbia

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The Giant Mascot mine (1958-1974) is the only significant past-producer of nickel in British Columbia. The Giant Mascot deposit belongs to a class of convergent margin or supra-subduction zone Ni-Cu-PGE deposits that are becoming an increasingly important yet under-explored economic resource (Nixon et al., 2015; Manor et al., 2016). Orthomagmatic Ni mineralization in this environment is typically hosted by small ultramafic-mafic intrusions containing hornblende and orthopyroxene in ultramafic cumulates. The occurrence of orthopyroxene distinguishes these intrusions from those of Alaskan-type affinity in convergent margin settings.

The Giant Mascot mine yielded over 4 Mt of ore from 22 distinct orebodies with an average grade of 0.77 wt % Ni and 0.34 wt % Cu, with minor cobalt, silver, and gold, and unreported platinum-group elements (Manor, 2014). The sulphide ores are hosted by the Giant Mascot ultramafic intrusion situated at the southeastern margin of the Coast Plutonic Complex. The intrusion forms an elliptical plug (~4 km^2) and is crudely zoned from a core of dunite and peridotite (hornblende-bearing harzburgite and lherzolite) through pyroxenite (hornblende-bearing orthopyroxenite and websterite) to a discontinuous rim of pegmatitic hornblendite-hornblende gabbro. The intrusion is hosted by amphibolite-grade, metasedimentary rocks of the Upper Triassic Settler schist and Late Cretaceous Spuzzum pluton.

U-Pb zircon dating of pyroxenite and hornblendite by chemical abrasion-isotope dilution-thermal ionization mass spectrometry (CA-ID-TIMS) has yielded Late Cretaceous dates (ca. 93 Ma), interpreted as crystallization ages for the ultramafic suite, and slightly older but statistically distinct dates (ca. 95 Ma) for crystallization of the Spuzzum diorite (Manor, 2014). These dates are concordant with observed contact relationships. ^{40}Ar/^{39}Ar dating of a mylonite zone cutting hornblendite-hornblende gabbro at the rim of the ultramafic intrusion indicates loss of radiogenic argon starting shortly after solidification (ca. 91-86 Ma). These results confirm the age of mineralization, and they establish the Giant Mascot ores as the world's youngest known magmatic Ni-Cu-PGE sulphide deposit (Manor, 2014).

The sulphide ores exhibit unambiguous magmatic textures and are mainly hosted in dunite, peridotite and pyroxenite. The main locus of mineralization trends roughly east-west through Zofka Ridge. The multiple ore zones form small, discrete bodies with pipe-like, lensoid and tabular morphologies, and enclose massive, net-textured and disseminated sulphides, mainly pyrrhotite, pentlandite and chalcopyrite (Aho, 1956; Manor et al., 2015). The orebodies commonly exhibit sharp contacts and textural and mineralogical differences with their wallrocks, and locally contain inclusions of ultramafic and noritic rocks in a sulphide-rich matrix. The sulphide ores have high tenors (3-14 wt % Ni, 0.1-17.1 wt % Cu, and 84 ppb to 5 g/t total PGE; recalculated to 100% sulphide), and distinct Ir-group PGE in the Western vs Eastern mineralized zones. Platinum-group minerals are mostly bismuthotellurides, exsolved during cooling and fractionation of base-metal sulphides (Manor et al., 2014).

The geometry, internal features, and contact relationships of the ore-bearing structures are consistent with the features exhibited by magmatic conduits. Some orebodies are cored by barren pyroxenite, potentially indicating multiple injections; others have arcuate shapes that may have formed by wedging out of injected material in blind conduits, or partial collapse and infilling by partially consolidated wallrock cumulates. These narrow, dynamic conduits pose a significant challenge to exploration, yet the presence of PGE-enriched, high-tenor sulphides underscores the potential for economic Ni-Cu-PGE deposits in convergent margin environments.

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Metamorphism of metapelitic units from the Snowcap Assemblage of the Yukon-Tanana Terrane, Stewart River area, west central Yukon

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The Snowcap Assemblage forms the siliciclastic-dominated foundation of the Yukon-Tanana terrane (YTT) and is predominantly composed of metamorphosed sedimentary units. These sediments were deposited along the Laurentian margin and subsequently drifted away during the opening of the Slide Mountain Ocean. The YTT re-accreted onto Laurentia in the mid-Jurassic to Cretaceous. Previous metamorphic studies applying conventional thermobarometry and garnet isopleth thermobarometry techniques indicate that the YTT was exposed to episodic and diachronous metamorphism from Permian to mid-Cretaceous. The Stewart River area exposes aerially extensive amphibolite facies metapelites of the Snowcap Assemblage that are the target of this study. Garnet-bearing samples of pelitic composition were analyzed to obtain detailed metamorphic pressure-temperature-time (P-T-t) information through the integration of electron probe-microanalysis, X-ray micro-computed tomography, phase equilibria and garnet crystallization modelling.

The bulk chemistry of the rocks indicates that the protoliths were deposited in a passive margin setting as shales and wackes. Textural observations suggest at least three episodes of deformation during metamorphism, forming a relic foliation (S_{M-2}) and crenulation cleavage (S_{M-1}), which are only locally observed as silicate and ilmenite inclusions in garnet, and a dominant transposition mica foliation (S_M). Compositional zoning of garnet with respect to its Fe, Mg, Mn, Ca, and Y contents reflects chemical disequilibrium across the garnet volume and between garnet and the rock matrix and is interpreted to be the result of chemical fractionation associated with garnet growth. According to our calculations on a key sample, garnet started to crystallize at 510 ^{o}C and 3.75 kbar and finished growing at 675^{o}C and 7 kbar. These conditions correspond to the metamorphic peak P-T conditions experienced by the rocks. The chemical composition of the garnet cores indicates significant modification of the initial garnet chemistry by intracrystalline diffusion at $T \geq 600$ ^{o}C for at least 20 Ma.

Magmatic Ni-Cu-PGE sulphide deposits at convergent margins

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Most of the world's major magmatic Ni-Cu-PGE deposits are hosted by ultramafic-mafic intrusions and volcanic rocks in various rift-related settings. Traditionally, subduction-zone settings have been regarded as unfavourable environments for nickel exploration due to the relative paucity of economically exploitable deposits. Consequently, mineral deposit models for magmatic Ni-sulphide mineralization at convergent margins have emerged only recently (e.g., Ural-Alaskan NC-7, Naldrett, 2010). Today, magmatic Ni-Cu-PGE sulphide deposits at convergent margins are becoming an increasingly important economic resource worldwide, yet remain poorly understood and underexplored (Nixon et al., 2015; Manor et al., 2016).

A global compilation of selected Ni-Cu±PGE deposits and prospects at convergent margins highlights their diversity and economic potential (Nixon et al., 2015). All mineralized ultramafic-mafic intrusions reside in deformed and metamorphosed accreted arc terranes and range in age from Late Cretaceous (ca. 93 Ma, Giant Mascot, the world's youngest deposit; Manor, 2014) to Neoarchean (Gordon Lake and Quetico intrusions, ca. 2.7 Ga). The intrusions are typically small (<4 km^2) and form composite to simple dykes, plugs and sills. They exhibit well-developed (rare) to crudely concentric, bilateral or unilateral zoning of rock units exhibiting sharp to gradational contacts and centimetre-scale (rare) to hectometre-scale layering, or no discernible internal structure. At least four types of mineralized ultramafic-mafic intrusion may be distinguished: orthopyroxene-absent Alaskan-type; orthopyroxene-rich Giant Mascot-type; gabbroic-type; and orthopyroxene-plagioclase(noritic)-type. All intrusions contain magmatic amphibole±phlogopite-biotite. The sulphide ores (mainly pyrrhotite, pentlandite and chalcopyrite) exhibit disseminated, net-textured, semi-massive and massive magmatic textures. These mineralogical differences largely reflect parental magma composition and ore-forming processes.

Significant Ni metal resources are contained in deposits formed in convergent margin settings. These include the 1842 Mt Turnagain deposit in northern British Columbia, which ranks 9th among the world's magmatic Ni sulphide deposits, and Aguablanca in Spain, Europe's only nickel mine. Some of the largest Ni-Cu±PGE deposits being mined in China today are found in the accreted island arc terranes of the Central Asian Orogenic Belt. Examples include the Kalatongke mine with ores grading ~0.6-0.9 wt % Ni and 1.1-1.4 wt % Cu; the 135 Mt Huangshandong deposit with a grade of 0.30 wt % Ni and 0.16 wt % Cu; and neighbouring Huangshanxi ores at 80 Mt with an average grade of 0.54 wt % Ni and 0.30 wt % Cu. The total Ni metal resource for magmatic Ni-Cu sulphide deposits in the Huangshandong-Huangshanxi district alone approximates 1 Mt (Nixon et al., 2015 and references therein).

Our current investigations of Ni-Cu-PGE mineralization in the Turnagain Alaskan-type and Giant Mascot intrusions emphasize magmatic processes involved in the generation of their Ni-sulphide ores: 1) the importance of wallrock assimilation in promoting sulphide saturation and formation of an immiscible sulphide liquid; and 2) the ability of narrow conduit systems to channel influxes of new metal-laden magma, and serve as traps for the collection of upgraded Ni-Cu-PGE sulphides. Processes fundamental to the production of economic Ni-sulphide deposits in the oxidized and hydrous primitive magmas generated at subduction zones are similar to those that produce world-class magmatic nickel deposits in other tectonic settings.

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Geochronology of the Turnagain Alaskan-type intrusion, British Columbia: implications for Ni-Cu-PGE mineralization and regional tectonic setting

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The Early Jurassic Turnagain Alaskan-type intrusion belongs to a global class of ultramafic-mafic intrusions emplaced in supra-subduction zone environments that are gaining prominence as an exploration target for magmatic Ni-Cu-platinum group element (PGE) mineralization (Nixon et al., 2015; Manor et al., 2016). The Turnagain body is unusually enriched in Ni-Cu-PGE sulphides compared to typical Alaskan-type intrusions. Low-grade Ni-sulphide mineralization at Turnagain ranks among the top 10 largest deposits in the world in terms of contained Ni metal, constituting a total resource of 1842 Mt @ 0.21 wt % Ni and 0.013 wt % Co (Mudd and Jowitt, 2014). The main Ni mineralization is hosted by wehrlite and clinopyroxenite, and the principal sulphide minerals are pyrrhotite, pentlandite and chalcopyrite. Enrichment of platinum group elements in sulphide-bearing rocks reaches concentrations of ~400 ppb Pd and ~400 ppb Pt. The origin of the mineralization is directly related to contamination of parental arc magmas by crustal material. Critical contributions of sulphur and graphite from carbonaceous phyllite in the wallrocks led to the reduction of oxidized parental arc magmas and triggered sulphide saturation (Scheel, 2007).

Geochronology (U-Pb, ^{40}Ar/^{39}Ar) and field mapping of ultramafic-mafic rocks comprising the Turnagain intrusion establish a multi-stage history of emplacement. Four distinct intrusive phases are now recognized (from oldest to youngest): Phase 1, interlayered wehrlite and clinopyroxenite; Phase 2, mainly dunite and wehrlite with minor clinopyroxenite and hornblendite; Phase 3, mela-diorite and hornblendite; and Phase 4 clinopyroxenite, hornblendite and minor leuco-diorite. Phase 2 hosts the main Ni(-Co-PGE) resource and Phase 4 contains additional occurrences of Cu-PGE-enriched sulphides. U-Pb dating by chemical abrasion-isotope dilution-thermal ionization mass spectrometry (CA-ID-TIMS) yields the following ^{236}U/^{208}Pb dates (±2σ) that are interpreted as crystallization ages: Phase 2 hornblendite, 190.3±4.5 Ma (titanite); Phase 3 mela-diorite, 188.11±0.14 Ma (zircon); and Phase 4 clinopyroxenite and leuco-diorite, 185.63±0.19 and 185.33±0.13 Ma (both zircon), respectively. ^{40}Ar/^{39}Ar dating of Phase 2 wehrlite and hornblendite yields plateau dates of 188.6±1.2 Ma (2σ, phlogopite) and 187.4±1.5 Ma (hornblende), respectively, that represent cooling ages. Thus, the Turnagain intrusion was emplaced in discrete stages over a period of at least 3 million years (ca. 188-185 Ma). The geochronology results constrain the origin of enriched chalcophile elements in the youngest Phase 4 intrusive event. Evolution towards sulphide saturation in Cu(-PGE)-enriched Phase 4 succeeded early Ni-Co(-PGE) mineralization in Phase 2, and evidently reflects completely independent mineral systems.

Greenschist-grade graphitic strata that host the Turnagain intrusion were interpreted to be part of the displaced North American margin (Cassiar terrane) by Gabrielse (1998), and correlated with Ordovician to Devono-Mississippian metasedimentary rocks of the (undivided) Road River and Earn groups. This unit was considered to conformably overlie miogeoclinal rocks of the Cambro-Ordovician Kechika Formation and underlying Lower Cambrian Atan Group. Erdmer et al. (2005) concurred with these stratigraphic assignments and documented a conformable relationship between the graphitic strata and overlying metavolcanic rocks. They concluded that the entire succession represents a volcanic arc or back-arc assemblage built on the edge of the North American miogeocline, and is not part of an accreted terrane. Erdmer et al. (2005) reported a weighted mean ^{236}U/^{208}Pb date of 339.7 ±1.2 (2σ) Ma (Middle Mississippian) for multigrain fractions of air-abraded zircon from a felsic schist in the lower part of the metavolcanic unit. Multigrain fractions of air-abraded detrital zircons from a volcanic wacke in an enclave of the same unit at the northern margin of the Turnagain intrusion yield a large range of concordant and discordant ^{236}U/^{208}Pb dates (ca. 244 to 1652 Ma), reflecting Pb loss and Proterozoic inheritance (Scheel, 2007). One concordant fraction yields a ^{236}U/^{208}Pb date of 301.4±1.2 (2σ) Ma (uppermost Pennsylvanian close to the Carboniferous-Permian boundary) which is interpreted to be the maximum depositional age of the volcanic wacke.

A regional airborne electromagnetic (EM) survey conducted by Hard Creek Nickel Corporation clarifies some important aspects of the tectonic setting of the Turnagain intrusion. The graphitic strata hosting the Turnagain body show a marked EM response (conductivity) not shared by ultramafic or surrounding metavolcanic and metasedimentary rocks. Our mapping traverses east of the Turnagain intrusion demonstrate that this sharp, curvilinear EM boundary separates highly conductive graphitic rocks from poorly conductive metasedimentary strata of the Atan Group and Kechika Formation. The EM boundary truncates miogeoclinal stratigraphy as mapped by Gabrielse (1998), and passes through a 800m gap in outcrop documented by Erdmer et al. (2005) that separates Atan Group rocks from graphitic phyllite of the presumed Road River/Earn Group equivalents. From these observations, we infer that this EM boundary represents a steeply dipping, terrane-bounding fault with a reverse sense of motion, herein named the Turnagain fault. This structure delineates the Early Jurassic, easterly directed thrust emplacement of accreted Mississippian-Pennsylvanian (and younger?) sedimentary and volcanic arc assemblages, representing the basement of Quesnellia (Yukon-Tanana terrane), onto the Ancestral North American margin. The inferred sense of eastward tectonic transport on the Turnagain fault is consistent with that derived from kinematic indicators in phyllites in the footwall of a fault defining the northern and eastern margins of the Turnagain intrusion, and with steep to overturned eastward-verging folds in the meta-volcanic/sedimentary package examined by Erdmer et al. (2005). This conclusion can be tested further by detrital zircon geochronology.

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Upper Mantle and Lower Crustal Xenoliths from Southeast Yukon Territory: Preliminary Results

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Xenoliths of spinel-bearing lherzolite and granulite facies paragneiss were recovered from basaltic dykes that intrude Neoproterozoic-Palaeozoic metasedimentary rocks in the upper Hyland River region of southeast Yukon Territory. The dykes are typically 1-5 metres in diameter and commonly exhibit columnar jointing along their margins. The age of the dykes is poorly constrained, but they post-date Early Cretaceous regional metamorphism and deformation. Whole rock geochemical data indicates the dykes are nepheline-normative alkali basalts, and they plot within the basanite field on a TAS diagram. The xenoliths occur as discrete subrounded to subangular fragments up to 8 cm in maximum dimension. The lherzolite samples, which consist of equidimensional crystals of olivine, orthopyroxene, clinopyroxene, brown spinel, and Fe-Ni sulphide, exhibit smoothly curved grain boundaries. Orthopyroxene locally contains fine exsolution lamellae. Granulite facies paragneiss samples contain K-feldspar, quartz, graphite, and 1-8 mm rounded domains that consist of patchy, symplectic intergrowths of sillimanite and orthopyroxene. These domains are interpreted as pseudomorphs (after Grt?) and may record post-peak metamorphic decompression. Ongoing work seeks to more fully characterize both xenoliths and host rock through whole-rock XRF analyses, mineral chemistry by electron microprobe analysis, and thermodynamic modelling of the xenoliths. The aim is to provide an estimate of pressure and temperature conditions of the xenoliths which may help inform our understanding of the nature of the upper mantle and lower crust in this region of the northern Canadian Cordillera.

The Slide Mountain ophiolite: Preliminary observations from Dunite Peak, Big Salmon Range, south-central Yukon.

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Understanding of the formation of accretionary orogens requires investigations of the timing, kinematics and mechanisms of terrane accretion. In the NW Cordillera, the Slide Mountain oceanic terrane (SMT) formed between Phanerozoic island arcs and the North American continent (NAC) during Devonian-Permian times and subsequently recorded multiple deformation events during ocean closure and arc accretion. We present preliminary findings from fieldwork in the Dunite Peak area of the Big Salmon Range, south-central Yukon; an area in which klippen of mafic-ultramafic rocks belonging to SMT structurally overlie rocks that are interpreted as island arc basement of the Yukon Tanana terrane (YTT). The allochthon / parautochthon suture between YTT and the Cassiar terrane (CT) of the NAC has also been mapped in this region by previous workers. As such, this area provides an excellent opportunity to study the structural relationships between multiple terranes of the NW Cordillera. Initial findings from fieldwork and geochemical analyses are presented, and include a new geological map and lithostratigraphic framework for the area. Trace element compositions from mafic-ultramafic assemblages suggests that the Slide Mountain ophiolite formed in a suprasubduction setting. Highly depleted geochemical signatures measured from ultramafic rocks at Dunite Peak are indicative of lower crustal cumulates rather than mantle peridotites. Currently, multiple tectonic models may be used to explain the formation and subsequent obduction and deformation of the SMT in this region. We assess these models in light of our work and propose future lines of investigation that should be undertaken in order to ascertain their validity and applicability to the NW Cordilleran orogen.

Implications for the Big Sky orogeny from amphibolites from the Highland Mountains in southwestern Montana

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Hornblende – plagioclase – quartz ± garnet ± clinopyroxene ± sphene ± ilmenite ± biotite ± epidote ± sericite ± chlorite comprise amphibolites from the Highland Mountains that occur in 1-5 m, laterally continuous, concordant layers and are intercalated within more abundant biotite – sillimanite – garnet schist. The bulk composition of these rocks is dominated by hornblende, which typically makes up at least 40% of the mode, and quartzofeldspathic material that is present in variable amounts between 15- 45%. Where it is present, garnet does not exceed 15% of the rock mode. Geothermobarometry analyses are based on the mineral assemblages, Grt-Cpx-Pl-Qt and Grt-Opx-Pl-Qt and yield metamorphic temperatures and pressures that range from 600-750° C and 7-8 kbars. Garnet grains, which are locally rimmed and/or replaced by plagioclase, are, in many cases, chemically zoned, with a decrease in pyrope from core to rim. These characteristics document retrograde reactions that occurred within these rocks, implying a period of decompression. Bulk rock geochemistry from this suite indicates that amphibolites metamorphosed from a basaltic protolith, allowing for the application of basalt discrimination diagrams in this study. Trace element signatures suggests that these rocks record the evolution of a subalkaline, tholeiitic magma chamber within a back arc basin.

The metamorphic conditions of amphibolites derived from this study overlap with the P-T path interpreted by Klein (2010) from the suite of Bt – Sil – Grt schist in which the amphibolites occur. Furthermore, the results of geothermobarometry are analogous to those in the Tobacco Root Mountains as reported by Cheney and others (2004) for the same collisional event. The comparable metamorphic histories of these two mountain ranges constrain the metamorphism of the Big Sky orogeny to the upper amphibolite to lower granulite facies. The interpretation of these rocks having derived from a back arc basin brings into question the polarity of a subduction zone believed to have been involved in the collision that amalgamated the Wyoming province with other Archean cratons to the north. Contextualizing the origin and metamorphism of amphibolites builds on the understanding of both the geometry and P-T history of the 1.77 Ga Big Sky orogeny.

New geological mapping of Yukon-Tanana Terrane in the Klaza River area, west-central Yukon

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New bedrock geological mapping in 2016 in the Klaza River area (southeast corner of the Stevenson Ridge map sheet) improved on reconnaissance work completed in the 1970's, and extends new published mapping in the Mount Nansen – Nisling River area (carried out in 2015) immediately to the southeast. Mapping was greatly assisted in this area of variable quality of bedrock exposure by recently acquired 400 m line spacing aeromagnetic data. Many of the older, more deformed and metamorphosed rock units in the area correlate to established units within Yukon-Tanana terrane, dominated by Snowcap assemblage siliciclastic rocks composed mainly of quartzite, micaceous quartzite and psammitic quartz-muscovite-biotite (± garnet) schist. Igneous lithologies characteristic of Yukon-Tanana terrane are generally restricted to area's easternmost extent. Two major mid-Cretaceous granitic batholiths dominate the map pattern and are divided into the Dawson Range batholith (DRB) in the north, characterized by blocky hornblende-bearing granodiorite, and the Maloney Creek batholith (MCB) in the south, characterized by monzogranitic composition, light smoky quartz phenocrysts, and higher abundance of biotite.

We discriminate mid-Cretaceous to Tertiary volcanic and hypabyssal rock sequences in the area in order to better understand their map distribution, and potential for mineralization (e.g., the Late Cretaceous Casino Suite). This task is complicated by similarities in appearance and character amongst these units. Our mapping clarifies a sequence of volcanic and hypabyssal rocks in the northern part of the area, and correlates them with the mid-Cretaceous Mount Nansen group, rather than with the early Late Cretaceous Open Creek volcanics, as currently exhibited on regional maps. The Casino suite porphyries and volcanic rocks that are prevalent in Mount Nansen area and around the Klaza deposit, are restricted to the easternmost side of the map area.

Constraining Metal and Magma Sources and the Provinciality of Cordilleran Porphyry Systems: The BC Pb Isotopic Advantage

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Economically significant Late Triassic to Early Jurassic porphyry Cu±Mo±Au systems in BC have a wide range of associated magmatic rocks, oxidation states, metal types and sizes, and preferentially form in certain districts or belts in Quesnellia and Stikinia. While magmatic and hydrothermal process are ultimately responsible for ore deposition, the source of the magmas, metals and sulphur are likely key constraints to their provinciality, endowment and metal character. Although geodynamic models have been proposed, there is little hard data that constrains the nature of the lithospheric melt sources and their modifications that reflect tectonic geometries, and evolution as they migrate through the crust.

Lead isotopes have long been recognized as robust indicators of signatures of various lithospheric and crustal influences, as well as constraining potential metal reservoirs in ore systems, and will be the primary tool utilized in this study. This research will bring forward and update the Leadfile (BCGS Paper 1988-2) with data in publications and lost in theses. With the new robust dataset, it will be queried, geographically, geologically, and with respect to plutonic suites and metal tenor of the ore systems in question to determine trends and patterns that contribute to magmatic evolution of the Late Triassic to Early Jurassic arcs.

Modeling the geometry of Shear Zone hosted gold + bismuth telluride bearing quartz veins at the historic Bunker Hill mine, south of Nelson, B.C. – a covert, mildly folded Tension Vein Array

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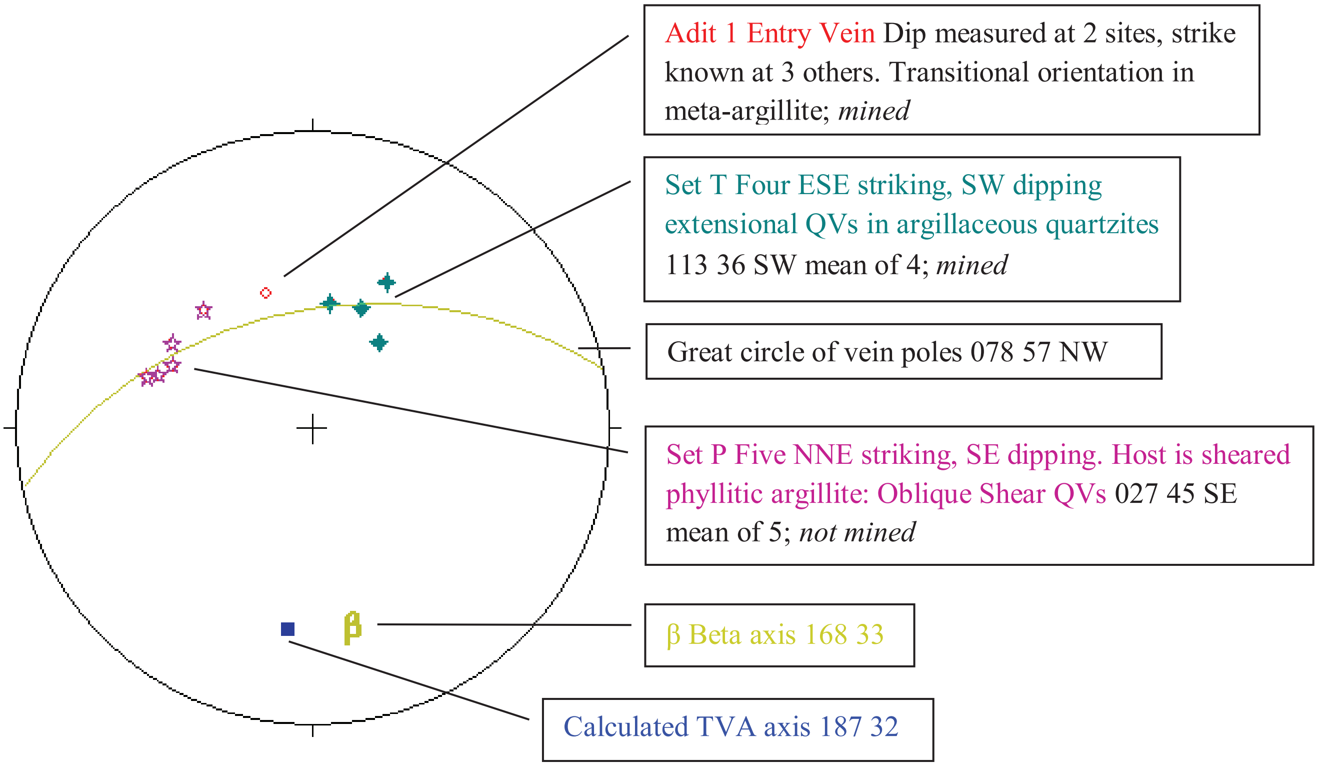
With a realistic model vein systems can be drilled effectively. Applying the Tension Vein Array model of Laing (2004) to quartz veins at the historic Bunker Hill mine, south of Salmo B.C., reveals the vein geometry, the state of strain and confirms they formed in a shear zone. At the outcrop scale the veins are not obviously folded; at 10’s of meters they are. The veins form a covert, Stage 2 low to moderate strain Tension Vein Array ‘TVA’ system. Within their formative shear zone they are folded 50-60°.

The BH mine is close to the Waneta-Tillicum Fault accretionary boundary between Quesnellia terrane and ancestral North America; ultramafics occur. The vein-locating shear zone is exposed once (*Figure 3*). Several vuggy veins grade ~0.3 oz / ton (11 g /t) gold. 9 of 13 gold-associated bismuth + bismuth telluride minerals identified in the Liese Zone Pogo gold deposit in Alaska (Rombach et al. 2002) occur, including unnamed Bi_2Te (Howard et al. 2009). First described in Canada are ingodite $Bi_2(TeS)$ and ikunolite Bi_4S_3.

Any or all of these vectors define the TVA axis: intersection lines of crossing veins, vein / parent shear zone intersections, dilational jog axes in the host shear zone, axes of vein bulges, vein tip lines and the linear orientations of any mined ore chutes [shoots] (Laing 2004).



Adit 1 Entry Vein Dip measured at 2 sites, strike known at 3 others. Transitional orientation in meta-argillite; *mined*

Set T Four ESE striking, SW dipping extensional QVs in argillaceous quartzites 113 36 SW mean of 4; *mined*

Great circle of vein poles 078 57 NW

Set P Five NNE striking, SE dipping. Host is sheared phyllitic argillite: Oblique Shear QVs 027 45 SE mean of 5; *not mined*

β Beta axis 168 33

Calculated TVA axis 187 32

Figure 1 Equal area lower hemisphere plot of poles (normals) to mean principal orientations of 10 individual veins in the Bunker Hill mine area, classed by production or not. Their mean great circle orients 078 57 NW. Its pole, the Beta axis β, is close in orientation to the Calculated TVA axis.

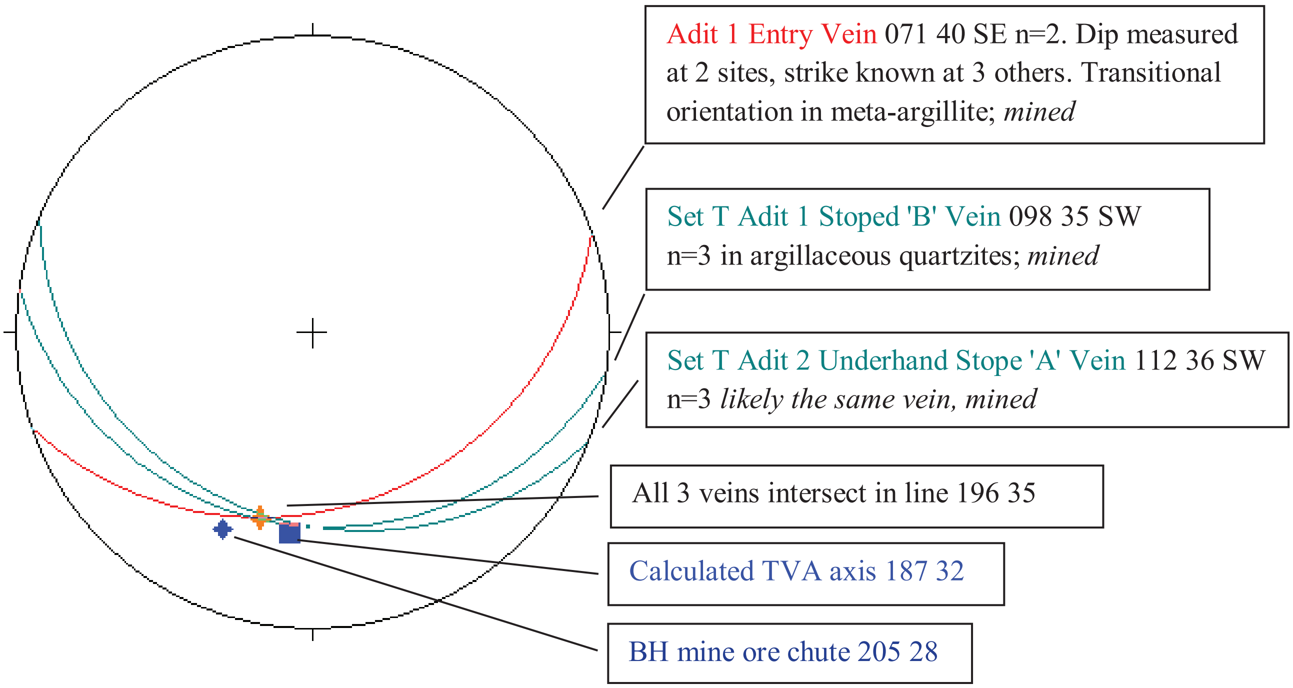


Figure 2 Three individual veins, exposed at surface and in two Bunker Hill mine adits, ***are all approx. co-linear.*** *Within error they contain their mutual intersection, the mined ore chute [ore shoot], and the calculated TVA axis. Equal area plot color-coded same as Fig. 1; veins as great circles.*

Three BH mine veins are approx. co-linear and include the calculated TVA axis 187 32. Set T extensional veins with ~0.3 oz / ton gold were mined; Set P shear veins are sub economic. Poles of 10 vein orients form a great circle with β Beta axis 168 33 (*Figure 1*). The BH mine ore chute [shoot] is a moderately plunging, oblate 'pancake shaped' ore body. Its long axis orients close to the calculated TVA axis 187 32 (*Figure 2*). Crossing veins formed it; in loose pieces "sulfides concentrate at the intersection of the two dominant vein orientations, suggesting highest Au and Ag values in those areas (Barry-Hallee 2016)."

Modeling the Bunker Hill QVs as a TVA system confirms a shear zone is the controlling structure; estimates the Stage 2 (low) state of rotational strain; differentiates the orientation of higher-grade veins; confirms one ore shoot formed at a triple-vein crossing; and identifies the optimum drill hole orientation (Corbett & Leach 1998). Other ore shoots are fully expected under drift cover; some will be blind.

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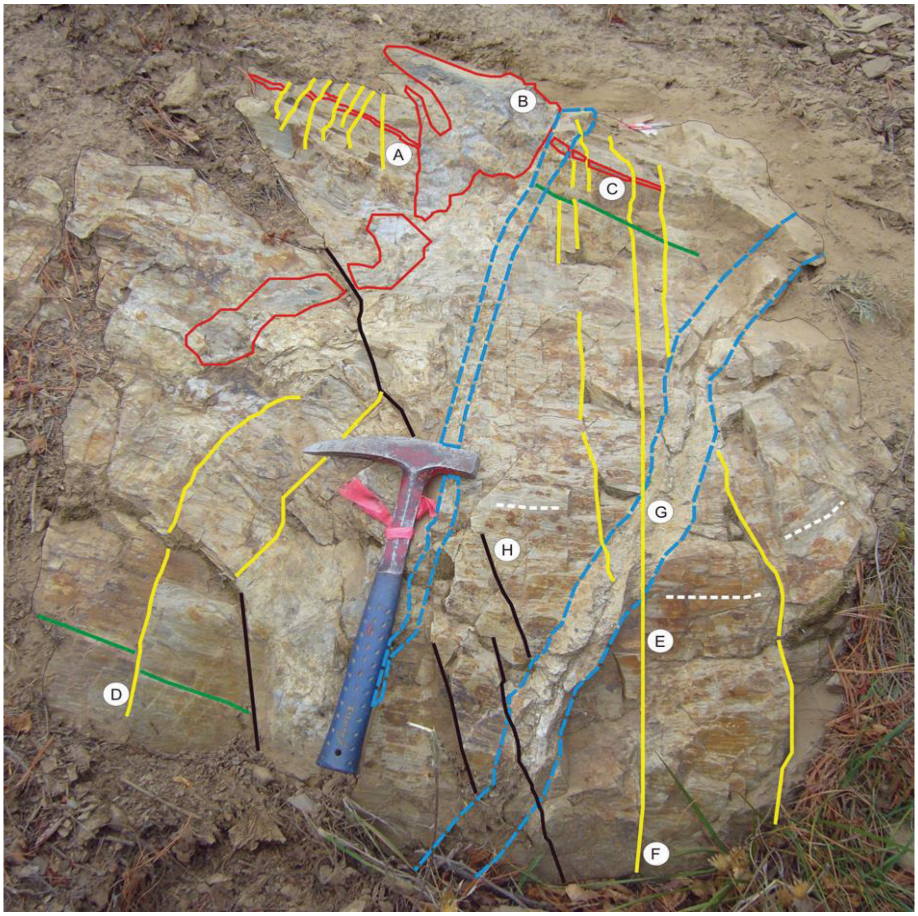

Figure 3 The single 'Curving Sheared Quartzite' exposure tens of meters from the Bunker Hill mine, on the access road. The argillaceous quartzite has shear lineations as green and white lines. Blue outlines two younger aplite dykes, in red greyish irregular quartz veins & veinlets. In yellow a series of fractures post-date all, except ones in black. Letters are orient sites; view is about East 070°. Veinlets at (A) and (C) orient like Set T extensional QVs. UTM Zone 11 471,324mE 5,434,490mN , from Tapsoba (2015).

Jurassic stratigraphy and tectonic evolution of the Whitehorse trough, central Yukon: Preliminary field and geochronology results

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The early growth of the northern Canadian Cordillera is in part recorded by the Whitehorse trough, an Early to Middle Jurassic sedimentary basin that developed on top of the Intermontane terranes after closure of the Cache Creek Ocean. The Whitehorse trough is a regionally significant depocentre that extends over 600 km from the Carmacks region of central Yukon to the Dease Lake region of northern British Columbia. Synorogenic strata of the Laberge Group filled the Whitehorse trough in central Yukon and were most likely sourced from exhumed basement units of Yukon-Tanana, Stikinia, and Quesnellia terranes. The Whitehorse trough displays north-to-south longitudinal changes in sedimentary facies. The northern apex is characterized by tidal to fluvial strata of the Tanglefoot formation whereas the middle of the trough is dominated by turbiditic strata of the Richthofen formation, implying a deepening of the Whitehorse trough to the south.

A two-year project was initiated in summer 2016 to investigate Laberge Group stratigraphy and test the relationships between the timing of exhumation, sedimentation, and terrane accretion in the Canadian Cordillera. Short-term objectives of this study are to define the physical stratigraphy, depositional setting and basal contact relationships of the Laberge Group strata along the Robert Campbell and North Klondike highways, the eastern shoreline of Lake Laberge and the flanks of Mount Laurier. The long-term objectives of the project are to constrain the source-to-sink pathways and paleodrainage systems of the Whitehorse trough using detrital zircon (U-Pb & Hf isotope) provenance signatures and link the timing and nature of Laberge Group sedimentation to the Jurassic exhumation of the Intermontane terranes.

TESTING THE OROCLINAL HYPOTHESIS FOR THE OLYMPIC MOUNTAINS, WASHINGTON STATE, USA

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The Olympic Mountains, located within the extreme northwest of the United States, form the immediate hangingwall of the Cascadia subduction zone, above the Juan de Fuca plate which subducts to the east beneath the west coast of the North American continent. The mountain belt consists of a highly arcuate, convex to the east, fold and thrust belt. Beck and Engebretson (1982), conducted a paleomagnetic study on the Olympics and showed that declinations fanned around the arcuate mountain chain. Based on these data, they suggested that the arcuate Olympic Mountains comprised an orocline. The implication is that the Olympics originated as a linear mountain belt that was subsequently buckled into its current arcuate geometry. Here we test this model by compiling available paleomagnetic data (more has been collected since the 1982 Beck and Engebretson study) and structural orientation data, and followed by a palinspastic restoration which was constructed to examine the feasibility of the oroclinal hypothesis.

Our analysis confirms the Beck and Engebretson finding: paleomagnetic declination varies as a function of structural strike around the arcuate mountain belt, and there is a linear correlation between fold axes trend and strike. We then employed the structural and paleomagnetic data, in order to construct a palinspastic restoration of the Olympics prior to oroclinal buckling. Our results imply that orocline formation accommodated 240 km of margin-parallel shortening. Regional plate tectonic considerations suggest that buckling accommodated northward translation of the coastal belt south of the Olympics. GPS data suggest that this northward translation may be ongoing.