

# CORDILLERAN TECTONICS WORKSHOP *XLVII*



Whitehorse, Yukon  
March 3<sup>rd</sup>-5<sup>th</sup>, 2023

## **Introduction**

Welcome to the Cordilleran Tectonics Workshop, 2023. The workshop is being held in the multipurpose room in the Kwanlin Dün Cultural Centre (KDCC), which is located beside the Yukon River, just north of the downtown area (1171 1<sup>st</sup> Avenue). All of the workshop events, with the exception of the dinner on Saturday night, will be held in this room.

To find the multipurpose room, enter the KDCC by the main (rotary) door. Turn left and walk along the corridor towards the north end of the building. The room will be on your right hand side. Wifi is available in this room (for password, check the folder near the door).

The first event will be the icebreaker/poster set-up/registration session on Friday March 3<sup>rd</sup> from 17:00-20:00. Beer and snacks will be provided. If you have a poster presentation this is the ideal time to install your exhibit. We will not be assigning poster boards to specific individuals – just find a free space and put up your poster on the provided boards (not the walls). Pins will be provided.

The presentations will start at 8:30 on Saturday 4<sup>th</sup>. Coffee/tea and breakfast snacks will be provided, starting at 8 am. Tea/coffee, snacks and lunch will be provided in this room during the day and a group dinner has been organized for the evening of Saturday 4<sup>th</sup>. This will take place in the Gold Rush Inn, which is located at 411 Main Street. The ‘Town hall’ and games rooms have been reserved from 18:00-22:00, and a buffet dinner will be provided. The food is included in your conference registration, but alcoholic drinks are not; there will be a cash bar in the dinner room.

The presentations will resume on Sunday 5<sup>th</sup> at 8:30 in the multipurpose room and the workshop will continue until 17:30. Tea/coffee, snacks and lunch will be provided through the day.

Thank you for your attendance, and we hope you will find the workshop informative and enjoyable

Organizers:

Tyler Ambrose, Rosie Cobbett, Maurice Colpron, David Moynihan, Patrick Sack

Yukon Geological Survey

## **Abbreviated Schedule**

### **Friday March 3rd**

Registration and Icebreaker (17:00-20:00; Multipurpose room, Kwanlin Dün Cultural Centre)

### **Saturday March 4th**

Morning session 1 (8:30-10:20)

Posters and refreshments (10:20-11:20)

Morning session 2 (11:20-12:40)

Posters and lunch (12:40-14:40)

Afternoon session (14:40-16:30)

Posters and refreshments (16:30-18:00)

Group dinner (18:30-22:00; Gold Rush Inn, Main Street)

### **Sunday March 5th**

Morning session 1 (8:30-10:20 am)

Posters and refreshments (10:20-11:20)

Morning session 2 (11:20-12:40)

Posters and lunch (12:40-13:40)

Afternoon session (13:40-15:30)

Posters and refreshments (15:30-17:30)

**SATURDAY MARCH 4<sup>th</sup>**

**8:30: Morning session 1**

**Geology of the Rackla River area: new insights into Proterozoic evolution of northwest  
Laurentia**

*Tyler Ambrose*

**Organic Carbon Burial and Paleoenvironmental Reconstruction of the Neoproterozoic  
Continental Margin of Northwestern Laurentia**

*Celeste M. Cunningham and R.W.C. Arnott*

**Sediment Provenance using Detrital zircons and Nd-St isotopes: implications for sediment  
routing in the Neoproterozoic Windermere Supergroup, southern Canadian Cordillera**

*Alexandra Pipe and R.W.C. Arnott*

**Sediment provenance and copper porphyry identification via non-negative matrix  
factorization of bivariate detrital data sets**

*Joel E. Saylor and Kurt E. Sundell*

**10:20 Posters and refreshments**

**11:20 Morning session 2 (Saturday)**

**On the Origins and Travels of Arctic Alaska**

*Justin V. Strauss*

**LA-ICPMS–CA-TIMS tandem dating of detrital zircon: Insights from n=1 MDAs of mid-Cretaceous Colville foreland basin strata, Slope Mountain, northern Alaska**

*Trystan M. Herriott, James L. Crowley, Marwan A. Wartes, David L. LePain and Mark D. Schmitz*

**Late Ordovician magmatism along the Dawson fault corridor: Evidence for reactivation of lithospheric-scale structures**

*Rose N. Cobbett*

**12:40 Posters and lunch**

**14:40 Afternoon session (Saturday)**

**Problems with Barrovian metamorphism**

*Pattison, D.R.M.*

**Differentiating and characterizing tectonic/metamorphic assemblages in the Yukon  
Tanana Upland**

*Travis J. Naibert, Rainer J. Newberry, Evan Twelker, Alicja Wypych, Michelle M. Gavel  
and Alec D. Wildland*

**A metamorphic record of the terminal accretion of the Insular terranes within southwest  
Yukon**

*Will McKenzie, Brendan Dyck and H. Daniel Gibson*

**A Late Paleocene - Early Eocene terrestrial Large Igneous Province in northwest North  
America and its relationship to tectonics and climate**

*Luke Ootes, Nancy Gruver Van Wagoner, Mitch Mihalynuk and Corey Wall*

**SUNDAY MARCH 5<sup>th</sup>**

**8:30 Morning session 1**

**Lithosphere of the Northern Canadian Cordillera: A synthesis from broadband seismology**

*Andrew Schaeffer, Clement Esteve, Pascal Audet, Derek Schutt, Rick Aster and Joel Cubley*

**Seismic characterization of Denali-Duke River fault system and its geothermal and hazard potentials**

*Jan Dettmer, Hersh Gilbert, Fernando Berumen-Borrego, Katherine Biegel and Jeremy M. Gosselin*

**Mapping the Tintina and Denali faults for geothermal energy exploration**

*Theron Finley, Guy Salomon, Edwin Nissen, Roger Stephen, John F. Cassidy and Brian Menounos*

**New insights on Cenozoic extension and fault reactivation in the southeastern Canadian Cordillera**

*Eva Enkelmann, Kade A. Damant and Scott Jess*

**10:20 Posters and refreshments**

**11:20 Morning session 2 (Sunday)**

**Barrovian metamorphism on the eastern flank of the Monashee Complex, British  
Columbia: Preliminary results from mapping and petrographic analysis**

*Collin Kehler and David R.M. Pattison*

**Dating Ductile Deformation by *In Situ* Rb-Sr Dating: Examples from the d'Abbadie and  
Shannon Faults, Yukon, Canada**

*Kyle Tollefson, Kyle Larson, Nathan Cleven and David Moynihan*

**Timing and emplacement depth of Mesozoic to Paleocene intrusions in southeastern British  
Columbia**

*Douglas MacLeod and David Pattison*

**12:40 Posters and lunch**

**13:40 Afternoon session (Sunday)**

**What really are the constraints on the ‘Klondike orogeny’?**

*Maurice Colpron, Jim Crowley, Bill McClelland, and Emma Kroeger*

**Are the quartz-gold veins of the Goodpaster district orogenic? Constraints from geochronology, geochemistry and vein textures**

*Douglas C. Kreiner, William Thompson, Jonathan Saul Caine, Chris Holm-Denoma, Paul O’Sullivan, Holly Stein*

**Tracing Cretaceous and younger strike-slip fault systems in the Yukon Tanana Upland, Alaska**

*Evan Twelker, Alicja Wypych, Travis J. Naibert, Rainer J. Newberry, Michelle M. Gavel, Alec D. Wildland and Abraham M. Emond*

**Late Mesozoic terrane assembly in the northwestern Cordillera through the lens of siliciclastic successions in eastern interior Alaska**

*Jamey Jones, Chris Holm-Denoma, Dwight Bradley and Paul O’Sullivan*

## **List of Poster Presentations**

(in alphabetical order of 1st author)

*R.W.C. Arnott and Thomas Hadlari*

**The world largest deep-marine turbidite system in outcrop, Neoproterozoic Windermere Supergroup in the southern Canadian Cordillera**

*Katherine Biegel, Jeremy Gosselin and Jan Dettmer*

**Interpretation of tectonic deformation in SW Yukon from relocation of earthquakes**

*Alex Brubacher, Jacob Kitchen, Jim Essman, Par Johansson, and Franck Valli*

**The Coffee Project, West Central Yukon: Geologic Mapping Provides New Insights into the Structural Setting and Deformational History**

*Caine, Jonathan Saul, Todd, Erin, McDermott, Robert G. and Jones, James V. III*

**Following the Crumbs: New Field Observations, Fault Rocks, and Preliminary Structural Geologic Analyses of Dismembered Ophiolite Klippen in the Alaska Yukon-Tanana Upland**

*Nathan R. Clevens, Jim J. Ryan, Dawn Kellett, Bill McClelland, Alex Zagorevski, Nancy Joyce, Jim Crowley<sup>5</sup> and Andy Parsons*

**Detrital zircon age distribution correlations between the Snowcap assemblage substrate of the Yukon-Tanana terrane and Proterozoic to Devonian stratigraphy of the Laurentian margin**

*Maurice Colpron, Don Murphy and Diane Skipton*

**The Late Triassic Galena and Snag Creek Sills, Yukon:  
Age, Geochemistry and Correlations**

*Lisel D. Currie, Carol A. Evenchick, Paul B. O'Sullivan and Julito Reyes*

**Relative timing of peak temperatures and the formation of structures in the northern  
Bowser and Sustut basins, British Columbia**

*Theron Finley, Guy Salomon, Edwin Nissen, Roger Stephen, John F. Cassidy, and Brian  
Menounos*

**High resolution topographic data along the Tintina and Denali faults**

*Theron Finley, Stephen T. Johnston, Martyn J. Unsworth, Jonathan Banks and Dinu-Ion Pana*  
**Right-lateral faulting in the southeastern Canadian Cordillera and its relationship to active  
hydrothermal systems**

*Jeremy M. Gosselin, Katherine Biegel, Mahdi Hamidbeygi and Jan Dettmer*

**Understanding tectonic stress in southwestern Yukon using earthquake focal mechanisms**

*Nathan Hayward, Luke Ootes and Dejan Milidragovic*

**Geometry and structure of the Hagem batholith, north-central BC, from the constrained 3-  
D inversion of potential field data**

*Richard Hieber and Steven D Boger*

**The multi-stage metamorphic evolution of the southern Ubendian Belt**

*R. G. McDermott, D.C. Kreiner, J. V. Jones III and S. P. Regan*

**Detrital magnetite as a provenance tool in Alaska's geologic and metallogenic terranes**

*Mitchell G. Mihalynuk, Luke Ootes, Corey Wall and Richard Friedman*

**Ultramafic-associated massive sulfides in the Index Formation of the Kootenay arc, southeast British Columbia: genetically upside-down?**

*Joel Padgett, Eva Enkelmann, David Moynihan and Dawn A. Kellett*

**Cenozoic exhumation in the Upper Hyland valley, southeastern Yukon: New insights from low-temperature thermochronology**

*Laura Pianowski, Jonathan Saul Caine, Christopher Holm-Denoma, Heather Lowers, Omero F. Orlandini and Robert G. McDermott*

**The Dawn of Denali? Enigmatic titanite U-Pb ages in Denali Fault zone mylonites**

*Taís Fontes Pinto, Eva Enkelmann and Viktor Terlaky*

**Initial assessment of detrital zircon (U-Th)/He thermochronology data from the southwestern Northwest Territories**

*Jim Ryan, Nathan Cleven, Katherine Landoni, Bahram Najafian, Zina Boileau, Christina Rutherford*

**Catalogue and physical rock properties of a 20 year Yukon-Tanana terrane legacy collection in Yukon**

*Guy Salomon, Theron Finley, Edwin Nissen, Roger Stephen, John Cassidy and Brian Menounos*

***Juicy Data — fine scale geomorphology along major Canadian Cordilleran faults from a new drone based lidar system***

*Derek L. Schutt, Robert W. Porritt, Clément Estève, Pascal Audet, Jeremy Gosselin, Andrew Schaeffer, Richard C. Aster, Jeffrey T. Freymueller, Joel F. Cubley*

**Large Lithospheric Seismic Velocity Variations Across the Northern Canadian Cordillera Imaged by Ambient Noise Tomography.**

*Diane Skipton and Steve Israel*

**Preliminary bedrock geology of the southern Nash Creek area (parts of NTS sheet 106D), central Yukon**

*E. Todd, J.S. Caine, M. Bizimis, M.M. Jean, M. Loocke, A. Wypych and G. Llewellyn*

**Tectonic Setting of the Seventymile and Kanuti Ophiolite complexes, Eastern Alaska**

*E. Todd, J.V. Jones III, D.C. Kreiner and A. Kylander-Clark*

**Hafnium isotope systematics of Permian to Eocene plutons of the Yukon Tanana terrane in eastern Alaska**

*Lucy Webb, Chadlin Ostrander, Sune Nielsen, Galen Halverson and Erik Sperling*

**Thallium isotopic constraints on global marine oxygenation during the early Neoproterozoic from the Reefal Assemblage in Yukon, Canada**

*Alicja Wypych, Travis J. Naibert, Evan Twelker, Michelle M. Gavel, Alec D. Wildland and  
Rainer J. Newberry*

**Geologic mapping in Yukon-Tanana Uplands, Alaska**

# **Geology of the Rackla River area: new insights into Proterozoic evolution of northwest Laurentia**

*Tyler Ambrose*

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Geological mapping in the Rackla River area provides new insight into the Proterozoic evolution of northwest Laurentia. The area, located at the southeast margin of the Wernecke inlier in east-central Yukon, is underlain by sedimentary strata of the Paleoproterozoic Gillespie Lake Group, Mesoproterozoic Pinguicula Group, Neoproterozoic Hematite Creek Group and Windermere Supergroup, and Paleozoic Bouvette Formation. Gabbro and diorite of the ca. 1.38 Ga Hart River suite intrude the Gillespie Lake Group. A swarm of east-west striking, mafic dikes intrude strata at least as young as the Tonian Hematite Creek Group. These dikes, which are undated, are alkaline and have an ocean island-like geochemical signature similar to Paleozoic mafic rocks in this region.

The northwestern part of the map area is dominated by northeast-southwest oriented structures that affected the ca. 1 Ga Hematite Creek Group but predate deposition of the ca. 755 Ma Callison Lake Formation (Windermere Supergroup). These constraints indicate that the dominant deformation event in this area is correlatable with the Corn Creek orogeny to the north, rather than the older (ca. 1.6 Ga) Racklan orogeny. Evidence for the Racklan orogeny in the map area includes an angular unconformity between the Pinguicula Group and underlying Gillespie Lake Group. In the southern and northeastern parts of the map area, structures are parallel to and likely related to younger, east-west and northwest-southeast striking Mesozoic–Cenozoic structures.

New detrital zircon geochronology constrains a maximum depositional age (MDA) of ca. 1128 Ma for the Pinguicula Group. This is nearly 200 million years younger than the previously published MDA and reveals that the Pinguicula Group was deposited along the margin of Laurentia during the assembly of Rodinia. Along with other geological relationships, the new MDA for the Pinguicula Group indicates that it is closely associated with the Hematite Creek Group—as originally proposed over 40 years ago—and constitutes the base of the Mackenzie Mountains Supergroup.

# The world largest deep-marine turbidite system in outcrop, Neoproterozoic Windermere Supergroup in the southern Canadian Cordillera

*R.W.C. Arnott<sup>1\*</sup> and Thomas Hadlari<sup>2</sup>*

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Originally termed the Windermere System by Walker (1926) from exposures in the Windermere valley of southeastern B.C., the now stratigraphically elevated Neoproterozoic Windermere Supergroup (WSG) has subsequently been shown to form an extensive outcrop belt from northern Mexico to the Yukon-Alaska border – a strike length of over 4000 km.



*Figure. 1. Distribution of exposed Windermere Supergroup strata in western North America (modified from Ross, 1991).*

Rocks of the WSG are particularly well exposed in the southern Canadian Cordillera (SCC) where alpine exposures of recently deglaciated strata provide an unparalleled opportunity for detailed geological study. Here the WSG forms an outcrop belt that extends across 35,000 km<sup>2</sup> (palinspastically unrestored) that in its lower and middle part consists mostly of deep-marine siliciclastic strata overlain by predominantly shallow-marine carbonate rocks in the upper part. In this area the WSG is of the order of 7-9 km thick and is interpreted to consist of two parts related to the rift and then post-rift of Laurentia (ancestral North America) from the Rodinia supercontinent (Ross, 1991). The lower rift part consists of a few-kilometer-thick assemblage of intercalated coarse clastic sedimentary and mafic extrusive igneous rocks. This, then, is overlain by post-rift strata consisting of a several-kilometer-thick succession of mostly siliciclastic upward

to carbonate sedimentary rocks representing a deep- to shallow-marine succession deposited on the margin of an expanding oceanic basin (Fig. 2).

In outcrop the most proximal part of the WSG in the SCC consists of mudstone interstratified with fine-grained, upper-division turbidites incised locally by >100 m deep scours filled with coarse, typically granule and pebble conglomerate, siliciclastic strata interpreted to be the fill of submarine canyons incised into continental slope mudrocks. Basinward the succession comprises locally

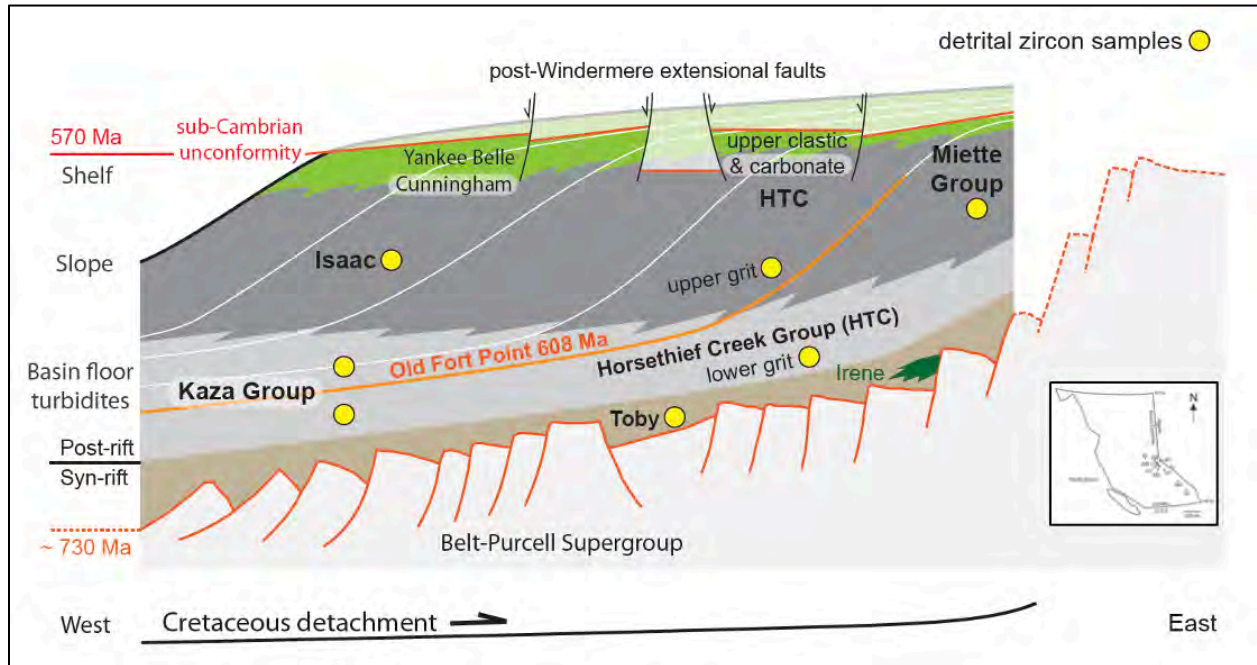
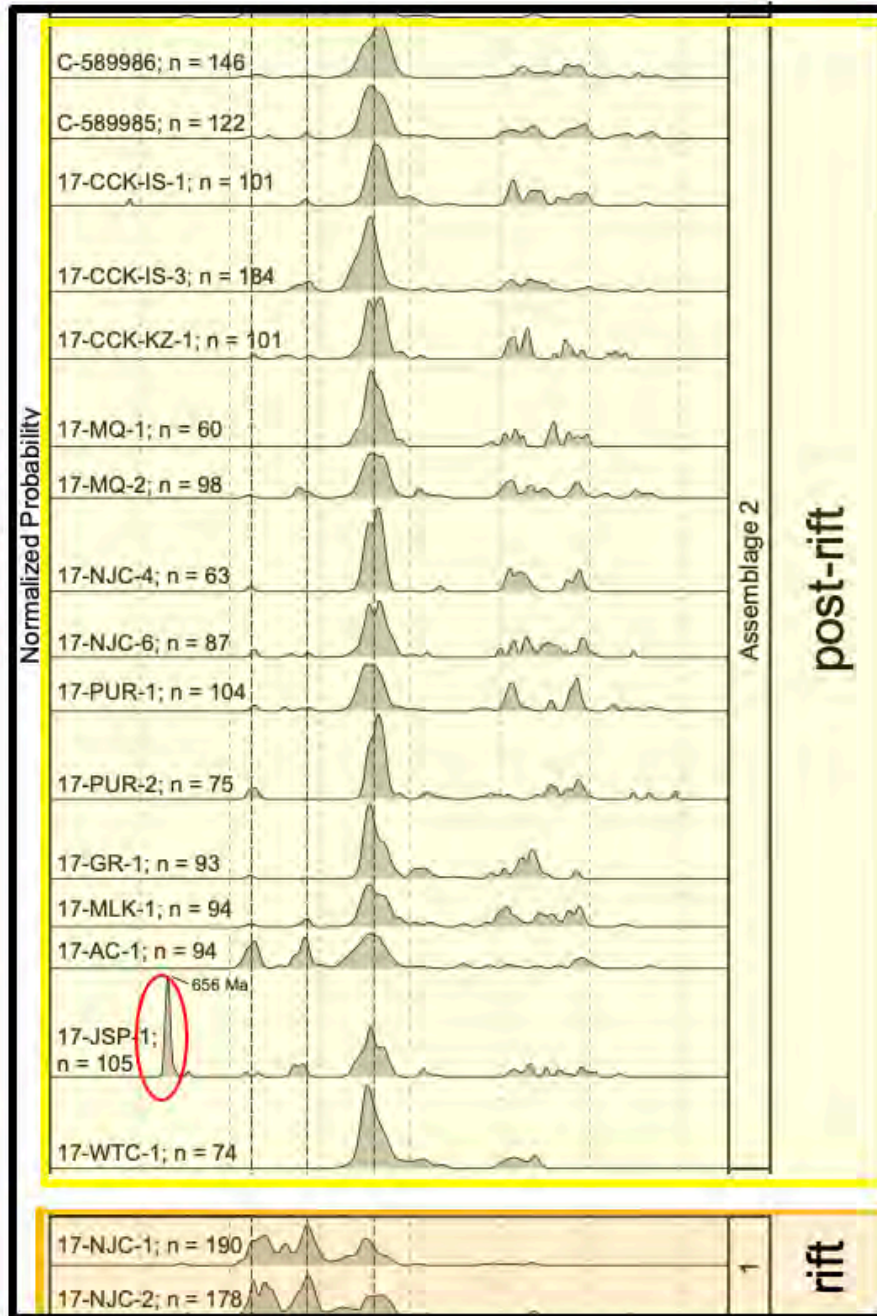


Figure. 2. Schematic of the temporal development of WSG in the southern Canadian Cordillera (Hadlari et al., 2021). WSG overlies the unconformity at the top of the Belt-Purcell Supergroup and generally thickens toward the northwest. The lower rift succession consists of intercalated mafic extrusive igneous rocks (black lens) and coarse siliciclastic sedimentary rocks that in many places accumulated in contemporaneous fault-bounded continental basins. The overlying post-rift succession consists of a several km-thick, upward-shoaling succession of basin floor (Kaza) to continental slope (Isaac) to continental shelf (Yankee Belle and Cunningham) deposits related to progradation of the Laurentian continent margin into the expanding Pacific miogeocline (Ross and Arnott, 2007). Note that the terms Kaza, Isaac, Cunningham and Yankee Belle refer to stratigraphic nomenclature in the Cariboo Mountains of east-central B.C. (Campbell et al. 1973), but the main characteristics of the single sequence are more widespread in our interpretation of the correlations. Inset map shows detrital zircon sample locations stretching from upper continental slope deposits in the Windermere valley of southeastern B.C. to basin floor strata just east of Prince George in central B.C..

developed channel complexes, some that range up to 250 m in thickness, within a succession dominated by thin-bedded turbidites. Channels are typically filled with medium- and coarse-grained sandstone flanked on their margins by well-developed, finer-grained deposits commonly consisting of distinctive multi-set ripple cross-stratified turbidites. Collectively these strata are interpreted to represent levee-bounded slope channels that formed downflow of the upslope canyons. In turn, these strata are succeeded and transition further basinward into a few-kilometer-thick succession of laterally extensive, several meter- to decameter-thick stratal packages composed of either sandstone-rich, lower-division turbidites or mudstone-rich upper-division turbidites interpreted to represent deposition by unconfined sand-rich and sand-poor turbulent suspensions on the basin floor.

In terms of the dimensions of its component stratal elements, for example leveed slope-channels, basin-floor depositional lobes, width and depth of submarine canyons, in addition to the areal extent of the entire outcrop belt, which with conservative palinspastic reconstruction is at least 80,000 km<sup>2</sup>, suggests that the Windermere turbidite system in the SCC is comparable to modern passive margin systems like the deep-marine Amazon, Congo and Mississippi turbidite systems. Moreover, based on detrital zircon assemblages the ultimate source area was the shield of northwestern Laurentia and the near uniformity of age spectra are consistent with a stable, long-lived continental drainage system. These data indicate two distinct provenance assemblages related to the long-term evolution of the WSG system in the SCC (Fig. 3). The first assemblage consists of abundant Mesoproterozoic (1.15-1.5 Ga) zircons and occurs in rift strata at the base of the WSG sedimentary pile, and likely reflects sediment derived from local bedrock sources, quite possibly on the raised margins of fault-bounded continental basins. The second assemblage makes up the post-rift succession, and as reported by previous authors (e.g. Ross and Bowring 1990) consists of a bimodal assemblage dominated by Paleoproterozoic (1.8 Ga) and Archean (>2.0 Ga) zircon ages. The ultimate source for this assemblage was the shield of northwestern Laurentia and the near uniformity of age spectra are consistent with a stable, long-lived continental drainage system. The absence of a western sediment source suggests that the Windermere turbidite system in the SCC formed along the west-northwest-facing passive margin of northwestern Laurentia.

*Fig. 3 (overleaf). Detrital zircon age distribution in WSG samples from the SCC. Note the abundant Mesoproterozoic but limited Archean ages in strata associated with rift sedimentation (orange). In contrast, note the characteristic and areally consistent bimodal (Paleoproterozoic and Archean) zircon age distribution in the post-rift assemblage. Also, note the prominent peak in the JSP-1 sample (red circle) at 656 Ma, which provides a maximum depositional age for initiation of the Windermere turbidite system in the SCC.*



**References:**

Campbell, R. B., et. al. 1973. Geological Survey of Canada, Paper 72-35, 104 p.

Hadlari et al. 2021. Lithosphere, doi.org/10.2113/2021/8356327

Ross, G.M. 1991. Geology, v. 19, p. 1125-1128.

Ross, G. M. and Bowring, S.A. 1990. Journal of Geology, v. 98, p. 879-894.

Walker, J.F. 1926. Geological Survey of Canada, Memoir 148, 69 p.

# Interpretation of tectonic deformation in SW Yukon from relocation of earthquakes

*Katherine Biegel<sup>1\*</sup>, Jeremy Gosselin<sup>1</sup> and Jan Dettmer<sup>1</sup>*

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The Southwest Yukon is undergoing active crustal deformation causing earthquakes due to its location at a plate boundary between the North American and Pacific Plates and the Yakutat Block. SW Yukon has multiple large, dextral strike-slip fault systems, including the Fairweather and Denali fault systems, with additional activity on multiple oblique thrust faults, including the highly active Duke River Fault. In this study, we present and interpret a double-difference relocation catalog of more than 5500 seismic events above magnitude 1.5 from 2010-2021. The relocated catalog highlights several unmapped fault features and significantly improves depth constraints on regional seismicity. The relative and absolute location improvements are supported by smaller travel time residuals and smaller residual standard deviations. We provide a detailed interpretation of modern motion along several faults throughout the region using our relocated catalog in combination with existing and recent earthquake focal mechanism catalogs. From these focal mechanism catalogs, we gain understanding of motion along regional faults by characterizing and sorting source mechanisms. Using these data, our interpretation shows tectonic motion in the SW Yukon is predominately occurring along rigid-block boundaries that represent major faults. Improved depths of earthquake hypocenters show that deformation is brittle in the top 10-12 km depending on fault feature. We interpret E-W faults connecting the Totschunda and Denali faults, as well as locate the Connector fault connecting the Totschunda-Duke River and Fairweather fault systems. From our interpretation, we conclude that the Fairweather and Denali fault systems are part of one large system that accommodates strain from Yakutat Block subduction and rotation of Southern Alaska due to plate motion.

# **The Coffee Project, West Central Yukon: Geologic Mapping Provides New Insights into the Structural Setting and Deformational History**

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The Coffee Gold project, located in the west-central Yukon Territory, Canada, is interpreted as an orogenic gold-only deposit emplaced ca. 97 Ma at a paleodepth of 5-6 km within Paleozoic metamorphic rocks and mid-late Cretaceous granite of the Yukon Tanana Terrane. Regionally, the trigger for gold mineralization at Coffee is thought to have been associated with the shift in relative motions between the North American and Pacific plates, c.a. 110-100 Ma. A detailed geologic reconstruction based on new mapping, however, records a delayed manifestation of this event at the location of Coffee. Our reconstruction documents a progressive rotation of  $\sigma_1$  from horizontal and NE-SW oriented at c.a. 100 Ma, associated with laccolith emplacement, to NNW-SSE oriented at c.a. 72 Ma, associated with dextral transpression and associated strike slip faulting, as well as a switch in  $\sigma_3$  from vertical to horizontal post 100 Ma. Stress-strain analysis of mineralized zones employing rock properties data from geotechnical studies at Coffee suggest the mineralized structures formed at a paleodepth of < 2 km, with  $\sigma_2$  oriented vertically. These new data and a revisited exhumation history which aligns geologic constraints and low temperature thermochronology data, support a revised model for the Coffee gold deposit, wherein mineralization formed closer to ~75 Ma and at a paleodepth of <2-3 km.

# Following the Crumbs: New Field Observations, Fault Rocks, and Preliminary Structural Geologic Analyses of Dismembered Ophiolite Klippen in the Alaska Yukon-Tanana Upland

*Caine, Jonathan Saul<sup>1\*</sup>, Todd, Erin<sup>2</sup>, McDermott, Robert G.<sup>2</sup> and Jones, James V. III<sup>2</sup>*

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The nature, continuity, kinematics, emplacement mechanisms and timing of ophiolite klippen in the Alaska Yukon-Tanana Upland (YTU) are poorly understood. In Alaska, the approximately 1,000 km-long by 5 to 50 km-wide arcuate belt of discontinuous ultramafic and mafic (UM/M) klippen rocks of the Salcha-Seventymile complex are akin to lithologically similar assemblages of the Dawson-Clinton Creek and(or) Slide Mountain assemblages in Canada. The belt has greater continuity to the north, whereas the southern area shows disparate small ( $\sim \leq 2$  km-diameter), isolated klippen. Peridotite-rich UM rocks are characteristic and associated with greenstones and oceanic siliciclastic sedimentary rocks of poorly constrained upper Permian to early Triassic age based on microfossil and U-Pb isotopic age data from cross-cutting dikes. Regionally dismembered greenschist facies klippen have been obducted onto, and are possibly imbricated with, amphibolite facies supracrustal Devonian-Mississippian rocks of the Fortymile River assemblage and Lake George basement of the composite Yukon-Tanana Terrane (YTT). Documenting the physical and chemical continuity of these UM/M rocks, from regional to outcrop scales, provide a new opportunity to refine existing hypotheses for the contractional, extensional, and(or) strain partitioned evolution of YTT crust.

New field observations and fabric measurements, structural analyses of foliations and lineations captured from existing geologic maps, and map pattern inspection provide new insights as well as new questions. If the UM/Ms in YTU klippen are petrogenetically, chemically, and geochronologically the same, and their basal contacts form a regional and gently inclined datum, they indicate the possibility of a large thrust sheet system up to  $\sim 350$  km wide. Spatially dispersed southern klippen may alternatively reflect previously hypothesized extreme upper crustal extension. In either case, if these rocks are cogenetic with physical continuity, they may reflect very large horizontal translations of as-yet poorly resolved timing and kinematics.

Initial structural analyses of UM/M foliations show subparallelism to their elongated regional map pattern with long-wavelength, low-amplitude open folds and associated lineations, consistent with overall belt-perpendicular, arcuate NW-N-NE directed shortening directions. In contrast to the variably serpentine-altered greenschist facies and open-folded northern klippen, complex near isoclinally folded amphibolite facies Mg/Ca silicate schists and gneisses exist in the southernmost studied klippen. These rocks may reflect complex thrust geometries associated with a component of local crustal thickening in the hinterland of a contractional belt. In contrast, lower plate basement shows radially concentric foliation domains with varying topographic expression, perhaps consistent with previously documented regional gneiss domes and basins. New field observations include unique exposures of upper and lower plate shear zones, some associated with

discrete carbonate-silica (listwanite) alteration possibly associated with local gold and Cr-mica mineralization. At the main Salcha-Seventymile belt to the NW the basal serpentinite shear zone is a few meters thick and shows NW-directed, subhorizontal shortening. In the Healy area to the south, basal shear zones are marked by talc-rich rocks without listwanites, but some have adjacent meter-long in-fabric anthophyllite crystals consistent with fluid-mediated, possibly deformation-related crystal growth. Healy shear zones show S-C kinematics indicative of W-directed subhorizontal shortening and are in knife-sharp contact with basement indicative of strain localization due to extreme rheological contrasts. New foliation data from this area, however, indicate NNW-SSE to NW-SE subhorizontal shortening. Evidence for SW directed subhorizontal shortening was also found in local basement, possibly also consistent with local, non-coaxial slip partitioned deformation.

In sum, the regional features of the YTU klippen are illustrative of complex lithologic, structural, and metamorphic contrasts between the upper and lower plates. Preliminary results are broadly consistent with contractional deformation in the upper plate klippen based on associated folding and fault rock kinematics that do not currently show evidence for regionally documented extension. However, evidence does exist for rheologically controlled non-coaxial slip partitioned, fluid-mediated, deformation among the peridotites, greenstones, orthogneisses, talc-rich schists, and the fault zones themselves. New results are not entirely inconsistent with YTT evolutionary models but new geochronology, chemistry, and continued structural analyses are needed to understand continuity and refine the regional evolution of the YTU upper crust more fully.

# **Detrital zircon age distribution correlations between the Snowcap assemblage substrate of the Yukon-Tanana terrane and Proterozoic to Devonian stratigraphy of the Laurentian margin**

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Reconstruction of the earliest tectonic history of allochthonous pericratonic terranes such as the Yukon-Tanana in the northern Canadian Cordillera is limited by the variably deformed, metamorphosed nature, and poor exposure of their basements or substrates. We demonstrate that detrital zircon U-Pb geochronology techniques can provide inter-terrane stratigraphic correlations that help define the origins and nature of the earliest tectonostratigraphy. We present detrital zircon data from 20 samples of Snowcap assemblage, the metasedimentary substrate within the Yukon-Tanana terrane, and its lithostratigraphic equivalents from twelve different regions. Additionally, detrital zircon data from 9 samples of Devonian-Mississippian units, 7 samples of Mississippian-Permian units, and 3 samples of Parautochthonous Laurentian margin White River assemblage were included to evaluate late Paleozoic terrane evolution, sediment recycling, and mixing. Statistical comparisons, using multi-dimensional scaling techniques based on Kolmogorov-Smirnov similarity tests, were made between Snowcap Assemblage and compiled reference data of Proterozoic through Devonian Laurentian passive margin strata. We conclude that Snowcap assemblage detrital zircon age distributions show similarity to those of some Neoproterozoic units from British Columbia to Arctic Canada, except that Neoproterozoic units exhibit a wider variety of age components. Cambrian Laurentian margin strata age distributions from the Pacific Northwest region have qualitative similarities implying Snowcap assemblage may have deposited in a similar time or tectonic setting. However, Pacific Northwest region units lack one key age component, ca. 2000 Ma, found consistently in Snowcap assemblage. Ordovician Laurentian units are similar to Snowcap Assemblage but are homogeneous along the length of the margin. Devonian Laurentian units and parautochthonous units in northern BC, Yukon and Alaska show strong similarities to a subset of Snowcap assemblage samples; they have similar major and minor age components, and are therefore a good possible stratigraphic correlation for a portion of Yukon-Tanana terrane. The key 2000 Ma age component is seen as a strong indicator of provenance from

the Taltson magmatic zone in central Canada, and is only found in Snowcap Assemblage and northern BC, Yukon, and Alaska Laurentian margin units. This implies that the Yukon-Tanana terrane substrate originated as a pericratonic fragment rifted from the Laurentian margin in the north, close to its estimated location of accretion in Permian-Triassic.

# **Late Ordovician magmatism along the Dawson fault corridor: Evidence for reactivation of lithospheric-scale structures**

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The distribution of lower Paleozoic continental margin facies define a zig-zag pattern along the eastern part of the North American Cordillera. Platformal and coeval basinal facies are offset along proposed rift transfer faults, including the Liard Line, St. Mary-Moyie fault, and the Snake River fault. We propose that the Dawson fault in central Yukon is a similar rift transfer fault because: 1) it coincides with an offset in continental margin facies; 2) there is a sharp contrast in geophysical properties across it; and 3) Cambrian to Upper Ordovician alkaline igneous rocks are concentrated along the fault corridor. Zircon U-Pb dates from mafic volcanic rocks and gabbro, and macrofossil ages from interbedded limestone debris flows constrain the ages of magmatic rocks along the Dawson fault to Miaolingian (Cambrian) and Upper Ordovician. Trace element geochemistry and Nd-Hf isotopic data indicate these rocks formed by low degree partial melting of the subcontinental lithospheric mantle within garnet stability (>75 km).

New bedrock mapping and facies analysis of mafic igneous rocks exposed north of the Dawson fault near Castle Mountain provide a detailed framework for geochronological, paleontological and petrological analysis and for unravelling the early to middle Paleozoic geologic history of this region. The age of submarine eruptions near Castle Mountain is tightly constrained by U-Pb zircon dates and fossils to the Late Ordovician (ca. 453-445 Ma). The magmatism was preceded by deposition of silty limestone and chert followed by progressive shallowing and subsequent development of a carbonate platform. These facies occur within a bend in the Dawson fault where the trace of the fault shifts from its east-west trend to a NW-SE orientation. We suggest that this bend developed during strike-slip reactivation of the Dawson fault in the Late Ordovician and that local extension accommodated the deposition of deeper-water silty facies and emplacement mafic igneous rocks. The post-rift, strike-slip reactivation of the Dawson fault in the Late Ordovician coincides with counter-clockwise rotation of Laurentia indicated by paleomagnetic data from the craton. We propose that the Late Ordovician continental rotation was an important factor controlling post-rift extension and magmatism along western Laurentia.

## What really are the constraints on the ‘Klondike orogeny’?

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Current models on the evolution of the Yukon-Tanana terrane involve: 1) Late Devonian rifting of a continental margin fragment (Snowcap assemblage); 2) latest Devonian to Early Mississippian development of a back-arc ocean (Slide Mountain terrane); 3) Mississippian to early Permian arc magmatism (Finlayson and Klinkit assemblages); and 4) mid- to late Permian arc magmatism (Klondike assemblage) related to closure of the Slide Mountain ocean. Final closure of the Slide Mountain ocean is thought to have led to the late Permian-Early Triassic ‘Klondike orogeny’; an event that has been compared with the Sonoma orogeny of the US Cordillera. Current models of the ‘Klondike orogeny’ involve crustal thickening, development of an amphibolite-facies transposition foliation, and development of a Triassic clastic wedge that onlaps Yukon-Tanana, Slide Mountain and Selwyn basin. But what are really the constraints supporting this model? Specifically, what is the evidence for crustal thickening and mid-crustal deformation in the Permian?

The cornerstone argument for mid-crustal deformation related to the ‘Klondike orogeny’ centres on relationships surrounding the Jim Creek pluton in the Klondike region of western Yukon. The Jim Creek pluton has been described as an undeformed quartz monzonite stock that intrudes foliated carbonaceous phyllite. The foliation in the carbonaceous phyllite has been related to deformation affecting the Sulphur Creek orthogneiss a few kilometres to the northeast. U-Pb dating of zircon by ID-TIMS (multi-grain, air abraded fractions) and LA-ICPMS indicate that the strongly deformed Sulphur Creek orthogneiss is ca. 260 Ma and the ‘undeformed’ Jim Creek pluton is ca. 252 Ma. These dates were taken to constrain the ‘Klondike orogeny’ to an 8 m.y. window ca. 260-252 Ma.

Evidence for late Permian amphibolite-facies metamorphism is conjectural. The main arguments for Permian metamorphism consist of poorly documented ca. 265-260 Ma metamorphic rims on zircon and rare ca. 260 Ma monazite from schist collected near ca. 260 Ma intrusions. None of the ca. 260 Ma metamorphic dates are linked to P-T estimates supporting amphibolite facies metamorphism. Ages with direct ties to garnet growth are Middle Triassic (ca. 245-243 Ma), not Permian, and associated with high T and low P metamorphism. The overwhelming evidence from

metamorphic studies is that development of a mid-crustal, amphibolite-facies penetrative foliation in the Yukon-Tanana terrane occurred in the Early Jurassic (ca. 195-190 Ma).

The main body of Jim Creek pluton is a two-mica, garnet-bearing, medium-grained quartz monzonite. Upon closer examination, field relationships show that the Jim Creek pluton is locally deformed along its margin and experienced some degree of recrystallization in its 'undeformed' core. A series of dikes ~1 km east of the pluton are composed of medium to coarse-grained two-mica, garnet-bearing granite that locally contains xenoliths of foliated carbonaceous phyllite. Two samples were dated using the CA-TIMS method, one from the Jim Creek pluton itself ( $260.84 \pm 0.07$  Ma) and another from a dike ( $260.91 \pm 0.07$  Ma); both localities were previously dated 252.5 Ma. A sample of strongly foliated quartz-feldspar augen granite from the Sulphur Creek orthogneiss was also dated by CA-TIMS and yielded an equivalent date of  $260.96 \pm 0.07$  Ma. These results eliminate the bracket previously inferred between the Jim Creek and Sulphur Creek plutons and the constraint on timing of the 'Klondike orogeny'.

The CA-TIMS results from the Jim Creek pluton further suggest that the previously reported ca. 252 Ma dates must result from undetected Pb loss in the multi-grains, air-abraded zircon fractions analyzed by ID-TIMS and in LA-ICPMS analyses. Lead loss is evident in our analyses of igneous and detrital zircon from the Klondike region. For example, LA-ICPMS analysis of a sample of Sulphur Creek orthogneiss yielded  $^{206}\text{Pb}/^{238}\text{U}$  dates between  $262.0 \pm 6.3$  and  $240.0 \pm 9.0$  Ma and a weighted average of  $248.7 \pm 2.8$  Ma; the CA-TIMS date from this sample is  $260.96 \pm 0.07$  Ma. Detrital zircons from psammitic schist in the Klondike Schist yielded a large number of discordant analyses (317 of 503 grains analyzed); concordant results in this sample range from  $288.5 \pm 3.6$  to  $237.2 \pm 1.6$  Ma and define age peaks at 264 and 247 Ma. Twelve zircons selected across the range of LA-ICPMS analyses yielded overlapping  $^{206}\text{Pb}/^{238}\text{U}$  dates between  $262.35 \pm 0.19$  and  $262.14 \pm 0.18$  Ma and a weighted average of  $262.25 \pm 0.06$  Ma.

Finally,  $^{40}\text{Ar}/^{39}\text{Ar}$  mica ages from the area surrounding the Jim Creek and Sulphur Creek plutons are ca. 188-180 Ma indicating cooling after Early Jurassic exhumation and the penetrative foliation in the Klondike region is most likely an Early Jurassic fabric, as documented in other parts of Yukon-Tanana terrane. The coeval Jim Creek and Sulphur Creek plutons occur in distinct structural panels separated by the Ninemile thrust and their different styles of deformation may only be reflection of their distinct structural positions. The apparent truncation of the foliation recorded in the carbonaceous phyllite by the Jim Creek pluton could be due to the rheological contrast between these lithologies, where the pluton remained dry during deformation, and only narrow zones along its margin were hydrated. Alternatively, the carbonaceous phyllite preserves a record of a pre-Permian foliation older than the postulated timing of the 'Klondike orogeny' and distinct from the Jurassic foliation in the Sulphur Creek orthogneiss.

## The Late Triassic Galena and Snag Creek Sills, Yukon: Age, Geochemistry and Correlations

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Gabbro sills of the Late Triassic Galena suite intrude Devonian to Carboniferous strata of the Earn and TsiChu (Keno Hill) groups in central Yukon. The sills occur in a narrow, east-west trending belt approximately 10-20 km wide, over 260 km in strike length, and are confined between the footwall of the Robert Service thrust and the hanging wall of the Dawson fault. The gabbro sills are generally fine-grained, foliated, folded and metamorphosed to greenschist facies; they are commonly described as greenstone sills. Sill exposures in the Tombstone Range at the western end of the belt are more commonly coarse to locally very coarse-grained or pegmatitic and typically exhibit little deformation. A sample of coarse-grained gabbro from the Tombstone Range was previously dated by U-Pb ID-TIMS analyses of 6 multi-grain zircon fractions and one fraction of baddeleyite. These analyses defined a 6-point discordia line with an upper intercept  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $232.2 \pm 1.5/-1.2$  Ma. Several attempts at dating greenstone sills from the eastern part of the belt were unsuccessful, but another sample of very coarse-grained gabbro collected in the Tombstone Range (~4 km east of previously dated sill) yielded zircon and was dated by CA-TIMS at  $230.49 \pm 0.07$  Ma.

Gabbro sills are also documented southwest of the Tintina fault in western Yukon, where they intrude Devonian to Triassic strata that are the eastern extension of parautochthonous continental margin rocks from the Yukon-Tanana upland of Alaska. In this region, the Snag Creek gabbro sills are medium to coarse-grained, variably foliated and intrude strata of the Ordovician-Devonian Scottie Creek, Devonian White River and Triassic Mirror Creek formations. The White River and Mirror Creek formations have been correlated respectively with the Devonian Earn Group and Triassic Jones Lake Formation northeast of the Tintina fault. Zircon from a sample of gabbro intruding schist of the Scottie Creek formation were dated by LA-ICPMS and yielded a  $^{206}\text{Pb}/^{238}\text{U}$  date of  $230.4 \pm 1.7$  Ma equivalent to the age of the Galena suite in the Tombstone Range, northeast of the Tintina fault. A single zircon grain from a sample from another gabbro sill intruding siltstone of the Mirror Creek formation, collected along the Alaska highway north of Beaver Creek, was dated by CA-TIMS at  $231.61 \pm 0.43$  Ma. These Late Triassic dates support correlation with gabbro of the Galena suite in central Yukon. Both the Galena and Snag Creek gabbros have similar geochemical signatures – they are mildly alkalic and of E-MORB affinity with moderately juvenile isotopic signatures ( $\epsilon\text{Nd}$  5-6;  $\epsilon\text{Hf}$  6-9).

A lone body of fine-grained, foliated gabbro mapped north of the Dawson fault in central Yukon (Rau gabbro) has been correlated with greenstone sills of the Galena suite to the south. The gabbro intrudes rocks of the Devonian Earn Group, but its age is otherwise unconstrained. The geochemistry of this gabbro is distinct from the Galena and Snag Creek suites; it is more alkalic in composition and shows more crustal influence in its isotopic signature ( $\epsilon\text{Nd}$  1.34;  $\epsilon\text{Hf}$  1.28). The Rau gabbro body is therefore clearly a distinct intrusive suite from the Late Triassic Galena sills.

# Organic Carbon Burial and Paleoenvironmental Reconstruction of the Neoproterozoic Continental Margin of Northwestern Laurentia

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Modern deep-marine fan systems are known to represent significant sinks of organic carbon. Carbon that becomes buried in these sediments can be stored over geologic timescales, thereby removing atmospheric carbon dioxide, an important greenhouse gas, and increasing atmospheric oxygen levels. This process can have significant impacts on the long-term regulation of global climatic and oceanographic trends. However, although organic carbon burial in modern deep-sea fan systems, and even in some Phanerozoic systems, has been studied, few have attempted to characterize carbon sequestration in systems that pre-date terrestrial vegetation.

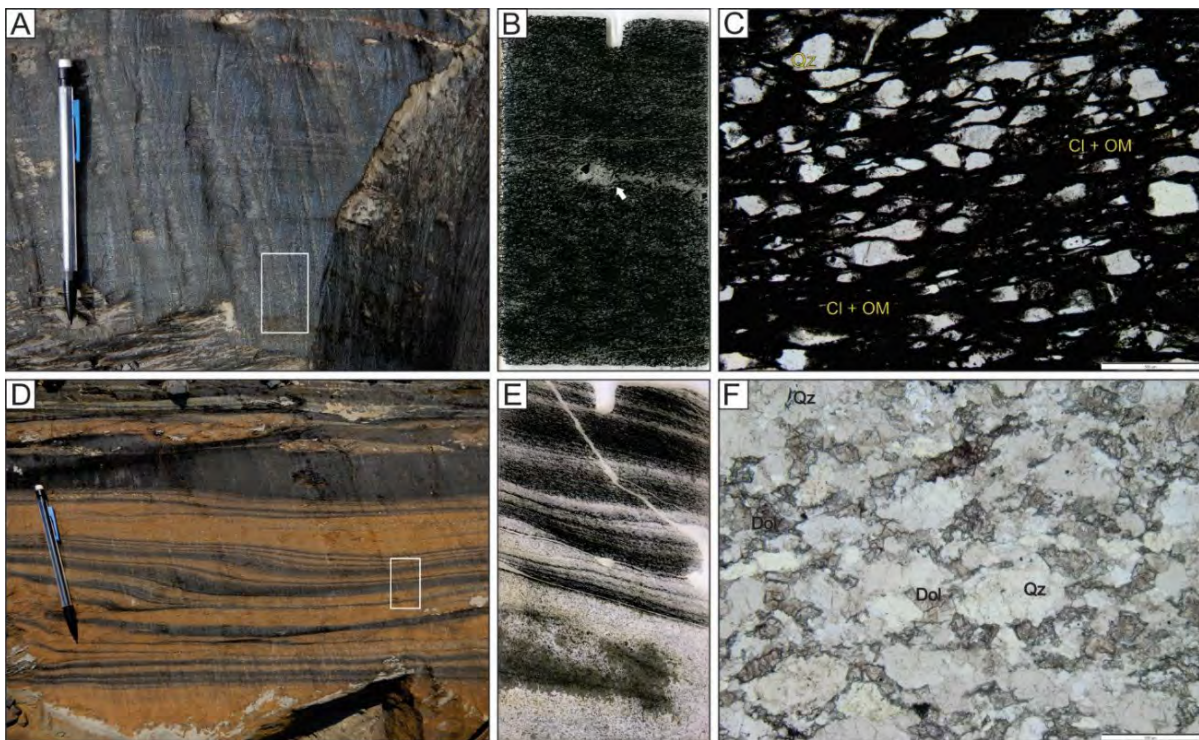
At the study site in the Cariboo Mountains, southern Canadian Cordillera, deep-marine levee deposits of the Neoproterozoic Windermere Supergroup are exceptionally well-exposed and form a conformable succession approximately 2.6 km thick and up to 8 km wide. In this study, detailed field-based description and stratigraphic logging were combined with measured total organic carbon (TOC) to evaluate trends in the distribution of organic carbon in a 300 m-thick succession. Elemental data from X-ray fluorescence analysis were used to reconstruct paleoenvironmental conditions, including primary productivity, ocean redox, weathering intensity and detrital sediment flux at the time of deposition.

In the succession, TOC ranges from < 0.1% to 4.04% (uncorrected for the effects of greenschist metamorphism). Organic-rich strata, taken to be  $\geq 1\%$  TOC, are principally confined to a single 60 m-thick stratigraphic interval, where they typically occur as anomalously thick, mud-rich banded sandstone turbidites (Figure 1). In these beds organic matter occurs mostly as micro-scale carbon sorbed onto the surface of clay grains but also as uncommon sand-sized organomineralic aggregates or discrete sand-sized amorphous grains (Figure 2).

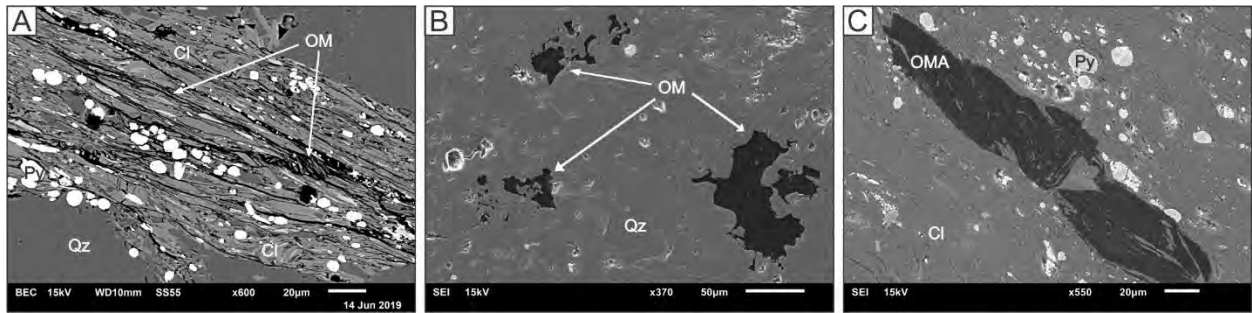
In this same interval, trends in elemental data indicate an increase in primary productivity, weathering intensity, and detrital influx, and a decrease in ocean oxygen levels. These data suggest that intense continental weathering, high terrigenous input, elevated sea level, and relatively low oxygenation conditions acted to enhance organic matter production in shallow marine environments and organic matter accumulation and preservation in the deep marine. However, although each of these components might individually contribute to increased organic production,

accumulation, and preservation, the results of this study suggest that it is the temporal coincidence of all of them in a “perfect storm” that is required for significant organic carbon enrichment. Additionally, because these strata are Neoproterozoic the preserved organic matter is exclusively of marine origin, which then raises the possibility that the conditions described here are unique to deep-sea turbidite systems before the evolution of metazoans or terrestrial plants.

By studying the geochemical trends of both organic-rich and organic-poor rocks in this ancient outcrop, this study provides insight into the paleoenvironmental evolution of the Laurentian margin during the late Neoproterozoic and reveals how the distribution of organic carbon in the ancient stratigraphic record is controlled by larger-scale environmental factors. This will ultimately improve our understanding of the complex interplay of physical, chemical, and biological processes that govern marine sedimentation and their relationship with the carbon cycle and past global climate, particularly in systems that pre-date terrestrial vegetation.



**Figure 1.** Black, clay-rich band of organic matter (OM)-rich sandstone (Facies 2). White box indicates the location of thin section shown in part B. B) Thin section (25 x 45 mm) of the clay-rich band shown in part A. Light band in the middle (white arrow) is a metamorphic quartz vein. C) Plane-polarized photomicrograph of part B. Note the dispersed quartz (Qz) sand grains in an opaque black matrix, which based on electron microscopy, consists of clay (Cl) and organic matter (OM). D) Alternating black, clay-rich and orange highly cemented bands in an organic-rich sandstone. White box indicates location of thin section in part E. E) Thin section showing alternating clay- and sand-rich bands in part D. F) Plane-polarized photomicrograph of a sand-rich band in part B. Note the abundance of pore-filling, rhombic ferroan dolomite (Dol) cement.



**Figure 2.** A) Backscattered electron micrograph of a black, clay-rich band in an organic-rich sandstone (perpendicular to bedding). Nano-scale rims of organic matter (OM, black) surround most clay particles (Cl, light grey). B) Secondary electron micrograph of dispersed carbon particles in an orange sandstone band. C) Secondary electron micrograph of an organomineralic aggregate (OMA) composed primarily of OM surrounded by pyrite framboids and clay grains.

## Relative timing of peak temperatures and the formation of structures in the northern Bowser and Sustut basins, British Columbia

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The Bowser and Sustut basins are clastic sedimentary basins in the Intermontane Belt of the north-central Canadian Cordillera that overlie Stikinia. The Bowser Basin accumulated a minimum of 6000 m of marine and nonmarine sediments during the Middle Jurassic to Early Cretaceous, and the Sustut Basin accumulated locally up to 2000 m of nonmarine sediments during the late Early and Late Cretaceous (Eisbacher, 1974; Tipper and Richards, 1976; Evenchick and Thorkelson, 2005; Evenchick et al. 2007). Deformation of these strata during Late Jurassic to Late Cretaceous, and possibly early Tertiary, resulted in the Skeena Fold Belt (Evenchick, 1991).

An understanding of stratigraphy, together with apatite fission track (AFT), zircon (U/Th)/He, and vitrinite reflectance results for surface samples from different stratigraphic and structural settings provide insight into the relationship between the timing of peak temperatures and the formation of structures in the northern Sustut and Bowser basins.

The areas examined include: 1) exposures of the highest Sustut Basin strata northeast of the deformation front; 2) a well exposed triangle zone at the front of the Skeena Fold Belt ; 3) a transect across an angular unconformity between Sustut Basin and Bowser Basin strata; 4) a structural domain with large displacement dip-slip faults that strike highly oblique to the contractional structures; and 5) exposures of some of the stratigraphically highest Bowser Basin rocks, which in part overlap with the region of highest thermal maturity.

Complete resetting of the AFT ages of almost all samples studied requires between 2.7 and 4.2 km of burial, assuming geothermal gradients that are appropriate for the Bowser Basin (between 31°C/km and 45°C/km). Heating is attributed to stratigraphic burial by latest Cretaceous to early Tertiary synorogenic strata deposited in the Sustut Basin, most of which is no longer preserved. For some samples, Jurassic and younger Bowser Basin sedimentation, and structural burial during Skeena Fold Belt deformation also contributed to heating.

Cooling recorded by AFT data predates some contractional deformation within the Skeena Fold Belt, and predates offset on Griffith Creek Fault, one of many steep, late, dip-slip structures that have affected both Bowser Basin and Sustut Basin strata.

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# Seismic characterization of Denali-Duke River fault system and its geothermal and hazard potentials

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Southern Yukon is characterized by complex tectonic processes due to proximity to the continental margin with conservative and destructive plate boundaries. As a result, major transform fault systems, including the Denali and Fairweather systems, exist that harbour significant potential for earthquakes. In addition, there is significant geoscientific evidence near these faults, as well as from global analogs, that increased geothermal potential is associated with these features. Geothermal energy is not widely used in Canada, and the location and extent of available resources are currently poorly understood.

Our group is carrying out a study to resolve the structures and deformation processes of these transform faults at regional to local scales, and to provide new knowledge about natural hazards and geothermal potential. At the regional scale, we will present an overview of the seismicity and its relationship to tectonic processes in southern Yukon. Results include new constraints on where earthquakes occur and how the region deforms as largely rigid blocks. The statistics of earthquake occurrence also provide insight about the type and magnitude of earthquakes to be expected in the region. These results have implications for seismic hazard along these faults.

The tectonic setting provides important context for our local, high-resolution studies along major transform faults. At the local scale, we will present an overview of the passive-seismic field campaign that is currently underway near Burwash Landing. Several data sets have been recorded to image the Denali and Duke River Faults, and the local lithology at the kilometer scale. Discoveries include the occurrence of repeating earthquakes which may be related to fluid movement in the subsurface, as well as new constraints on seismic velocities and overburden thickness.

# **New insights on Cenozoic extension and fault reactivation in the southeastern Canadian Cordillera**

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The long narrative of southeastern Canadian Cordilleran geology mostly ends in the Eocene with the development of metamorphic core complexes in the south and transtensional to strike-slip motion in the north of the Canadian Cordillera. But what happened after the Eocene in the southeastern Canadian Cordillera? To answer this question, we acquired low-temperature thermochronology data crossing large structures such as the Rocky Mountain Trench (RMT) and the Columbia River Fault.

The RMT is a 1500 km long valley that coincides with normal and strike-slip faults separating the Foreland belt (Rocky Mountains) from the Omineca belt (Columbia Mountains) in the southern Cordillera. At depth the RMT coincides with a sharp change in lithospheric thickness that possibly represents the western limit of the ancient continental margin. We studied a 100-km-long section of the RMT that coincides with the northernmost exposure of high-grade basement rocks in the Malton Gneiss Complex. To the south is the Columbia River Fault, a brittle-ductile normal fault that bounds the eastern margin of the Monashee Core Complex.

New apatite (U-Th)/He and fission-track data reveal several phases of fault reactivation and rock exhumation following the Eocene. We integrate our new results with published thermochronology data and field observations that collectively suggest exhumation continued throughout the Miocene. We show that the Malton Complex exhumed as a horst structure during the early to mid-Miocene time, bounded by the North Thompson Albreda Fault to the west and the RMT to the east. Normal faulting along both faults continued in the late Miocene, but west side down motion is implied along the RMT (Fraser et al., 2021). Similarly, the Columbia River Fault was reactivated in the early Miocene (~20 Ma) and continued to exhume the Monashee Complex an additional ~2 km (Damant et al., 2023).

We propose that late Cenozoic deformation was driven by the high gravitational potential of the southeastern Canadian Cordillera and the tectonic reorganization along the Pacific–North American margin that resulted in increased transtension that changed later to transpression (~12 Ma). We suggest the Columbia River Fault and the North Thompson Albreda Fault reactivated as

splay faults due to dextral motion along the RMT. In contrast, the shallower dipping thrusts of the Foreland belt are unfavourable to slip and explain the general lack of young extension and the higher topography in the Rocky Mountains.

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## Mapping the Tintina and Denali faults for geothermal energy exploration

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The communities of Burwash Landing and Watson Lake in the Yukon seek geothermal energy resources to improve energy and food security. These two communities are respectively situated adjacent to the Eastern Denali fault (EDF) and Tintina fault (TF); both faults are theorized to act as conduits for geothermal water to the near surface. The modern strain rate, stress orientation, kinematics, and geometry of faults are key controls on permeability and are thus highly relevant to geothermal exploration. The EDF is known to have hosted at least four > M6 earthquakes in the past 6800 years, but a lack of high-resolution imagery or lidar coverage has hindered understanding of its kinematics and prevented detailed mapping of its trace. No paleoseismic studies have been conducted on the TF, although a slip rate of 0.5 mm/yr has been estimated from seismicity rates. Here, we present new mapping of segments of these faults using high resolution topographic data, including lidar datasets collected with a rotary-wing drone and crewed fixed-wing aircrafts. Along the EDF, we map 70 km of the Holocene surface rupture in detail and identify segments that would be more likely to be permeable (i.e., zones of localized extension). We also improve constraints on kinematics and earthquake recurrence; stream-channels and risers are observed to be dextrally offset between 5-75 m, with greater offsets on older geomorphological surfaces, implying that cumulative offset from multiple ruptures can be distinguished. Along the inferred trace of the TF near Watson Lake, the lidar reveals a previously unmapped fault scarp dextrally offsetting an early Holocene glaciofluvial outwash channel. To the northwest near Dawson City, ArticDEM data shows a distinct fault scarp deforming Pliocene to Pleistocene glacial deposits. These are the first modern surface ruptures ever to be identified along the TF. Our results will help guide decisions about geothermal drilling and exploration along the EDF and TF, and also highlight the need to consider seismic hazard along these fault zones.

## High resolution topographic data along the Tintina and Denali faults

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This poster is complementary to the talk presented by Theron Finley entitled “Mapping the Tintina and Denali Faults for Geothermal Energy Exploration”; the high-resolution bare-earth digital terrain models (DTMs) discussed in the oral presentation are provided here for close inspection and discussion. We collected a crewed airborne lidar dataset (100 cm pixel resolution) along a 70 km segment of the Eastern Denali fault (EDF) from Tān Chù (Slims River) to Burwash Creek. This dataset is the first large-scale lidar acquisition along the EDF, which is Canada’s fastest slipping (~2 mm/yr) onshore fault. We also collected data with a new drone-based lidar system at Quill, Burwash, Nines, Copper Joe, Topham, and Telluride Creeks, as well as Shár Ndü Chù (the Duke River), where these features intersect the EDF surface trace. These data produce DTMs with 25 cm pixel resolution, allowing for higher confidence in interpretations of fault kinematics. Near Watson Lake, we acquired a crewed airborne lidar dataset (100 cm pixel resolution) along the Tintina fault (TF) and adjacent Watson Lake fault. These data reveal a subtle fault surface rupture 12 km southeast of Watson Lake, 700 m from the inferred trace of the TF. Near Dawson City, we examine existing ArcticDEM data for evidence of neotectonic activity along the TF. ArcticDEM data are provided at 200 cm pixel resolution, and are not truly bare-earth, but the sparse vegetation in this region allows for high quality imaging of tectonic features. A 120 km long series of parallel, semi-continuous fault-like features are observed cross-cutting late Pliocene to early Quaternary glacial landscapes. Collectively, these data demonstrate the importance of acquiring high-resolution topographic data over known or suspected tectonically active faults.

## **Right-lateral faulting in the southeastern Canadian Cordillera and its relationship to active hydrothermal systems**

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We present new data from structural mapping along the Columbia River, Slocan Lake, Purcell Trench, Southern Rocky Mountain Trench, and Redwall faults. Fault plane and slickenfiber orientations measured in the field indicate a previously unidentified, post-Eocene phase of right-lateral strike-slip kinematics on these faults, which have historically been mapped primarily as Eocene extensional structures. The NESW maximum principal stress required for these kinematics shares a similar orientation to the present-day stress field derived from crustal earthquake focal mechanisms, which suggests dextral slip may be a recent and ongoing development that continues at the present time. These major fault zones are also thought to control the locations of thermal springs, which are targets for geothermal energy exploration. Both the current stress field and the most recent kinematics of these faults likely play a significant role in localizing hydrothermal upwellings. We show that on a regional scale, there is a positive correlation between the locations of springs and regions with elevated seismicity. At the local scale, geothermal upwellings may be controlled by zones of enhanced permeability including fault intersections and strain-transfer zones in an overall right-lateral setting. The identification of favorable structural settings may enable discovery of hidden (a.k.a. blind) geothermal energy resources.

# Understanding tectonic stress in southwestern Yukon using earthquake focal mechanisms

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Earthquake source characteristics provide a valuable constraint on fault behaviour, crustal stress, and regional plate tectonics. In southwestern Yukon, a region of complex active tectonics, studies of earthquake sources have historically been limited by sparse seismic network coverage. In this work, we leverage improvements in seismic station coverage over the last decade to estimate focal mechanisms for small and moderate-magnitude ( $M \geq 2.0$ ) earthquakes from P-wave first-motion polarity data. We invert these data using a probabilistic method that rigorously quantifies earthquake focal mechanism uncertainties. Furthermore, we use updated earthquake hypocentre locations from a recently relocated regional catalog, which significantly improves event depth estimates. New focal mechanism solutions for several hundred events significantly improve the spatial coverage for southwestern Yukon and enable new tectonic interpretation.

We observe contrasting P-axis orientations for events on either side of the Fairweather fault. For events within southwestern Yukon, the distribution of faulting mechanism types and P-axis orientations are relatively consistent. Our focal mechanism solutions support the existence of several unmapped faults south of the Duke River fault. Finally, we propose a method to accurately propagate earthquake focal mechanism uncertainty into inversions for the orientation of regional tectonic stress. Together, this work provides a valuable contribution towards estimating regional tectonic stress, and improves our understanding of regional tectonics throughout southwestern Yukon.

# Geometry and structure of the Hagem batholith, north-central BC, from the constrained 3-D inversion of potential field data

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A multistage approach to the constrained 3-D inversion of potential field data is used to investigate the geometry and internal character of the Hagem batholith, Quesnel terrane, north-central British Columbia. The batholith consists of four temporally and petrologically distinct intrusive phases, with associated geophysical and petrophysical signatures, emplaced between 200 to 130 Ma. The batholith intruded Nicola Group (Late Triassic) sedimentary rocks to the east, and is bound by the Pinchi-Ingenika right-lateral strike-slip fault to the west. New compilations of Bouguer gravity and aeromagnetic data, that merge Geological Survey of Canada and Geoscience BC Quest data, are used to model the geometry and depth of the batholith through independent 3-D gravity and pseudogravity inversion. The resulting 3-D geometry model shows the southern part of the pluton to reach depths of ~15 km, but greater depths of ~35 km in the north. The 3-D geometry model is used to constrain the 3-D inversion of aeromagnetic data within the batholith, integrating magnetic susceptibility data from physical property measurements made in outcrop. The 3-D magnetic susceptibility model reveals the NW-SE structural trends within the southern part of the batholith, which is comprised of Thane Creek suite diorite (ca. 200 Ma) and Duckling Creek suite biotite-pyroxenite and monzonite (ca. 180 Ma). In contrast, the low magnetic susceptibilities in northern part of the batholith, associated with the Mesilinka suite (ca. 130 Ma) granitic intrusions and lesser tonalite, which aside from a few localised zones of relatively higher magnetic susceptibility, do not lend themselves to strong geophysical contrasts.

# LA-ICPMS–CA-TIMS tandem dating of detrital zircon: Insights from n=1 MDAs of mid-Cretaceous Colville foreland basin strata, Slope Mountain, northern Alaska

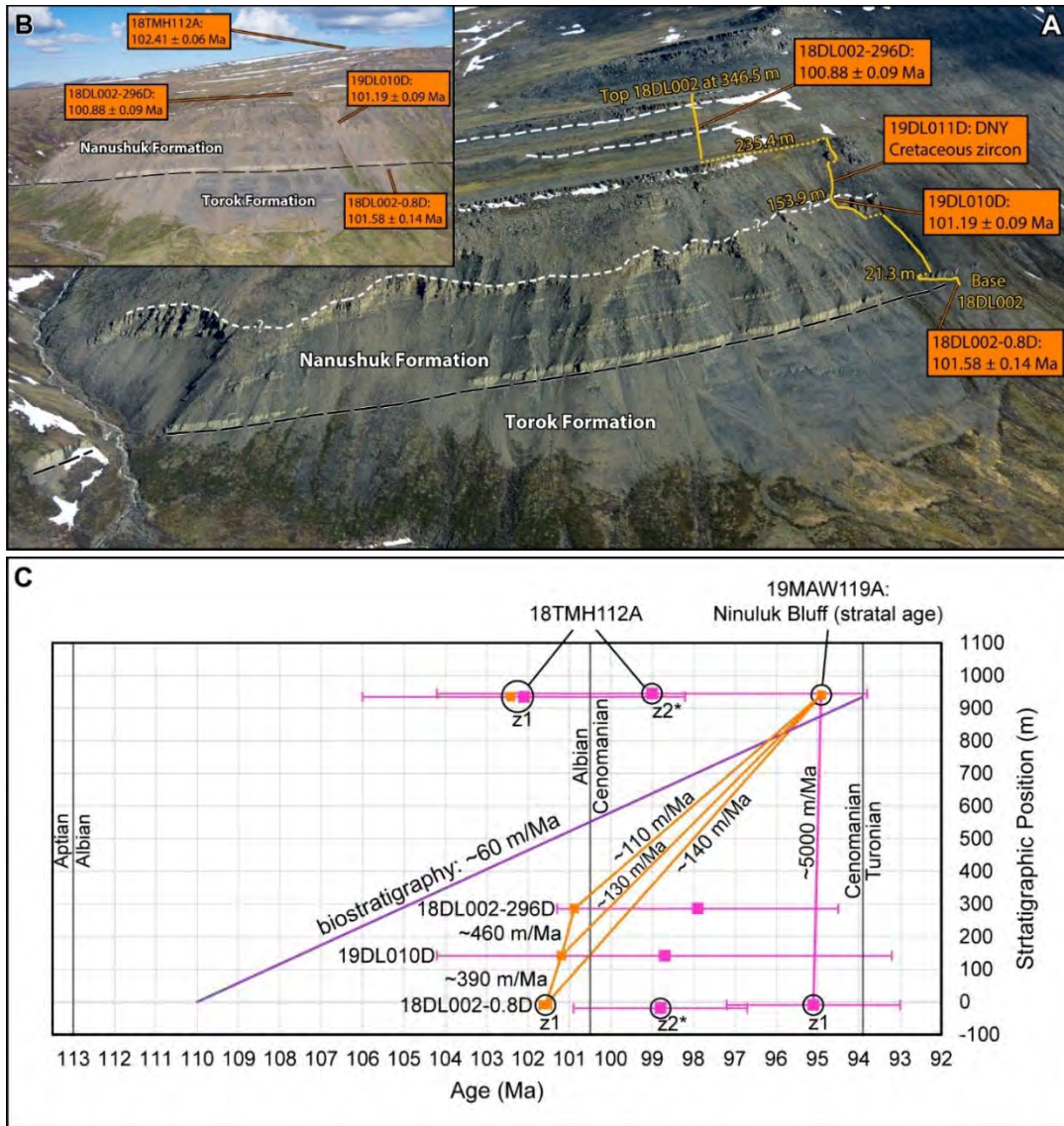
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Recent advances in detrital zircon (DZ) maximum depositional age (MDA) research are notable, yet the persistent array of laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS)-based DZ MDA algorithms portends opportunity for further progress. Sound geologic reasoning must underpin MDAs, but interpreting youthful date distributions requires many analytically and statistically driven decisions, including whether to use single- or multi-grain MDAs. Furthermore, the reliability of MDA algorithms is usually assessed by chronostratigraphic benchmarking that does not ascertain MDA accuracy, and even careful consideration of known challenges can still lead to inaccurate MDAs. Here, we present tandem LA-ICPMS–chemical abrasion-thermal ionization mass spectrometry (CA-TIMS) U–Pb results for five DZ samples from a ~950-m-thick section of mid-Cretaceous Torok and Nanushuk Formations at Slope Mountain. Youthful DZ yields are extremely sparse and only permit n=1 MDAs. LA-ICPMS dates are 0.3–6.4% younger than CA-TIMS ages from the same grains. The biostratigraphy suggests ~110–94 Ma sedimentation; the CA-TIMS-based MDAs reduce this window by ~8.5 Ma. These MDAs and a new CA-TIMS tephra zircon age correlated to the section’s top render reasonable minimum sedimentation rates (100s m/Ma). However, using the youngest single-grain LA-ICPMS dates as MDAs yields an improbably rapid rate (~5 km/Ma) that affirms their inaccuracy. We examine the new results and two published tandem DZ datasets to assess whether analytical dispersion and Pb-loss are formidable or discountable. These tandem dates indicate pitfalls for LA-ICPMS MDAs, with too-young offsets per study that are impactful (~2–3% avg.) and pervasive (~85–100% of pairs). Tandem date-pair plots reveal relations that DZ MDA algorithm comparisons can obscure, and too-young biases in LA-ICPMS dates likely reflect complex combinations of analytical scatter, matrix effects, and low-temperature Pb-loss. The youngest date in an LA-ICPMS distribution maximizes any too-young bias regardless of the contributing sources, but multi-grain MDAs are also prone to negative offset. We demonstrate the value of tandem LA-ICPMS–CA-TIMS geochronology for establishing DZ MDAs—and assessing the validity of MDA algorithms—in a demanding, n=1 application.



**Figure A.** Oblique aerial photograph of the lower southeast flank of Slope Mountain, where uppermost Torok and lower Nanushuk crop out. DZ sample locations and CA-TIMS-based MDAs are labeled in the context of measured section 18DL002. DNY—did not yield. **Figure B.** Oblique aerial view northwestward, showing area visible in A and higher topography of Slope Mountain, including the summit sample site (18TMH112A) that yielded an older DZ MDA. **Figure C.** Age–depth plot of new and existing age constraints for the Slope Mountain section. Magenta and orange labels are LA-ICPMS and CA-TIMS constraints, respectively. DZ results are tandem date pairs; z-grain labels are provided when n=2 (grains), although the z2 asterisks indicate that those CA-TIMS experiments did not yield results. The Ninuluk Bluff CA-TIMS-based tephra zircon stratal age is correlated to the top of the Slope Mountain stratigraphy (sample site 18TMH112A). Stratigraphic accumulation rates between an MDA and the capping stratal age are minimums; rates between MDAs are neither minimums nor maximums (i.e., actual rates can be slower or faster than the simple line-slope-derived rates). Uncertainties listed and portrayed in Figures A, B, and C are  $\pm 2\sigma$ , including analytical and standard (LA-ICPMS) or tracer (CA-TIMS) calibration contributions.

# The multi-stage metamorphic evolution of the southern Ubendian Belt

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Malawi is located in the central-eastern part of Africa and records a long and complex metamorphic history. It lies within the East-African-Rift-System which controls the present-day topography of the country, although it experienced at least three major metamorphic events beforehand: the Palaeoproterozoic Ubendian-Usagaran Orogeny (2200-1800 Ma), the Mesoproterozoic Irumide Orogeny (1050-950 Ma) and the Neoproterozoic Pan-African Orogeny (800-500 Ma).

Thermodynamic modelling of metapelitic granulites of the southern Ubendian Belt in central Malawi suggests a generally clockwise  $P$ - $T$ - $t$  path. The granulite facies metamorphism and  $P$ - $T$ - $t$  path reflect crustal thickening and subsequent exhumation of this belt in the Palaeoproterozoic.

These granulites are crosscut by steeply dipping shear zones which formed schist zones that were retrogressed under significantly lower temperatures. Electron probe microanalyser (EPMA) U-Th-Pb dating of monazite of these schists yields three age populations which correspond to previously reported tectono-metamorphic events in the area: Irumide Orogeny, rift-related magmatism and Pan-African Orogeny. Combined with textural relationships, these ages reveal that these schistose zones might have formed during the Irumide Orogeny and were overprinted and retrogressed in localised shear zones during the Pan-African event.

Following a model of the Broken Hill area in southern Australia, the schists in this work can be interpreted to have formed in normal faults in the Ubendian basement and got rehydrated, buried, and transgressed later under greenschist to amphibolite facies conditions.

## **Late Mesozoic terrane assembly in the northwestern Cordillera through the lens of siliciclastic successions in eastern interior Alaska**

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New geologic mapping and detrital zircon geochronology help to define age and provenance patterns of Mesozoic siliciclastic strata from the Manley basin in eastern interior Alaska that provide essential constraints on the assembly of accreted terranes in the northwestern Cordillera. Successions including the Wolverine quartzite and Wilber Creek/Minto units were deposited on pericratonic terranes such as Yukon-Tanana, Farewell/Livengood, and Ruby outboard of the northwestern Laurentia margin. The successions presently define a complex suture zone between the pericratonic terranes that has accommodated hundreds of km of shortening and strike-slip translation. On the northwestern side of the basin, the Late Jurassic–Early Cretaceous Wolverine quartzite appears restricted to the Ruby and (or) Livengood terranes. Circa 159–131 Ma maximum depositional ages from the quartz-rich Wolverine confirm limited fossil ages, and diverse older age populations suggest recycling of the Ruby and (or) Farewell terranes. To the southeast, the Lower Cretaceous Wilber Creek and Upper Cretaceous Minto units are less compositionally and texturally mature and have prominent ca. 200–150 Ma zircon age populations suggesting Yukon-Tanana terrane igneous sources. The successions and associated pericratonic terranes are all presently interleaved in folded and faulted panels that also contain slivers of other allochthonous terranes. Distinct provenance on either side of the Manley basin suggests that major shortening began in the Late Cretaceous and was likely completed prior to ca. 60 Ma plutonism that cross-cuts all of the deformed successions. Subsequent strike-slip displacement along major structures such as the Tintina and Victoria Creek faults continued to modify the terrane and suture zone geometries. Continuing work on the provenance and structural evolution of the siliciclastic successions will help further refine tectonic models for accretionary orogenesis at the apex of the Cordillera.

# **Barrovian metamorphism on the eastern flank of the Monashee Complex, British Columbia: Preliminary results from mapping and petrographic analysis**

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The metamorphism and structure of a portion of the Selkirk Mountains south of Revelstoke, British Columbia, has been investigated. The domain of interest is bound on its western flank by the Eocene Columbia River fault, juxtaposing it against upper amphibolite to granulite-facies gneisses of the Monashee Complex. The eastern boundary is gradational with the Selkirk fan structure, and the southern boundary is approximately coincident with the southern margin of the Jurassic Kuskanax batholith near Nakusp.

Structural analysis indicates three phases of deformation, termed D2 through D4; D1 is a Devonian-Mississippian fabric which is only recognizable on the southeastern margin of the study area. D2 is the dominant phase of deformation in the southern and eastern part of the study area, characterized by kilometer-scale upright folds and a steeply dipping penetrative foliation. D3 is the dominant phase of deformation to the north of Beaton Arm, characterized by northeast-vergent, open to tight recumbent folds and an associated crenulation to axial-planar schistosity. D4 is a locally developed crenulation along the east shore of the Columbia River north of Beaton Arm. The age of D2 is Early to Middle-Jurassic, bracketed by the 162 Ma Galena Bay stock which cuts D2 structures. D3 structures are younger than the Galena Bay stock and are cut by the 104 Ma Albert Stock. The age of D4 remains unconstrained.

Between Revelstoke and Beaton Arm on Upper Arrow Lake is a sequence of Barrovian metamorphic zones. These increase in grade from east to west, and comprise chlorite/biotite, garnet, staurolite, staurolite-kyanite, and sillimanite zones developed in metapelites. Mapping of mineral assemblages reveals shallowly east-dipping isograds. To the south, between Beaton Arm and Nakusp, metamorphic grade decreases from the staurolite zone to chlorite/chloritoid zones. Barrovian metamorphic recrystallization developed approximately coevally with the development of the D3 structures, indicated by early-D3 growth of garnet and late-D3 growth of staurolite and kyanite.

Preliminary phase equilibrium modelling indicates a narrow pressure-temperature (P-T) range of ~6.5-7 kbar (~23-25 km depth) and ~650°C where kyanite is predicted to appear at the expense of staurolite. However, the lack of textural evidence for kyanite development at the

expense of staurolite, combined with the narrow width of the staurolite zone, are at odds with predictions by phase equilibrium modelling. If kyanite was instead produced alongside staurolite by the reaction of matrix minerals (muscovite and chlorite), this could expand and lower the range of P-T conditions to ~5-7 kbar (~18-25 km depth) and ~580-650°C in the kyanite zone.

Future U-Pb monazite dating will be conducted to try and pin down more precisely the age of metamorphism.

## **Are the quartz-gold veins of the Goodpaster district orogenic? Constraints from geochronology, geochemistry and vein textures**

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The origin of Au-bearing, low sulfide quartz veins in the Goodpaster and Tibbs Creek regions of interior Alaska remain enigmatic. Intrusion-related Au and mesozonal orogenic vein models have both been proposed (Thompson and Newberry, 2000; Rhys et al., 2003; Dilworth et al., 2007; Goldfarb and Pitcairn, 2022). To date, studies of igneous geochronology and metamorphic timing have shown that gold veins are broadly coeval with magmatism and post-date regional metamorphic fabrics. Relatively little description of detailed mineralogy, and absolute timing of mineralization exist – which leads to the enigmatic origin of the deposits. This study attempts to relate these parameters through investigation of new U-Pb crystallization and Re-Os mineralization ages combined with detailed descriptions of vein textures to constrain genetic models for the veins.

New and existing geochronology highlight three major pulses of mid Cretaceous magmatism. Early unfoliated to weakly foliated and recrystallized two-mica and garnet-bearing granite and granodiorite yield LA-ICPMS U-Pb zircon crystallization ages of ca. 113-108 Ma. An intermediate age suite, characterized by tonalite to granodiorite, yields U-Pb LA-ICPMS monazite, zircon, and SHRIMP-RG zircon crystallization ages of ca. 107-105 Ma (Day et al., 2003; Dilworth et al., 2007). The youngest suite is characterized by granodiorite to quartz diorite that have LA-ICPMS U-Pb zircon crystallization ages are ca. 98-93 Ma.

Secular trends in the geochemistry of igneous suites are pronounced. Granite of the early suite is strongly peraluminous and straddles the syn-collisional to volcanic arc fields on a Y+Nb and Yb+Ta versus Rb Pearce plot (Pearce, 1968). Intermediate age tonalite is characterized by weakly peraluminous to weakly metaluminous phases. Intermediate age tonalite to granodiorite and late diorite plot in the volcanic arc field on the Pearce plot. Zircon trace elements analyzed on the SHRIMP-RG in all igneous suites exhibit steep light with flat middle to heavy REE patterns. These

patterns are consistent with shallow non-garnet residual sources. All suites exhibit strong negative Eu anomalies with weak to absent Ce anomalies.

Veins in the district exhibit diverse textures ranging from massive quartz with thicknesses ranging from 1 to >10m, to breccia with angular to milled clasts and bladed carbonate-open space quartz. Sulfide minerals are sparse, constituting less than 1% of the vein in most cases. Sulfide minerals in the veins are characterized by abundant pyrite, pyrrhotite, arsenopyrite, Au and other minor As- and Bi-bearing mineral phases. Locally, thick intercepts of arsenopyrite or pyrrhotite-pyrite mineralization occur. Pyrrhotite is commonly early, whereas arsenopyrite is found throughout the paragenesis. Generally, gold is poorly correlated with As and exhibits a strong correlation with Bi. However, some intervals and veins in the deposits exhibit strong As-Au correlations. Gold occurs as inclusions within As, Bi, and Te sulfides and sulfosalts, or as free gold interstitial to quartz grains. Brecciation is common in many veins across both the Pogo and Tibbs Creek deposits and occurrences. Early Au-bearing quartz clasts are cemented by younger quartz-gold, or arsenopyrite-gold matrix. The matrix is cataclastic characterized by milled and rounded arsenopyrite-rock flour, suggesting brittle syn-tectonic deformation. Gold locally post-dates the milling event, occurring as rims or patchy cement between milled arsenopyrite grains. Gold-bearing calcite and bladed calcite-quartz veins cut the breccias.

An NTIMS Re-Os age of ca. 104 Ma was determined for molybdenite in a quartz vein in the main Liese zone (Selby et al., 2002). New Re-Os NTIMS dating of arsenopyrite that encapsulates gold, is co-precipitated with gold, or post-dates early gold at Pogo corroborates an age of ca. 106-105 Ma for Au mineralization. At Tibbs Creek, direct dating of mineralization is in process, though veins such as Blue Lead and Wolverine, are hosted within the ca. 108-104 Ma granite. This indicates a similar age of gold mineralization across the entire region. Preliminary Lu-Hf dating via LA-ICPMS of bladed carbonate vein assemblages that occur within the mineralized zones, and co-precipitate with quartz yield Mesozoic ages. However, the 2-sigma errors are large (ca. 44-53 Ma).

Regional synthesis of the geochronology of igneous crystallization and mineralization indicates a temporal overlap between Au mineralization and emplacement of mid Cretaceous granitoids. At Pogo, the intermediate-age tonalite suite, although not directly observed within the deposits, is coeval with mineralization, but rarely altered or mineralized. At Tibbs, gold-bearing quartz veins are coeval with, and locally hosted within the intermediate-age Black Mountain granite. With the exception of early peraluminous granites, the intermediate and late tonalite and granites exhibit arc-like geochemistry with hydrous mineral assemblages. However, little to no evidence is observed for magmatic hydrothermal fluids associated with the intrusions. Scarcity of hydrothermal alteration of intermediate-age small dikes or stocks may have been coeval with the formation of veins, but they are unlikely to have contributed significant fluids.

Previous studies of Al-in-hornblende barometry from granitoids and fluid inclusions have placed inferred depths of vein formation and gold mineralization at ~5-9 km (Dilworth, 2003) for the Goodpaster district, consistent with published depths of mesozonal orogenic Au veins (e.g. Goldfarb and Pitcairn, 2022 and references therein). New observations of vein textures suggest at least four generations of Au mineralization in highly brecciated, largely brittle, cyclical depositional events. Recognition of Au-bearing calcite and associated bladed carbonate with coeval liquid-vapor and vapor rich fluid inclusions in quartz across the Pogo and Tibbs Creek occurrences suggest boiling occurred locally in the mineralized zones. Geochronology of the bladed carbonate indicates this boiling event occurred in the mid-Cretaceous, likely around ~105 Ma. Brittle vein and structural features combined with boiling textures suggest a relatively shallow (< ca. 2 km) paleodepth for the formation of the veins. Scarce evidence for magmatic-hydrothermal fluids, and the presence of shallow (< ~2 km paleodepth) boiling textures imply a new genetic model may be warranted for the formation of the Pogo deposit.

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# Timing and emplacement depth of Mesozoic to Paleocene intrusions in southeastern British Columbia

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The Purcell and Selkirk Mountains of southeastern British Columbia form part of the hinterland to the Canadian Cordillera and host Mesozoic and Cenozoic igneous rocks emplaced during mountain building in the Mesozoic. While Mesozoic orogenesis is well constrained, the timing and extent of exhumation following this orogenesis remains undetermined in many parts of the region. This study elucidates this exhumation history by examining the emplacement depth, timing of emplacement, and cooling history of major intrusive igneous rocks within the Purcell and Selkirk mountains. Fifteen new U-Pb LA-ICP-MS ages will be presented as part of a map combining these new data with existing geochronology datasets on igneous intrusions within the region. An unexpected result of this analysis is that the Fry Creek batholith, commonly assumed to be part of the mid-Cretaceous Bayonne suite, intruded during the Paleocene (~60-65 Ma) and thus forms part of newly identified suite of intrusions of a similar age.

Emplacement depths for the analyzed intrusions were obtained by comparing observed mineral assemblages in the contact aureoles around these intrusions with phase equilibrium models. There is a systematic difference in mineral assemblage sequences from aureoles formed at higher pressures (3.5-4.5 kbar, 12-15km depth) which exhibit St-And bearing sequences, and those from lower pressure (2.5-3.5 kbar, 9-12 km depth) which exhibit Crd-And bearing sequences. Jurassic intrusions from the mapped area were found to have been emplaced over a range of 9-15km (Crd-And, St-And), while Cretaceous and Paleocene intrusions were predominately emplaced between 9 and 12 km (Crd-And). Together, the age of the intrusions and their depth of emplacement serve as foundational 'pins' for ongoing low to mid-temperature thermochronology work in the Purcell and Selkirk Mountains.

# Detrital magnetite as a provenance tool in Alaska's geologic and metallogenic terranes

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Understanding links between Alaska's geologic and metallogenic framework is challenged by poor rock exposure and remote field sites, motivating development of detrital mineral tools for inferring the distribution of lithotectonic units and possible associated resources. Magnetite (Mt) occurs in a variety of (non-) mineralized rock types, exhibits unique geochemical "fingerprints", and is amenable to (U-Th)/He (He) dating. Here, we test combined detrital Mt (DMt) geochemistry and He dating as a provenance tool in Alaska's Yukon-Tanana Upland. We present DMt minor and trace element geochemistry measured by electron probe microanalyzer (EPMA) from stream sediments (N=9 samples, n=684 grains) that drain the Taurus porphyry Cu-Mo(-Au) deposit and environs, textural and inclusion count data, and EPMA analyses from local hydrothermal porphyry-related (HTP) and catchment bedrock sources (N=20, n=164). Principal component (PC) analysis and Gaussian mixture modeling (GMM) of DMt EPMA data resolves ten geochemical populations across our dataset, with any given population comprising 0% to 57% of an individual sample. To interpret DMt provenance, we compare PC-projected mean geochemical compositions of known bedrock and HTP Mt sources to those independently constrained by GMM. For DMt populations not represented in our bedrock and HTP dataset, we utilize a combination of Mg-in-Mt thermometry, published geochemical discriminant plots, and DMt inclusion assemblages to infer provenance. Resolved DMt populations are ultimately compatible with derivation from felsic to intermediate igneous, metamorphic, and HTP sources.

Three DMt provenance patterns highlight broad applicability of our proposed technique. First, HTP Mt comprises  $\sim \geq 30\%$  of DMt adjacent to mineralized rocks but is present (2-6%) several km downstream of presently known sources. Second, we identify HTP Mt where prior bulk stream sediment geochemistry and indicator mineral studies suggest possible unrecognized Taurus-style alteration. Third, we find that local parautochthonous and allochthonous units are distinguishable by Mt geochemistry, and that the distribution of DMt derived from each mirrors geologic map patterns. Helium dating of Mt isolated from geochemical populations is ongoing and will provide constraints on the age and(or) thermal history of DMt populations. Our results suggest DMt is a promising tool in aiding geologic and metallogenic framework studies in Alaska and potentially other regions.

# **A metamorphic record of the terminal accretion of the Insular terranes within southwest Yukon**

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A wealth of information regarding the complex Mesozoic evolution of the North American Cordillera is held within a series of inverted Jura-Cretaceous basins that occur at the interface between the pericratonic Intermontane terranes and the Insular terranes that originated in the Arctic realm in Paleozoic time. The Kluane Basin represents such a basin, being sutured between the Yukon Tanana terrane (Intermontane) and Alexander and Wrangellia terranes (Insular), within the southwest Yukon. The Kluane Schist is the primary assemblage of the Kluane Basin, which consists of variably metamorphosed and deformed low-Al pelites that were intruded by granodioritic plutons of the Paleocene-Eocene Ruby Range batholith. We propose the Kluane Schist represents a single lithological package which experienced two distinct phases of deformation: 1) an early greenschist-facies phase that resulted in the development of a bedding-parallel chlorite–muscovite–titanite fabric, and 2) a later amphibolite-facies phase that represents the progressive transposition of the earlier chlorite–muscovite fabric into a penetrative biotite-rich schistosity that transitions structurally upward into a biotite–cordierite and plagioclase–quartz (+/- sillimanite–K-feldspar–melt) gneissic fabric. The Kluane Schist can also be divided into seven distinct petrologic zones that preserve the evolution from initial flattening fabrics to non-coaxial, tops-to-the WSW shear structures during progressive regional metamorphism.

By integrating our structural and petrographic analysis with the results of phase equilibria modelling and thermobarometry we demonstrate that the metamorphic character of Kluane Schist reflects an inverted field gradient from 3.0–3.5 kbar at 375–400 °C to 4–4.5 kbar at 700 °C. Monazite petrochronology tracks the progressive development of this inverted sequence between ca. 71–55 Ma. The preservation of a single Buchan-style field gradient and tops-to-the WSW non-coaxial shear structures are consistent with the override of the Kluane Basin from the northeast by the thermally mature Yukon-Tanana terrane, which represented part of the northwestern North American plate margin at this time. These findings have implications for currently contested models of Mesozoic Cordilleran orogenesis; we suggest that Insular terrane accretion was primarily driven by east-dipping subduction that resulted in the west-directed override of the North American continent rather than slab pull from an outboard, west-dipping subduction zone.

# Ultramafic-associated massive sulfides in the Index Formation of the Kootenay arc, southeast British Columbia: genetically upside-down?

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In 1977 black smokers were discovered astride the Galapagos mid-ocean ridge, ending speculation about the genesis of fossilized seafloor volcanogenic massive sulfide deposits (VMS). By the mid 1990's deep-sea exploration extended beyond the ridges to where a new type of VMS was discovered. These were forming on or near mantle exhumed by detachment faults. Like the underlying mantle, these ultramafic associated massive sulfide deposits (UAMS) are enriched in Co-Ni and Au in addition to Cu-Zn-Ag of axial ridge-type VMS. Size, tonnage, and grade estimates for modern UAMS and hybrid-type mounds range up to 20 m x 2700 m x 1600 m, ~40 million tonnes (Semenov, the largest known hybrid), with average grades (n = 97) of 10.5% Cu, 17.6% Zn, 87.7 g/t Ag, 3.5 g/t Au, 1975 g/t Co and 163 g/t Ni, reported for Ashadze UAMS (Cherkashev et al., 2013, Oceanology). Precious and critical metal enrichments in UAMS and their tendency to form chains of mounds make them especially attractive exploration targets.

Fossilized distal versions of UAMS might be found within the Index Formation (Lardeau Group) strata of southeastern BC, within a previously unrecognized belt containing talc-carbonate, iron-carbonate, and chrome-mica schist. The belt has been traced intermittently for 15 km, although the ultramafic-massive sulphide association extends for at least 150 km through the Kootenay arc, to north of the past-producing Goldstream deposit. To better understand the stratigraphy, and in particular the provenance of this horizon, we sampled multiple units for detrital zircon U-Pb analysis. Maximum depositional ages that are younger than the previously accepted age of the Index Formation rekindle the upside-down Index controversy of the early 1990s. The possibility of an upside-down Index Formation containing lenses of mantle has implications for tectonic evolution of the Canadian Cordillera, but also simplifies its genesis in many ways.

## **Differentiating and characterizing tectonic/metamorphic assemblages in the Yukon Tanana Upland**

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The Alaska Division of Geological & Geophysical Surveys (DGGS) intends to produce  $\geq 1:100,000$ -scale geologic maps of the entire Yukon Tanana Upland. The current field campaign has been ongoing since 2017. The Yukon Tanana Upland is composed of rocks of the Yukon-Tanana terrane (YTT) and the parautochthonous North American margin (pNA). These terranes can be further subdivided into tectonic assemblages, each consisting of components with shared age ranges, depositional settings, and tectonic histories. Multiple tectonic assemblages and subunits in eastern Alaska and adjacent parts of Yukon reached amphibolite-facies metamorphic conditions, including the Fortymile River assemblage, Snowcap assemblage, Finlayson assemblage, and Ladue River assemblage in the YTT as well as the Lake George assemblage and Australia Mountain domain in pNA. These units are intensely deformed and often preserve multiple observable deformation fabrics. The YTT is generally accepted to share a pre-Late Devonian basement and sedimentary history with the continental margin prior to rifting and initiation of arc volcanism in the Early Mississippian. Assemblages in both terranes include a mixture of metasedimentary and metaplutonic layers with similar chemistries and overlapping Devonian-Mississippian protolith ages. It is therefore difficult to map the various assemblages and terrane bounding structures, which is compounded by poor exposure in eastern Alaska. The tectonic assemblages have often been differentiated based on differing exhumation histories as recorded by  $^{40}\text{Ar}/^{39}\text{Ar}$  cooling ages. We continue to use  $^{40}\text{Ar}/^{39}\text{Ar}$  thermochronology to assist our mapping efforts in eastern Alaska.

In addition to thermochronology, DGGS has started to systematically collect electron microprobe geochemical data for plagioclase feldspar and amphibole from metamafic samples. We find that percent anorthite in plagioclase (Ca content) varies by terrane. Klondike assemblage (YTT) samples from Alaska only contain albite (<10% anorthite), which is consistent with greenschist-facies metamorphism. Plagioclase samples from the amphibolite-facies Fortymile River assemblage and Ladue River assemblage (formerly Ladue River unit) in the YTT never contain more than 35% and 25% anorthite, respectively. In contrast, the Lake George assemblage (pNA) contains plagioclase with a much wider range of Ca up to >90% anorthite. Every Lake George sample analyzed includes at least one measured

plagioclase crystal with over 35% anorthite. Low-Ca plagioclase occurs in the cores of grains and high-Ca plagioclase is often observed on grain margins. We also find that amphibole compositions vary with only minimal overlap between the Lake George assemblage and the amphibolite-facies YTT assemblages. We plan to continue to use electron microprobe data to differentiate pNA and YTT assemblages where thermochronology data is limited or cost-prohibitive to generate.

The Chicken assemblage (formerly Chicken Metamorphic Complex) is mapped in the Taylor Mountain area near Chicken, Alaska, and is considered part of the YTT. The Chicken assemblage is dominated by fine to coarse-grained mafic to intermediate metaigneous rocks with arc geochemistry and minor metasedimentary rocks including fine-grained quartzite, meta-arkosic sandstone, and locally thick but discontinuous marble layers. These rocks have been metamorphosed to greenschist-facies, primary igneous textures are commonly observed in hand sample, and the rocks are generally weakly deformed, in contrast to the moderately to strongly foliated metamorphic units in other Yukon-Tanana Terrane assemblages. Electron microprobe data from plagioclase reveals three generations of feldspars in Chicken assemblage gabbros. High-anorthite plagioclase measured in over half of the samples, often found in the core of crystals, are interpreted as relicts of primary igneous feldspars. Low-anorthite albites were

measured in all but one sample and are interpreted as greenschist-facies metamorphic feldspars. Crystal rims with moderate-anorthite percentage were measured in 6 of 7 samples and are interpreted as recording hornblende-hornfels contact metamorphism. Contact metamorphism is also suggested by amphibole compositions measured on the microprobe, which often include both igneous and metamorphic hornblende in addition to greenschist-facies actinolite, with multiple amphibole compositions recorded in most samples. The most likely cause of widespread contact metamorphism in the Chicken assemblage in the Taylor Mountain area is the Late Triassic Taylor Mountain Batholith and nearby coeval intrusions.

We assign the Chicken assemblage a Mississippian age based on metagabbro samples that yield U-Pb zircon ages between 339 and 347 Ma and an interlayered quartzite that yielded a detrital zircon maximum depositional age of 355 Ma. The detrital zircon sample also yielded Precambrian grains indicating sediment recycling from either the Fortymile River assemblage or the Laurentian margin. The Chicken assemblage has previously been correlated with the Seventymile assemblage of the Slide Mountain terrane, but the Chicken assemblage lacks ultramafic rocks characteristic of the Slide Mountain terrane and the mafic volcanics have arc geochemistry in contrast to the MORB geochemistry of the Seventymile assemblage. The Chicken assemblage may be correlative with the Little Salmon formation, part of the Klinkit assemblage in Yukon. A cross-cutting dike in the Eagle A-2 Quadrangle yielded a hornblende  $^{40}\text{Ar}/^{39}\text{Ar}$  age of ~305 Ma and hornblende  $^{40}\text{Ar}/^{39}\text{Ar}$  ages in Chicken assemblage greenstones range from 201-213 Ma, likely recording contact metamorphism during intrusion of the Late

## Triassic Taylor Mountain Batholith.

The lack of penetrative deformation fabrics, the greenschist-facies metamorphic conditions, and evidence of hornblende hornfels-grade contact metamorphism around the Taylor Mountain Batholith suggests that the Chicken assemblage occupied a much higher structural position prior to the Late Triassic than the currently exposed Fortymile River assemblage to the north. We suggest that a relatively high-angle fault separates the Fortymile River and Chicken assemblages in the vicinity of Gold Creek and the lower Mosquito Fork of the Fortymile River. Jurassic  $^{40}\text{Ar}/^{39}\text{Ar}$  cooling ages in the Fortymile River assemblage suggest that this fault may have been active during the Early Jurassic and the presence of Jurassic plutons with similar chemistry and texture in both the Fortymile River and Chicken assemblages suggests that they may have been at similar structural levels by the Middle Jurassic.

The Ladue River assemblage in the eastern Tanacross Quadrangle includes Devonian to Mississippian as well as Permian metaplutonic rocks, is polydeformed, and reached amphibolite-facies metamorphic conditions, which previously led to correlation with the Fortymile River assemblage. The Ladue River assemblage lacks the Triassic and Jurassic plutons that intrude the Fortymile River assemblage and has distinctly older Triassic to Permian  $^{40}\text{Ar}/^{39}\text{Ar}$  cooling ages compared to Jurassic cooling ages throughout the Fortymile River/Finlayson/Snowcap assemblages. These differences suggest that while the Ladue River assemblage and the Fortymile River assemblage may have been related prior to the Late Permian, the Ladue River assemblage has a distinct tectonic history since at least the Triassic.

# **A Late Paleocene - Early Eocene terrestrial Large Igneous Province in northwest North America and its relationship to tectonics and climate**

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In the Cordilleran orogen of northwest North America, Late Paleocene through Early Eocene (~58 to 47 Ma) volcanic complexes are preserved as isolated remnants over ~2500 km, from southern Yukon, Canada, to Wyoming, USA. Similar age intrusions make up significant components of the Ruby Range, Coast plutonic complex, Coryell intrusive suite, Idaho batholith, Great Plains magmatic province, and other local intrusive complexes. Orogen-parallel, crustal-scale dextral strike-slip faulting and exhumation of high-grade metamorphic core complexes coincided with the magmatism. This study demonstrates this magmatic/orogenic event constitutes a Large Igneous Province (LIP).

The volcanic rocks are sub-areal, intermediate flows and ignimbrites, most consistent with fissure eruptions in localized graben environments. Radiogenic isotopic data (Nd, Sr) indicate the volcanic rocks inherited their signatures from the basement terrane upon which they erupted. Interrogation of available geochronological data indicates rapid onset and offset of the magmatic/orogenic event, beginning in the north (Yukon; ca. 58 Ma) and sweeping in time and space to the south (northwest US; ca. 47 Ma). The above is considered within a paleogeographic reconstruction, re-positioning the volcanic complexes to the geographic location of eruption, allowing new evaluations of the tectonic cause of the magmatic/orogenic event.

The consequences of this study are many: 1) short-lived yet voluminous magmatism now preserved over 2500 km and representing a terrestrial LIP of intermediate composition. 2) The radiogenic isotopic composition of the volcanic rocks help identify underlying terranes and assist in mapping their extent. 3) Eocene lithosphere-dominated melting transitioned to Oligocene/Miocene asthenosphere-dominated, indicating either lithosphere delamination, or the basement terranes transited and overrode different mantle domains between those times. 4) The magmatic/orogenic event may have resulted from plate-scale changes that no longer supported crust that was overthickened by collisions since Jurassic time. 5) The onset of magmatism immediately pre-dates the Paleocene-Eocene thermal maximum, and perfectly paces the Early Eocene climatic optimum; potential connections will be evaluated.

## **Cenozoic exhumation in the Upper Hyland valley, southeastern Yukon: New insights from low-temperature thermochronology**

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The Upper Hyland fault (UHF) is one of many faults in the Northern Canadian Cordillera that strike subparallel to the Tintina fault. This lithospheric-scale structure strikes over 1,200 km N-NW and accommodated at least 430 km of mostly-Eocene dextral displacement. The UHF is ~130 km east of the Tintina fault in the Upper Hyland valley within the Selwyn Fold Belt, ~150 km north of Watson Lake, YK. The Selwyn Fold Belt is dominated by Neoproterozoic–Devonian platform-to-basinal carbonate and clastic rocks deposited on the ancestral Laurentian margin that were subsequently deformed during Cordilleran orogenesis. Offset of mid-Cretaceous plutons that intruded into the Selwyn Fold Belt suggest that the UHF may have accommodated ~75 km of dextral displacement. Key questions motivating this research include: (i) how much Cenozoic exhumation has occurred in the Upper Hyland valley; (ii) does the amount of exhumation vary spatially and, if so, can it be linked to faults in the area; and (iii) how does the timing and style of faulting in the Upper Hyland valley compare with other major structures in the region such as the Tintina fault?

Here we present low-temperature thermochronological data and thermal modeling to quantify the timing and magnitude of exhumation in the Upper Hyland valley, and investigate the relationship between exhumation and faulting. We applied apatite (U-Th)/He, apatite fission track, and zircon (U-Th)/He thermochronometers (AHe, AFT, and ZHe, respectively). We dated 26 samples and present 24 new mean AHe ages from 117 single-grain dates, 10 new AFT ages, and 15 new mean ZHe ages from 45 single-grain dates. Contrasting trends in our AHe ages between the east and west sides of the UHF suggest differential cooling across the fault. East of the UHF, AHe ages increase towards the north. In contrast, west of the UHF, AHe ages decrease towards the north. These younger AHe (44–38 Ma) and AFT (45 Ma) ages come from samples just west of the Shannon fault, a NW-striking splay west of the UHF. In contrast, one sample directly east of both the Shannon fault and the UHF yields a much older AHe age (75 Ma). We also observe that, unlike the AHe ages, ZHe ages young towards the north on both sides of the UHF.

Our thermal modeling results also suggest differential cooling rates across the UHF and the Hyland Valley fault, a NE-SW striking fault west of the UHF. Just west of the Hyland Valley fault, samples

did not experience rapid cooling through  $\sim 180\text{--}40$  °C during the Cenozoic. East of the fault, a sample shows a rapid cooling pulse ( $\sim 15$  °C/Myr) at  $\sim 55$  Ma through  $\sim 120\text{--}70$  °C followed by protracted cooling ( $< 2$  °C/Myr) to present. The contrasting cooling patterns across the fault may suggest vertical displacement along this portion of the Hyland Valley fault. Samples just west of the Shannon fault show rapid cooling ( $\sim 13$  °C/Myr)  $\sim 60\text{--}50$  Ma through  $\sim 180\text{--}40$  °C.

Taken together, our preliminary analysis of the new thermochronology data suggests that cooling in the Upper Hyland valley was coeval with dextral motion along the Tintina fault and early-to-middle Eocene transtension in the Yukon-Tanana Uplands.

## Problems with Barrovian metamorphism

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Barrovian metamorphism is the classic type of regional crustal metamorphism in collisional mountain belts away from subduction zones. One would think that the pressure(depth)-temperature conditions of Barrovian metamorphism are well established. One would be mistaken in thinking so. The issue turns on interpreting the formation of mineral assemblages containing staurolite(St) and kyanite(Ky), the classic Barrovian indicator association. If thermodynamically-calculated equilibrium assemblage diagrams are interpreted literally, St+Ky-bearing mineral assemblages in the dozens of Barrovian settings worldwide – from Barrow’s zones in Scotland to the Himalaya – must have developed in a restrictive, high-pressure window greater than ~6.5 kbar and ~650 °C. Conversely, the large (in terms of pressure) predicted range for St+sillimanite(Sil) sequences (~4 to 6.5 kbar), in which neither kyanite nor andalusite is developed in the sequence, is represented by very few settings worldwide. Exacerbating this conundrum is the prediction that, for all but unusually aluminous bulk compositions, the incoming of kyanite is due to the consumption of staurolite, whereas in very few natural samples do textures suggest this relationship; rather, the two minerals most commonly appear to have developed independently at about the same time. In the absence of anything obviously wrong with the experiments on which the thermodynamic modelling is based, kinetic explanations need to be entertained.

## The Dawn of Denali? Enigmatic titanite U-Pb ages in Denali Fault zone mylonites

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Little is known about the absolute age of Denali fault zone inception and its relationship to the earliest accretionary tectonics of the Northern Cordillera orogen (NCO). Rare bedrock exposures of the NW-SE-striking eastern Denali fault zone (EDFZ) in the Kluane Ranges of SW Yukon, Canada, show the juxtaposition of Wrangellian, Permian to Mississippian Hasen Creek metapelites with late Triassic Bear Creek overlap assemblage metavolcanics.

Strain localization in the metapelites SW of the juxtaposition is manifest as ultramylonite overprinted by a 30 to 60-meter-wide principal slip zone composed of clay-rich carbonaceous (CM) cataclasite. The ultramylonite is strongly foliated and tightly folded with fold axes parallel to fault strike, consistent with a component of subhorizontal NE-directed shortening. The ultramylonite contains Ab, Qz, Ms, Chl, Ep, Cal, Ttn, Ap, and CM. Ttn grains are anhedral and blocky, but a few are rounded with disaggregated stringers aligned with foliation consistent with a dextral slip component. Chl, Ep, and Cal form a retrograde assemblage and the Ttn is internally altered showing complex textural diversity. Electron backscatter diffraction (EBSD) on representative ultramylonite samples indicates intracrystalline plastic deformation in Pl, Qz, and Ttn also consistent with fault-parallel dextral slip. Raman spectroscopy of CM indicates the ultramylonite reached a maximum temperature of ~400°C, consistent with EBSD results. LA-ICP-MS U-Pb analyses of ~150 Ttn grains suggest mineral growth at 148.2 ± 4.4 Ma based on the lower intercept of a closed-system mixing line of common and radiogenic Pb. Ttn from this sample is characterized by low U concentration (0.2-118 ppm, with an average of 7 ppm) and relatively high, but variable, common Pb. Major element signatures of the titanite measured by microprobe are consistent with a metamorphic or hydrothermal origin.

This Late Jurassic age is significant as it is younger than the Permian Hasen Creek metapelites, but older than the earliest fault movement indicated by cooling dates adjacent to the EDFZ (~95 Ma). Our results are the only absolute ages from principal slip zone ultramylonites along the EDFZ thus far. Although there is >400 km of dextral separation documented along the EDFZ at this site, the enigmatic ages and map relations suggest that the ultramylonite may be part of a

“xenolithic”, but not far-travelled fault sliver. If true, and the Ttn formed in a dynamothermal setting, these rocks may record the dawn of the highly localized proto-Denali fault zone perhaps associated with accretion of the Insular superterrane to Laurentia.

# Initial assessment of detrital zircon (U-Th)/He thermochronology data from the southwestern Northwest Territories

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The Western Canada Sedimentary Basin (WCSB) covers an extensive portion of western Canada, including Alberta, Saskatchewan, and Northwest Territories (NWT). It overlies Precambrian basement rocks and comprises Cambrian to Jurassic passive margin strata that are overlain by Jurassic to Cenozoic strata of the Cordilleran foreland basin. The sedimentary strata in the west were folded and thrust during Cordilleran fold-and thrust belt evolution. The southwestern part of the NWT, comprising the Liard Basin and Great Slave Plain (herein referred to as the Liard Area), is distinguished today by a geothermal anomaly and a change in the strike of the Cordilleran Deformation Front. These features may be linked to the tectonic history of the region. To understand this history, we use zircon (U-Th)/He (ZHe) thermochronology. The ZHe method records cooling between 160–200°C, which can be linked to tectonic and surface processes that affect the upper crust. This method is therefore ideal to unravel the erosional and exhumational history of the region.

We dated 29 samples comprising basement (3 samples) and sedimentary clastic rocks of the WCSB (26 samples). For each sample, we aimed to date five zircon grains. In the eastern part of the study area (Great Slave Lake), near the margin of the basin's subcrop and the sedimentary basin fill is thinnest, we collected sample pairs from basement and Cambrian strata from outcrops and boreholes. In the western part (Liard Basin), we collected outcrop samples from the eastern Cordilleran fold-thrust belt, and borehole samples from the undeformed portion of the basin. The depositional ages of the samples are Cambrian, Devonian, Carboniferous, Triassic and Cretaceous.

Preliminary results show that the maximum post-depositional temperatures experienced by strata in the east (Great Slave Lake) were lower than in the west (Liard Basin). This pattern is observed in borehole data, where Cambrian sedimentary rocks from the east have wide intrasample date variation (535–1856 Ma) and are older than depositional age (not reset). However, Carboniferous borehole samples in the west yield dates that are older and younger than the depositional age (partially reset) and exhibit less date variation (336–1116 Ma). The date variation suggests the Carboniferous samples underwent more reheating than the Cambrian, which is expected due to deeper burial in the west. The reheating can be also observed in the Devonian borehole sample

located close to one Carboniferous borehole sample, with most of the single-grains dates being younger than the depositional age (80–524 Ma) (reset).

Within the Cordilleran fold-thrust belt, outcrop samples are also partially reset and generally younger than borehole samples located east of the deformation front. An exception to this pattern are the Triassic samples that are fully reset (67–166 Ma). This suggests that those rocks experienced higher temperatures, which are likely linked to tectonic subsidence caused by lithospheric flexure during foreland basin evolution and tectonic burial due to eastward thrusting. The timing and mechanism that caused cooling in our samples will be investigated involving thermal history modeling and integration of apatite thermochronology data.

# **Sediment Provenance using detrital zircons and Nd-Sr isotopes: Implications for sediment routing in the Neoproterozoic Windermere Supergroup, southern Canadian Cordillera**

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Events surrounding the origin of the passive margin forming the western edge of Laurentia (ancestral North America) are an important constraint on the breakup of the Rodinia supercontinent and set the stage for the Phanerozoic evolution of western Laurentia. One of the prime areas to study this history is the 7–9 km-thick Neoproterozoic Windermere Supergroup (WSG) in the southern Canadian Cordillera. At the Castle Creek study area (CC) in east-central British Columbia a continuous succession of sheetlike, sandstone-rich basin-floor deposits of the upper Kaza Group (UKG) conformably overlain by continental slope deposits comprising 7 informal channel complexes (ICC0-ICC6) of the Isaac Formation were sampled ~ 10 m stratigraphically upward over the 2000 m-thick section. Geochemical data derived from these mudrock samples were combined with detrital zircon data from sandstones to provide a highly resolved understanding of temporal changes in sediment provenance and sediment supply during development of the continent-margin Neoproterozoic Windermere turbidite system in the southern Canadian Cordillera. Based on their geochemical characteristics strata in the study are subdivided into four compositionally unique groups: Assemblage 1, comprising UKG up to ICC1, Assemblage 2, comprising ICC3, ICC4 and ICC5, and Assemblage 3, comprising ICC6 and all strata above to the base of the Cunningham Formation.

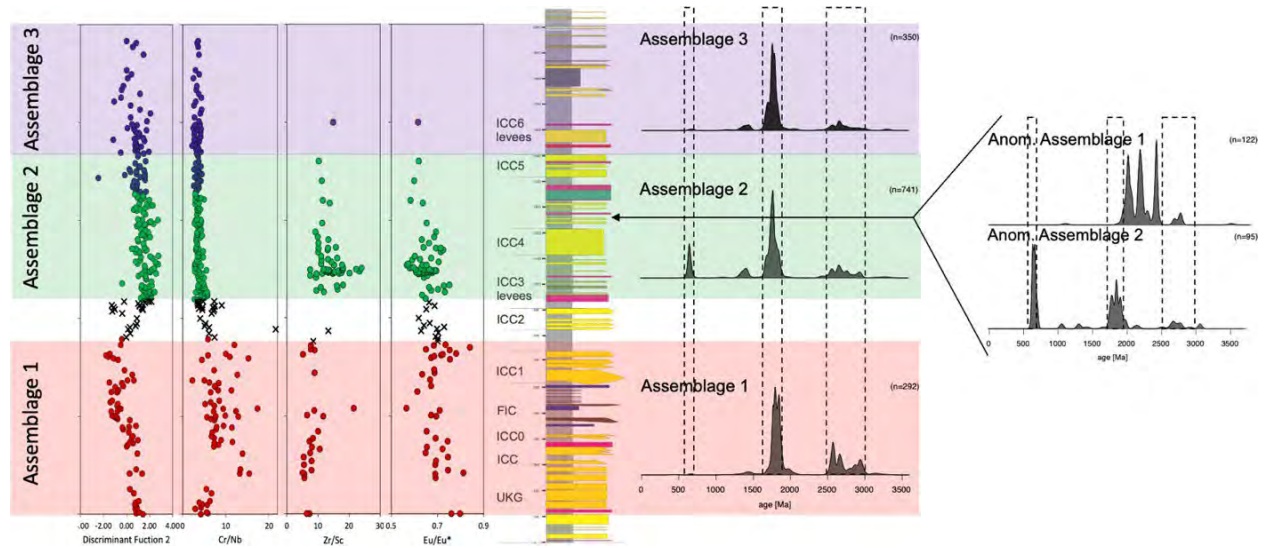
Detrital zircon ages in Assemblage 1 have a characteristic northwestern Laurentia bimodal distribution with major populations between 3.0 to 2.5 Ga and 1.9-1.75 Ga, and an absence of grains between 2.5 and 2.0 Ga (Fig. 1). This zircon age distribution, in addition to  $\epsilon_{\text{Nd}}(600 \text{ Ma})$  values that range from -19.1 to -17.6, are consistent with derivation from nearby Precambrian basement domains in the subsurface of western Canada, specifically the Rimbey domain and adjacent domains in the southern Hearne province. Geochemical data from Assemblage 1 suggest a mafic component in some of the strata, specifically: a flatter REE pattern ( $\text{La}/\text{Yb}_\text{N} = 25.3$ ), a low  $\text{Zr}/\text{Sc}$  ratio, and smaller negative Eu anomaly that is higher than in standard UCC ( $\text{Eu}/\text{Eu}^* = 0.7$  versus 0.64 – the latter being the UCC). Additionally, Assemblage 1 has a higher  $\text{Cr}/\text{Th}$  ratio ( $\text{Cr}/\text{Th} = 7.5$ ) and lower  $^{87}\text{Sr}/^{86}\text{Sr}(0)$  values (0.7320 to 0.7582) compared to other assemblages. Two potential sources for the additional intermediate-mafic source include the Wopmay Orogen, specifically the Fort Simpson,

Hottah, Great Bear terranes (Fig. 2 – Scenario A) and Archean mafic and ultramafic suites in the central Hearne province supracrustal belt of northern Saskatchewan, Manitoba and Nunavut (Fig. 2 – Scenario B). Problematic with Scenario A is the absence of 2.4-2.0 Ga detrital zircons from the area between the CC study area and the Wopmay Orogen magmatic belts (i.e. Kiskatinaw, Ksituan, Chinchaga, and Buffalo Head terranes), whereas Scenario B is more consistent with the general east-to-west sediment dispersal pattern during the Neoproterozoic (Hadlari et al., 2021; Matthews et al., 2017; Saylor and Sundell, 2021).

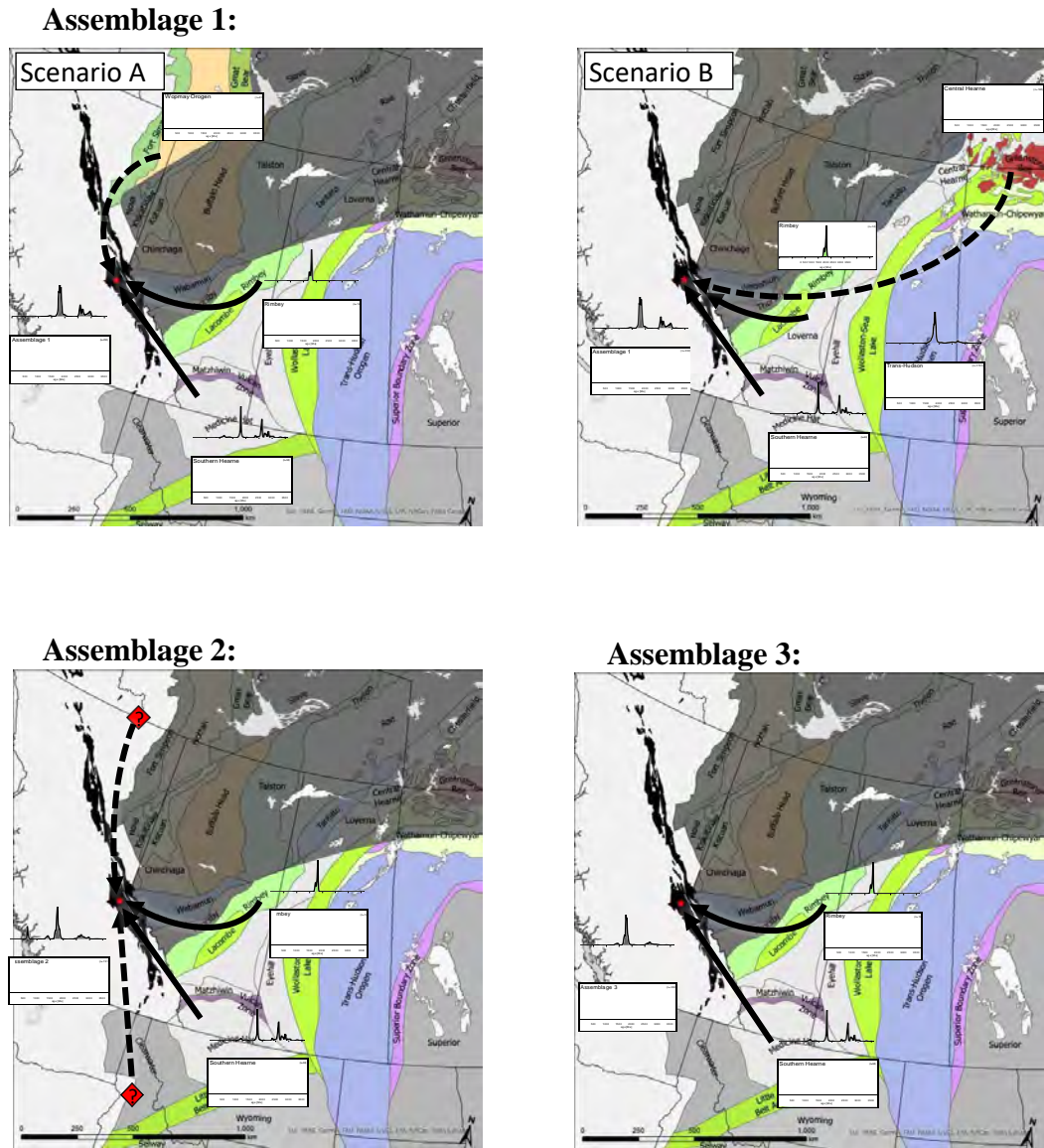
Detrital zircon ages in Assemblage 2 are consistent with a northwestern Laurentia provenance, but rather than being bimodal are trimodal. This includes major populations between 3.0 to 2.5 Ga, 1.9-1.8 Ga, and a third at 655 Ma (Fig. 1). The resulting detrital signature reflects mixing of two distinct sources. Like Assemblage 1, the Mesoproterozoic and Archean detrital zircon signatures are attributed to the southern Hearne and associated Rimbey domain. The source of the ca. 655 Ma age peak, however, is more uncertain. Assemblage 2 exhibits a range of  $\epsilon\text{Nd}(600 \text{ Ma})$  values from -16.5 to -9.9, which is broader than in Assemblage 1 and significantly lower than lithostratigraphically similar strata in the Horsethief Creek and Miette groups (-22.0 to -20.3; Boghossian et al., 1996). This would suggest input from a more juvenile source, which is consistent with the prominent 655 Ma detrital zircon age population. On the provenance discrimination diagram (Fig. 1), most of these samples plot in fields for felsic igneous and quartzose sedimentary provenance based on their relatively low MgO, Fe<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> content. Furthermore, trace element ratios, such as high Th/Sc (0.68-1.85) and Zr/Sc (7.4-24), and low concentrations of Cr and Ni, suggest a mostly continental source. REE patterns are similar to PAAS with LREE enrichment and negative Eu anomalies ranging from 0.57 to 0.74 (average = 0.68). These geochemical data, in addition to the 655 Ma detrital zircon age population and the more positive Nd isotopic ratios, are suggestive of a highly recycled continental source, but with a significant Neoproterozoic igneous rift-related source for Assemblage 2. Currently the only known occurrence of igneous rocks crystallized between ~ 660-640 Ma are a suite of 665-651 Ma alkalic felsic plutons in central Idaho (Lund et al., 2009), and the 650-640 Ma Pool Creek syenite in the Yukon Territory (Pigage and Mortensen, 2004). If detrital zircons were sourced from the Pool Creek syenite to the north, the absence of 2.4-2.0 Ga zircons and lack of north to south paleocurrent indicators is problematic (Fig. 2). More likely the 655 Ma age population was sourced from the south-east, for example from the alkalic plutonic suites in central Idaho, although the possibility of isolated intrusive units related to late-stage rifting in the SCC or even more local anorogenic magmatism cannot be ruled out.

Like Assemblage 1, detrital zircons in Assemblage 3 exhibit the characteristic bimodal age distribution, namely 3.0 to 2.5 Ga and 1.9-1.8 Ga (Fig. 1), suggesting derivation from adjacent Precambrian basement domains in the subsurface of western Canada (Fig. 2). In the provenance discrimination diagram (Fig. 1), samples from Assemblage 3 plot mostly in the

felsic igneous provenance field, but stratigraphically upward trend towards a more intermediate/mafic igneous composition reflecting the upward increase in MgO, Fe<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>. Assemblage 3 is interpreted to mark the end of the input of juvenile ca. 655 Ma sources, and a return to the characteristic bimodal detrital zircon Laurentian signature.



**Figure 1.** Summary of provenance proxies for assemblages 1, 2 and 3, showing major and trace element ratios are from left to right: a) discriminant function (calculated by normalizing major element oxides to Al<sub>2</sub>O<sub>3</sub> following Roser & Korsch (1988)); b) Cr/Nb, c) Zr/Sc, d) Eu/Eu\*. Also shown are kernel density estimation (KDE) diagrams showing compiled detrital zircon U-Pb data for each assemblage. The stratigraphic location of two anomalous age populations within assemblage 2 (anomalous assemblages 1 and 2) are displayed on the far right.



**Figure 2.** Hypothetical sediment catchment and drainage pathways based on detrital zircon signatures superimposed on sub-Paleozoic subcrop map. Darker tinted areas represent non-sourced areas; lighter areas represent the potential regional drainage basin. Black solid and dotted arrows represent most likely and less likely sediment source pathways, respectively. Red diamonds represent potential igneous sources for the 655 Ma age peak.

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## **Catalogue and physical rock properties of a 20 year Yukon-Tanana terrane legacy collection in Yukon**

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Cataloging, photography and physical property measurements of Geological Survey of Canada (GSC) legacy Yukon-Tanana terrane sample collections were completed during the 2020-2023 Covid-19 hiatus from fieldwork. Approximately 6000 samples were measured, and work has been completed to reconcile all samples with digital field records and georeferencing. The collections represent bedrock outcrops in Yukon of geological units dominantly associated with the Yukon-Tanana terrane and the parautochthonous North American margin, as well as Mesozoic to Cenozoic successor units such as the Whitehorse suite, and Carmacks group. Thus, the collection predominantly comprises tectonized, metamorphic rocks. GSC workers involved in collecting of these samples between 2000 to 2018 include Jim Ryan, Steve Gordey, Alex Zagorevski, Charlie Roots, Nathan Cleven, and Andrew Parsons. Also, fieldwork collaborators include Maurice Colpron (YGS) and Steve Piercey (MUN), and numerous students and assistants over the years. Samples were taken in support of geological mapping efforts in 2000-2003, 2008-2011, 2014-2018, and contributed to numerous academic research efforts. Most of the mapping work has been synthesized into the YGS Yukon compilation geological map.

Rock physical properties measured from samples include density and magnetic susceptibility. Magnetic susceptibility was determined with a commercial hand held unit (SM20), and density was calculated from sample masses in atmosphere and submerged in water. Results of the measurements for the provide a view into the lithological characteristics of the units involved. Henkel plots (density vs. magnetic susceptibility) allow evaluation of the effects of metamorphism, alteration and weathering relating to units' geological histories. For example, measured ultramafic rocks from throughout Yukon-Tanana terrane show characteristic high density, but low density-high magnetic susceptibility associated with alteration and serpentinization. Granitic rocks show a fairly narrow range of density, and a higher range of magnetic susceptibility. Many granitic samples record lower density than typical, which may be attributed to regional weathering history. The majority of the collection originates in a uniquely non-glaciated regions in Canada, the Beringia land bridge. We compare density of rocks from deeply weather, not glaciated regions, with rocks from glaciated areas.

## **Juicy Data — fine scale geomorphology along major Canadian Cordilleran faults from a new drone based lidar system**

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Over the last two decades, light detection and ranging (lidar) has become one of the most effective and reliable ways of obtaining high-resolution topography, especially in densely vegetated regions. This data is usually collected using crewed airborne laser scanning (ALS) systems, which can cost upwards of tens of thousands of dollars per survey. More recently, the proliferation of off-the-shelf uncrewed aerial vehicles (UAVs) equipped with cameras has led to photogrammetric techniques such as Structure from Motion (SfM) becoming a common tool for field geologists. As of yet, UAVs equipped with lidar have had limited implementation in geomorphic studies. We present results from our newly built UAV laser scanning (ULS) system with specific application towards studying fault-related surface topography. The platform, a Riegl MiniVux 1-UAV laser scanner mounted to a DJI M600 Pro drone, provides a unique, cost-effective way to collect lidar datasets. We showcase the platform's performance with surveys of crustal faults in Western Canada, including the Eastern Denali Fault, Rocky Mountain Trench and San Juan Faults — all well known geological faults with large Eocene offsets but whose present day activity is uncertain. Where possible, we make comparisons between our acquisition and pre-existing ALS and SfM datasets. The platform offers a marked increase in point density ( $\sim 40$  pts/m<sup>2</sup>) and canopy penetration over conventional ALS ( $\sim 10$ -15 pts/m<sup>2</sup>) due to lower flight altitude and slower acquisition speeds. Higher resolution topography allows fine-scale features, such as small channel offsets, glacial scouring and secondary faulting, to be better resolved. However, the platform does suffer from practical and regulatory constraints that limit the area covered in a single day to  $\sim 2$  km<sup>2</sup>. We propose several improvements that will address these limitations.

# **Sediment provenance and copper porphyry identification via non-negative matrix factorization of bivariate detrital data sets**

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Non-negative matrix factorization (NMF) has been used to reconstruct radiometric age distributions of unknown sediment sources based on analyses of derivative samples (a.k.a., basin sinks). However, NMF may be confounded when multiple sources share similar age distributions. Such non-uniqueness can be mitigated by incorporation of secondary geochemical information. We present a novel application of NMF to bivariate (two-dimensional) detrital petrochronological data sets. As a proof-of-concept, we applied bivariate NMF to synthetic sink data sets which were produced by numerical mixing known sources and were able to successfully recover the known sources. Breakpoint analysis of the factorized data sets yields an optimum factorization rank that matches the known number of source samples. Factorized mixture weights also closely correlate with known mixing weights ( $R^2 > 0.7$ ). Following this successful proof-of-concept we apply bivariate NMF to two empirical data sets: a continent-scale U-Pb and  $\epsilon\text{Hf}_T$  data set and a deposit-scale porphyry indicator mineral geochemistry data set.

The first data set includes paired U-Pb age and  $\epsilon\text{Hf}_T$  values of detrital zircons from Neoproterozoic–Triassic strata from the western margin of Laurentia. Breakpoint analysis shows that the optimum factorization rank is six sources. Those six factorized sources best match empirical samples from NE Canada, a group of sources from the Appalachian foreland, and the Mojave. Significantly, factorized sources yield  $\epsilon\text{Hf}_T$  values that discriminate between potential sources where univariate data sets are equivocal. For example, factorized sources with late Neoproterozoic–Paleozoic age modes have  $\epsilon\text{Hf}_T$  values that are more negative than those documented from the Franklinian Basin in the Canadian Arctic. Rather, they are most consistent with age and  $\epsilon\text{Hf}_T$  values from the Appalachian foreland basin or Ordovician granites from Scotland. Similarly,  $\epsilon\text{Hf}_T$  values and age modes from factorized sources with Paleoproterozoic age modes (1600–1800 Ma) point to both juvenile and evolved sources, which are most consistent with Mojave and NE Canadian sources, respectively. These results support previous hypotheses that late Paleozoic transcontinental rivers brought sediment from eastern to western Laurentia, transecting or bypassing the transcontinental arch. Bivariate NMF of these data sets coupled with statistical comparison to potential sources provides a means to quantitatively query complex data sets that are opaque to other forms of investigation.

We also apply the NMF algorithm to geochemical data from zircons from the Highland Valley Porphyry District in southern British Columbia. We analyze bivariate data sets consisting of  $Eu^*/Eu$  (i.e., Eu anomaly) and  $Dy/Yb$  data from multiple till samples on the Triassic Guichon Creek Batholith. Sampled till is both on and off the Holocene glacial ice-flow direction. Analysis successfully discriminates geochemical indicators of porphyry copper fertility and attributes high-fertility indicators to samples down ice-flow direction from known copper deposits. The success of this method suggests that it can be successfully used to assess regional detrital data sets and identify exploration targets.

# **Lithosphere of the Northern Canadian Cordillera: A synthesis from broadband seismology**

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Temporary seismic network deployments such as the Earthscope USArray-Transportable Array (TA) have drastically improved the station coverage across northwestern Canada over the last ten years, enabling application of high-resolution passive-source seismology methods (*i.e.*, seismic tomography, receiver functions and SKS splitting). This review highlights the main discoveries pertaining to the seismic velocity structure, origin and deformation of the lithosphere in the northern Canadian Cordillera (NCC), which benefited significantly from the USArray-TA seismic data in addition to other recent seismic network deployments. High-resolution seismic tomography models reveal that the lower crust in the NCC is marked by low velocity anomalies extending from the Gulf of Alaska to the Cordilleran deformation front, which is interpreted to reflect elevated temperatures that buoyantly support regional high elevations and potentially represent the seismic signature of strain transfer from the Yakutat collision zone to the Mackenzie Mountains. The Moho is relatively flat and shallow across the NCC and is underlain by a thin layer of Cordilleran mantle lithosphere. Seismic velocity models further unveiled large-scale mantle structures associated with the unexposed Mackenzie craton in the north, and the Liard Transfer Zone in the south, which appear to buttress the NCC and further focus deformation in the eastern NCC. Seismic anisotropy and tomography provide evidence that the Tintina and Denali faults penetrate into the lithospheric mantle and played a first order role in shaping the present-day NCC. We propose that future studies should aim to: 1) resolve the shape of the Cordillera-craton boundary at upper mantle depths; 2) accurately estimate the lithosphere thickness in the NCC; and 3) improve coverage in the Beaufort Sea to understand the controls on convergent tectonics in the northern NCC.

# Large Lithospheric Seismic Velocity Variations Across the Northern Canadian Cordillera Imaged by Ambient Noise Tomography.

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Global-scale seismic velocity models of the Northern Canadian Cordillera show high velocities to the east of the Cordilleran deformation front and low velocities to the west. This velocity contrast is consistent with other geophysical observables, such as regional seismological studies, that indicate a weak and thin lithosphere to the west that transitions quickly to a strong and thick craton-like lithosphere at the deformation front. We present new results using data collected by the Mackenzie Mountains EarthScope Project, which included an ~875 km-long line of 40 broadband seismographs across the Cordillera and into the craton extending from roughly Skagway, Alaska to Great Bear Lake, Northwest Territories. The 3-year overlap of this deployment with other broadband seismic stations in the region, most notably the EarthScope Transportable Array and the Yukon Northwest Seismic Network, allows for detailed 3-D Rayleigh wave ambient noise imaging of the upper lithosphere. Results show large velocity variations west of the deformation front. Notably, we image a 5%  $V_s$  low that extends from the upper crust to the asthenospheric mantle. This plume-like structure, and associated weakening, may be a primary cause for the ongoing uplift of the Mackenzie Mountains at their unusually eastward location. We also image a low velocity feature in the lower crust extending to the west of the deformation front, which may facilitate eastward crustal translation along a large-scale (~800 km) decollement system driven by the Yakutat indenter consistent with the orogenic float hypothesis of Mazzotti and Hyndman (2002). We also note strong lithosphere-scale lateral heterogeneity suggesting that 3-D effects are important in focusing deformation in the Mackenzie Mountain area.

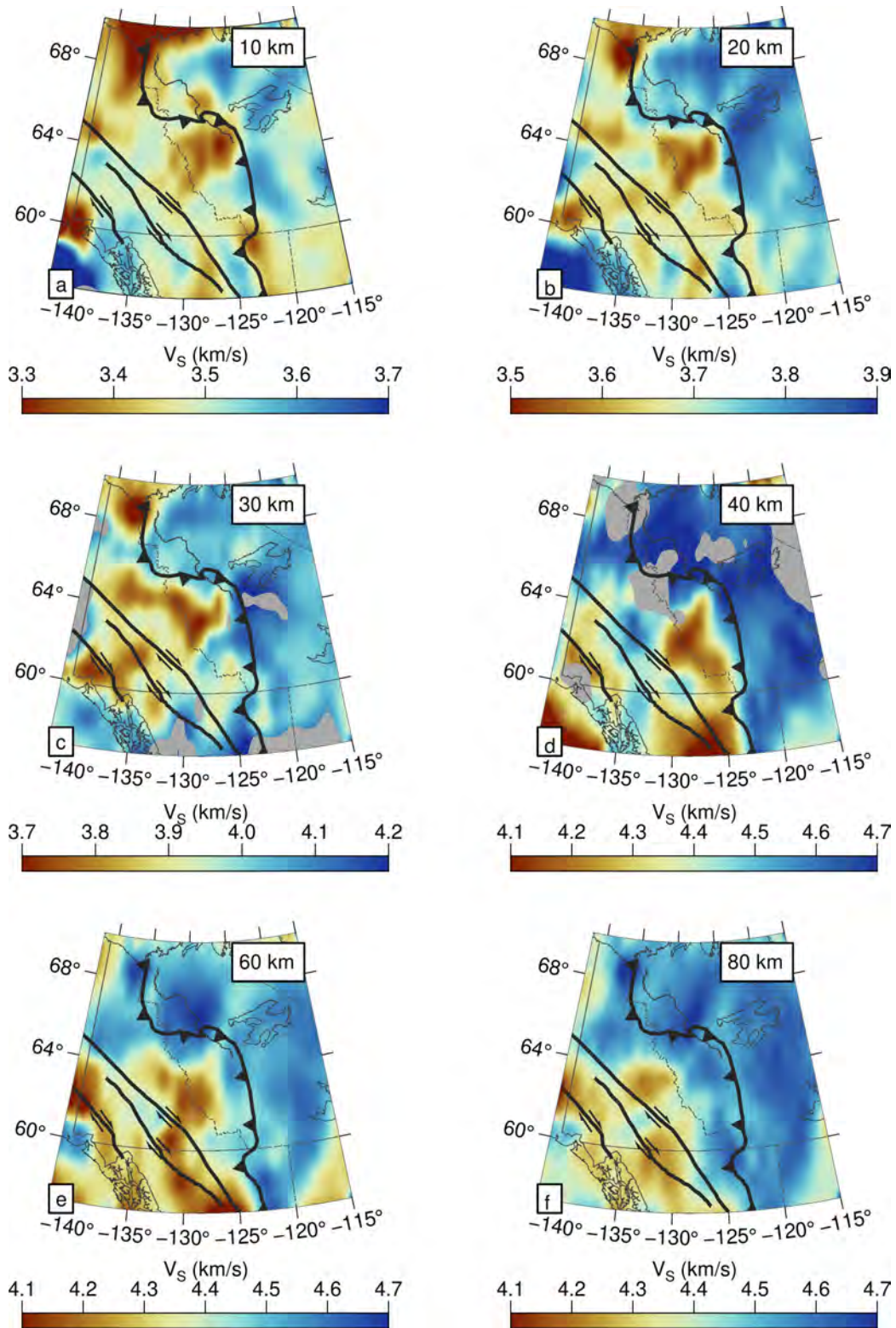


Figure: a-f) S-wave velocity under the Mackenzie Mountains and surroundings.

## **Preliminary bedrock geology of the southern Nash Creek area (parts of NTS sheet 106D), central Yukon**

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<sup>2</sup>*Archer, Cathro & Associates (1981)*

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The southern Nash Creek area is located in central Yukon, along the boundary between the Selwyn basin and Ogilvie platform. Initial bedrock mapping of the area was conducted during the 1960s at mostly 1:250,000-scale. To improve our understanding of the area's stratigraphy, structural evolution and economic potential, new bedrock mapping at 1:50,000-scale was conducted by the Yukon Geological Survey (YGS) in parts of NTS sheets 106D/2, 3, 6 & 7 during three field seasons. Surrounding rocks host carbonate-replacement Au mineralization (Tiger deposit), Carlin-type Au deposits (Nadaleen trend) and Au-Ag-Pb-Zn mineralization (McKay Hill deposit). New bedrock mapping at 1:50,000-scale was also conducted in the Rau (Tiger Au) area by ATAC Resources Ltd. in collaboration with YGS. The mapped area is mainly comprised of siliciclastic and lesser carbonate rocks of the Ediacaran–Cambrian Hyland Group, upper Cambrian mafic volcanic rocks, shale and siltstone of the Devonian–Mississippian Earn Group, and the Mississippian Keno Hill Quartzite. The Hyland Group is locally overlain by Permian limestone. Ordovician–Devonian platformal carbonate rocks and lesser mafic volcanic rocks occur in the Rau (Tiger Au) area and elsewhere north of the Dawson fault. Hyland Group strata locally host (likely Cambrian) gabbro sills, and the Earn Group and Keno Hill Quartzite host gabbro sills of the Triassic Galena suite. The mapped area contains several southeast-striking thrust faults, including the Robert Service thrust, which juxtaposes Hyland Group strata over the Keno Hill Quartzite. Hyland Group rocks are juxtaposed over Paleozoic shelf and slope rocks of the Ogilvie platform along the Dawson fault. Rocks in the map area exhibit a predominantly southeast-striking, southwest-dipping foliation that is axial planar to southeast-trending folds. Discrete occurrences of northwest-vergent shear in the southwestern part of the mapped area likely represent evidence of the Tombstone high strain zone.

## **On the Origins and Travels of Arctic Alaska**

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The composite Arctic Alaska terrane of the northernmost North American Cordillera records a complex Neoproterozoic–Cenozoic tectonic history, from disparate origins along the northern Laurentian and Baltican margins, to protracted Devonian–Cenozoic deformation and (re)accretion to the Laurentian margin. Over the past decade, researchers have made significant progress on furthering our understanding of the origins and travels of this complex composite crustal fragment, but many uncertainties remain, including fundamental questions about its role in the opening of the Arctic Ocean. Here, I will provide an overview of recent progress on our understanding of the tectonic evolution of Arctic Alaska. This includes evidence for the composite nature of the pre-Mississippian basement, new insights into the amalgamation of these disparate basement domains during protracted Devonian–Carboniferous deformation, and preliminary data that suggest Arctic Alaska did not simply rotate away from the Canadian Arctic Islands during the opening of the Canada Basin.

## **Tectonic Setting of the Seventymile and Kanuti Ophiolite complexes, Eastern Alaska**

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Fault-bounded mafic/ultramafic (M/UM) complexes preserved throughout interior Alaska are thought to represent dismembered ophiolite components and provide unique insights into terrane evolution and accretion. We present new bulk rock and mineral geochemistry, isotope ratios, and radiometric age data from the ultramafic complex of the Seventymile terrane and the Kanuti ophiolite. The Seventymile complex, which is correlated with similar lithologies from the Slide Mountain terrane in Canada, occur in thrust sheets that contain upper Permian to early Triassic mafic and ultramafic rocks that overlie and/or are possibly imbricated with rocks of the allochthonous Yukon Tanana terrane (YTT). Two major Seventymile klippe bodies (near Mt. Sorensen and along Salcha River) are in fault contact with amphibolite-facies supracrustal rocks of the allochthonous Devonian–Mississippian Fortymile River and parautochthonous Late Devonian Lake George assemblages. Ultramafic bodies of the Jurassic Kanuti complex are exposed in thrust sheets comprising the southeastern margin of the Angayucham terrane, and the mafic and ultramafic rocks define the contact between Angayucham and the Ruby terrane to the south. Kanuti complex M/UM rocks are likely coeval with similar M/UM rocks of the Brooks Range ophiolite. Both the Seventymile assemblage and Kanuti complex contain variably serpentinized peridotite and low-grade metamorphosed mafic magmatic rocks. Oceanic sediments (argillite and metasandstone) are a minor component of the preserved Seventymile complex but are not found at Kanuti. Peridotite is the dominant lithology in both terranes, mostly harzburgite with minor lherzolite to dunite. Clinopyroxenites, typically as small veins in harzburgite, are common in Kanuti; they are rare in Seventymile. Mafic rocks sampled for this study include gabbro and diabase from each suite that typically occur as dikes, veinlets, or rare massive stocks that intrude peridotite. Podiform chromite is often found within Kanuti peridotite (mostly dunite), whereas similar chromite textures are rarely observed among observed Seventymile localities.

Few modern petrologic techniques have been applied to rocks from the Seventymile or Kanuti complexes. Published studies on correlative systems such as the Slide Mountain and Brooks Range complexes suggest that both formed in marginal/back-arc basins rather than mid-ocean ridge settings. New trace element systematics from mafic magmatic rocks associated with the Seventymile and Kanuti complexes typically lack evidence for subduction-modified mantle, but there are some local exceptions. Spinel compositions from both complexes vary from abyssal to suprasubduction-like, though the most chromian/Fe-rich compositions occur either as rims or coexist with lower-Cr/Fe spinel in the same sections. Hf-Nd isotope systematics of M/UM rocks indicate that both complexes contain a DMM-like depleted component that overlaps with Pacific MORB, which is similar to the isotopic composition of peridotite xenoliths in Pleistocene alkali basalt erupted in the same region at Prindle Volcano. Among studied Seventymile complex rocks, some from more eastern klippen have the highest initial  $\epsilon_{\text{Hf}}$ ; those with the lowest  $\epsilon_{\text{Hf}}$  at similar  $\epsilon_{\text{Nd}}$  are from more western klippen. In contrast, the Kanuti complex mafic rocks extend to significantly less radiogenic  $\epsilon_{\text{Hf}}$  and  $\epsilon_{\text{Nd}}$  than Seventymile, indicating the involvement of an enriched component. Further constraining the petrogenesis and extent of petrologically conformable and broadly distributed Seventymile klippen is key to understanding its obduction history. The presence of ophiolite sections that represent broadly similar settings spanning ca. 100 Myr across a large region of central and eastern Alaska provide important constraints on the evolution and interactions of terranes at the apex of the northwestern Cordillera.

# Hafnium isotope systematics of Permian to Eocene plutons of the Yukon Tanana terrane in eastern Alaska

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The Yukon-Tanana terrane (YTT) is a complex, intensely deformed mid-to late-Paleozoic pericratonic allochthonous arc assemblage in tectonic contact with parautochthonous North American margin (NAM). We present new geochemistry, U-Pb ages, and radiogenic isotope ratios from Permian to Eocene plutons in the YTT-NAM assemblage in eastern Alaska that span terrane accretion, arc development, regional shortening, and orogenic collapse. Our data describe previously recognized Mesozoic suites but also include two previously unrecognized late Permian plutons (ca. 264–252Ma) and small Eocene stocks. Permian to Jurassic plutons were emplaced only in the YTT whereas Eocene and most mid-Cretaceous plutons were emplaced only in NAM. Late-Cretaceous plutons and associated volcanics were emplaced in both YTT and NAM basement. Permian plutons are evolved ( $\epsilon\text{Hf} -10$ ) high-K granodiorite to monzogranite. Triassic plutons, defining an E-W band along the southern margin of the YTT in Alaska, are low- to medium-K and bimodal, with median gabbro and granodiorite groups. Older Triassic rocks (ca. 218 – 208 Ma), on an E-W axis through the broader Triassic core, are juvenile ( $\epsilon\text{Hf} +10$ ). Off-axis, younger rocks (to 200 Ma) are more evolved ( $\epsilon\text{Hf} +2$  to  $-15$ ). Jurassic rocks outcrop north of the Triassic band and are also bimodal, with low-K gabbro, and high-K to shoshonitic monzonite/syenite. In total, they resemble the latest-Triassic  $\epsilon\text{Hf}$  range but are less radiogenic ( $\epsilon\text{Hf} > 0$ ) in eastern plutons, whereas they are sub-chondritic in a NE-trending syenite body to the west. Mid- and late-Cretaceous rocks are high-K ( $> 60$  wt.%) tonalite to alkali granite without compositional gap. Late Cretaceous rocks range to higher K and  $\text{La}_\text{N}/\text{Yb}_\text{N}$  than mid-Cretaceous, which are evolved ( $\epsilon\text{Hf} -4$  to  $-20$ ). Late Cretaceous  $\epsilon\text{Hf}$  is bimodal, correlated spatially;  $\epsilon\text{Hf}$  is high ( $-6$  to  $+3$ ) to the SE, and low to the NW ( $-8$  to  $-12$ ). Few Eocene plutons were analyzed, all high-K ( $\epsilon\text{Hf} -2$  to  $-4$ ) syenogranite. No suites definitively have a depleted mantle component, but (early) Triassic comes closest. Triassic to Jurassic magmatism is progressively more crustal; mid- to Late-Cretaceous ( $\pm$ Eocene) are decreasingly so. Permian, syenitic Jurassic, and mid-Cretaceous rocks resemble YTT + NAM gneiss, suggesting similar source components and/or partial melting of pre-existing crust.

## Dating Ductile Deformation by *In Situ* Rb-Sr Dating: Examples from the d'Abbadie and Shannon Faults, Yukon, Canada

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Determining the timing of ductile deformation is fundamental to understanding shear zone evolution and related tectonic processes. Current methods for dating ductile deformation focus on targeting accessory minerals including dynamically recrystallized titanite and/or fluid mediated (re)crystallized apatite. With the recent development of reaction chamber triple quadrupole ICP-MS, *in situ* analyses targeting radioactive decay schemes with isobaric interference (e.g. Rb-Sr), are now possible. This advancement makes it possible to analyse major mineral phases that participate in deformation (i.e. K-feldspar and mica) via *in situ* Rb-Sr analysis. Mica is generally weaker than K-feldspar and readily participates in deformation through (re)crystallization making it a prime candidate to record the timing of ductile deformation.

This study applied microstructural analysis and *in situ* Rb-Sr geochronology to specimens collected from transects in proximity to two shear zones. The first transect was collected from multiple lithologies of differing ages (i.e. Devonian meta-volcanic/quartzite, Devonian granite, Permian granite, mid-Cretaceous granite:  $97.52 \pm 0.29$  Ma (2SE) U-Pb CA-TIMS on Monazite) near the d'Abbadie Fault in south-central Yukon. The second transect was collected from a single granitic mid-Cretaceous pluton (i.e. Shannon Pluton:  $98.82 \pm 0.04$  Ma (2SE) U-Pb CA-TIMS on Zircon) adjacent to the Shannon Fault in southeastern Yukon, Canada. Both shear zones have mappable field strain gradients and record dextral movement synchronous with emplacement of mid-Cretaceous plutons.

Microstructural characterization of specimens from across the field strain gradients associated with the faults, shows that the aspect ratio of dynamically recrystallized quartz grains generally increases, and the size of these same grains decreases, toward shear zone cores. Moreover, differential stresses calculated through quartz sub-grain piezometry yield values that also increase toward the cores of the high-strain zones (i.e. d'Abbadie: 21 to 49 MPa, Shannon: 17 to 93 MPa). These microstructural data confirm the mapped field strain gradient for each area.

*In Situ* Rb-Sr dates of biotite from samples collected near the d'Abbadie fault, range from  $102.18 \pm 0.61$  to  $97.11 \pm 0.82$  Ma (2SE). Analysis of muscovite from the d'Abbadie specimens yielded *in situ* Rb-Sr dates that range from  $154 \pm 11$  to  $101.1 \pm 3.6$  Ma; the mid-Cretaceous granite contains no suitable muscovite for dating. All *in situ* Rb-Sr dates for biotite and the younger portion of dates for muscovite are all within externally propagated uncertainty of the mid-Cretaceous granite crystallization age (ca. 98 Ma), indicating ductile deformation synchronous with emplacement of the mid-Cretaceous pluton in the d'Abbadie area. The older portion of muscovite dates (i.e. ca. 154 and 151 Ma) don't correspond to any known event in the region.

All specimens from the high-strain zone associated with the Shannon fault are from a mid-Cretaceous granite. Most specimens yield biotite Rb-Sr dates that range from  $103.34 \pm 0.69$  to  $95.46 \pm 3.84$  Ma. The same specimens give muscovite *in situ* Rb-Sr dates that range from  $107.58 \pm 8.96$  to  $83 \pm 13$  Ma (2SE). All biotite and muscovite *in situ* Rb-Sr dates are within externally propagated uncertainty of the mid-Cretaceous granite crystallization age (ca. 99 Ma), consistent with ductile deformation synchronous with emplacement of a mid-Cretaceous Shannon pluton.

## **Tracing Cretaceous and younger strike-slip fault systems in the Yukon Tanana Upland, Alaska**

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The Alaska Division of Geological & Geophysical Surveys (DGGs) is working to complete modern and detailed geological, geophysical, and geochemical datasets covering the mineral-rich Yukon Tanana Upland (YTU)—a region that has produced 24 million ounces of gold and hosts further unmined resources of around 32 million ounces of gold. The metallogeny of the northwestern YTU is anchored by mid-Cretaceous intrusion-related gold systems, while Late Cretaceous porphyry-related mineralization dominates the southeastern portion of the area. Understanding the Cretaceous elements of the geologic framework—including fault systems and magmatic belts—is a primary focus of DGGs’s research in the YTU.

While major northwest-trending fault systems (e.g. Teslin and Big Creek faults) play a significant role in the geology and metallogeny of Yukon, the geology of the YTU in Alaska is presently dominated by northeast-trending, strike-slip-dominant faults linking the Cenozoic Denali and Tintina faults. Through detailed mapping and identification of fault piercing points, DGGs is beginning to restore these younger faults to their mid-Cretaceous positions. The restorations simplify the distribution of U-Pb ages in mid-Cretaceous plutonic rocks in the eastern YTU. Furthermore, many previously mapped northwest-trending fault segments fall along two trends that can be traced back to the Big Creek (via Moose Creek) and possibly Teslin fault systems in the Yukon. Together, the two parallel fault trends define a structural corridor through the central YTU that bounds the major mid-Cretaceous gold mining districts, including Fairbanks (Fort Knox mine) and Goodpaster (Pogo mine), as well as latest-Cretaceous porphyry-related systems such as Taurus and LWM.

Recent magnetic and gravity surveys and ongoing geologic mapping highlight the significance and continuity of the major northeast-trending fault systems, especially the Sixtymile-Pika fault system, but also the Harper-Kechumstuk and Shaw Creek faults. Our preliminary mapping results suggest these structures have both left-lateral and, locally, right-lateral offsets. When traced southwestward into the Alaska Range, these structures coincide with boundaries between domains of differential uplift and mountain-building, suggesting that they bound zones of fold-and-thrust shorting, and that differential block motion in the YTU helped shape the Alaska Range.

The Sixtymile-Pika and Harper-Kechumstuk systems apparently initiated between 90 and 70 Ma, as they cut ca. 96 Ma plutonic belts and localize swarms of latest Cretaceous intrusions. This timing predates the clockwise block rotation (“bookshelf”) faulting model, wherein universally left-lateral displacement on Interior Alaska’s northeast-trending faults accommodates shortening between the Cenozoic Denali and Tintina faults; our observation of both left- and right-lateral offsets on northeast-trending structures fits better within a pre-Cenozoic, pre-Denali Fault tectonic regime. Whether the Sixtymile-Pika fault system can be traced across the Denali and Tintina faults is a question for future research, and one that would be relevant to understanding latest-Cretaceous mineral systems that occur in the Y TU, the western Alaska Range, and in Yukon north of the Tintina fault.

## Thallium isotopic constraints on global marine oxygenation during the early Neoproterozoic from the Reefal Assemblage in Yukon, Canada

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Changes in the amount of oxygen present in the atmosphere are frequently invoked to explain coeval biotic changes throughout Earth history, especially with respect to early animal evolution. However, to be able to effectively link these evolutionary changes to Earth's oxygenation history, better constraints on the timing and nature of oxygenation events are required. Specifically, late Mesoproterozoic to early Neoproterozoic oxygen levels are not well constrained, with estimates of atmospheric oxygen ranging from 0.1-10% of present atmospheric levels (reviewed by Cole et al., 2020). This study presents thallium (Tl) isotope data from the Neoproterozoic Reefal Assemblage in the Coal Creek inlier to estimate the global extent of marine bottom water anoxia during the early Neoproterozoic. The Reefal Assemblage is laterally variable, with stromatolitic reefal buildups that transition to basinal, shale-rich successions (Macdonald et al., 2012). A tuff in the upper Reefal Assemblage yielded an age of  $811 \pm 0.25$  Ma (Macdonald et al., 2010). Thallium isotopes are a redox proxy that can be used to interpret the global extent of oceanic bottom water anoxia. When bottom waters are oxygenated, manganese oxides are deposited and Tl is adsorbed onto these oxides. The heavy Tl isotope is preferentially adsorbed onto Mn oxides which results in seawater being enriched in the lighter Tl isotope (Owens et al., 2017; Ostrander et al., 2020). Tl isotope measurements from modern organic-rich marine sediments deposited under anoxic conditions record the global Tl isotopic composition of seawater (Ostrander et al., 2020). Thus, more negative seawater Tl isotopic compositions (reported as  $\epsilon^{205}\text{Tl}$ ) measured in black shales are consistent with oxic bottom waters globally. Within the Reefal Assemblage, 16 of the 18 samples analyzed have  $\epsilon^{205}\text{Tl}$  values that are lighter than the continental weathering input value ( $\epsilon^{205}\text{Tl} \sim -2$ , Nielsen et al., 2005) but heavier than the modern seawater value ( $\epsilon^{205}\text{Tl} \sim -6$ , Owens et al., 2017). These values can be explained by fractionation of Tl during adsorption onto Mn oxides, which suggests widespread presence of oxygen at the sediment water interface at this time.

Future work will involve measuring stratigraphic sections and sampling the Mesoproterozoic Pinguicula Group. The aim of this work is to build on the environmental interpretation of Medig et al. (2016) and access deep-water facies of these successions for redox geochemistry. This work will involve using iron speciation analyses to interpret the local redox change in the basin and Tl

isotopes to build a record of global redox conditions. Ediacaran Tl isotope data from the Sheepbed, Nadaleen, and Blueflower formations have already been published (Ostrander et al., 2020), and we are also analyzing Cryogenian and Cambrian units. Ultimately this Tl isotope record will span all black shale units in the Yukon stratigraphic record from Mesoproterozoic to Cambrian and offer new insight on how global marine anoxia changed during these critical geobiological intervals.

## Geologic mapping in Yukon-Tanana Uplands, Alaska

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The Alaska Division of Geological & Geophysical Surveys (DGGS) has a long-standing history of geologic mapping in the Yukon-Tanana Uplands, Interior Alaska. The latest efforts, prompted by USGS Earth MRI and STATEMAP programs, lead to detailed, 1:100,000 or greater scale mapping accompanied by geochemical and geochronological sampling of the Tanacross and adjacent quadrangles (Fig. 1). These projects aim to produce more detailed geologic maps and supporting data to promote mineral discovery in Interior Alaska. Here we present our published mapping and preliminary 1:100,000-scale geologic maps for the areas mapped in 2021, the results of geochemical and geochronological sampling, and regional observations based on our on-going mapping in interior Alaska.

The Yukon-Tanana Uplands are underlain by two major geologic terranes: the parautochthonous margin of North America (pNA) and the allochthonous Yukon-Tanana Terrane (YTT). Metamorphic units within pNA include the Lake George assemblage, Jarvis Belt and the Divide Mountain augen gneiss. Metamorphic units within YTT include the Fortymile River assemblage, the Chicken assemblage (previously defined as a complex), the Klondike Schist, and the Ladue River assemblage (previously defined as a unit). The metamorphic terranes are intruded by multiple Triassic to Paleogene igneous suites.

The detailed mapping, geochronology, and geochemical analysis facilitated by the new programs lead DGGS to propose redefining Ladue River unit and Chicken complex as assemblages. The Ladue River assemblage has been mapped along the Alaska/Canada border, along the Ladue River. The Chicken assemblage was mapped along the northern boundary of the Taylor Mountain Batholith. Even though the rocks from both Ladue River and the Chicken assemblages record Mississippian/Devonian U/Pb age, like that of Fortymile River assemblage, they present multiple characteristics suggesting they are related, but distinct from the Fortymile River assemblage. The Ladue River assemblage has older uplift history than the Fortymile River - Triassic vs Late Jurassic. Our mapping also highlights the lack of Triassic and Jurassic plutons within Ladue River assemblage, and presence of faults bounding the assemblage. The Chicken assemblage is characterized by lower grade metamorphism (lower to mid- greenschist) than both Ladue River and Fortymile River assemblages (amphibolite locally retrograded to greenschist). The Chicken assemblage is commonly upgraded to hornblende hornfels near contacts with the Taylor Mountain

Batholith. The Chicken assemblage is characterized by weakly metamorphosed largely fine- to coarse-grained mafic to intermediate igneous rocks, whereas other YTT terrane assemblages are strongly foliated, predominantly metasedimentary with subordinate metaigneous units. The contact between the Fortymile River and the Chicken assemblages is mapped as a high-angle normal fault that down-drops the lower-grade Chicken assemblage.

Our evolving understanding of the units present in the pNA part of the eastern Alaska Interior lead us to the redefinition of Jarvis belt units (previously mapped as greenschist metamorphic grade predominantly metasedimentary with lesser metavolcanic units) and reconsideration of the necessity of the Macomb unit (amphibolite grade metaigneous with lesser metasedimentary rocks). Both the units are mapped in the southern portion of the Tanacross Quadrangle. We are advocating that Jarvis belt has reached amphibolite grade metamorphism and has since seen retrograde metamorphism. The unit was intruded in the Triassic by gabbroic sills, which in many cases have been metamorphosed to amphibolite, and preserve the gabbroic textures and mineralogy only in the thickest parts of the sills. The Macomb unit seems very similar in the general unit composition, uplift history and metamorphic grade to the Lake George. The most compelling point on merging the Macomb with Lake George assemblage is the presence of the Divide Mountain augen gneiss. We are currently waiting to test our hypothesis with additional geochemical and geochronological data.

A north-dipping extensional detachment between the underlying Lake George assemblage and the overlying Fortymile River assemblage was mapped in detail by DGGS in the Northeastern Tanacross map. 2021 mapping efforts identified a similar structure along the southern boundary of the Taylor Mountain batholith where the detachment is concealed by unmetamorphosed Cretaceous to Tertiary sedimentary rocks and minor felsic volcanic rocks. North dipping shear zones along several ridges on the south and west margins of Mosquito Flats are interpreted to be continuations of the same detachment, extensively crosscut by later high-angle faults. The presence of Jurassic plutons, which are only found within YTT elsewhere in eastern Alaska, support mapping the Fortymile River assemblage on the west side of Mosquito Flats. Previously published argon thermochronology in interior Alaska suggests that exhumation of the Fortymile River assemblage occurred during collision of the YTT with pNA in the Early Jurassic. The pNA units in eastern Interior Alaska were exhumed by widespread extensional deformation recorded throughout the Northern Cordillera during the mid-Cretaceous. Samples collected for  $^{40}\text{Ar}/^{39}\text{Ar}$  thermochronology are currently being analyzed to confirm the location of the detachment in the recent map areas.

We have identified multiple piercing points along the northeast-striking Sixtymile-Pika, Mount Harper-Kechumstuk, and Shaw Creek fault systems that suggest that faults in this orientation can have both left-lateral, right-lateral, and vertical offsets. Using these offsets, we have attempted to trace the extension of the older, northwest-striking Big Creek fault system from Yukon into

Alaska. This fault system may play an important role in Cretaceous magmatism and mineralization.

The Western Tanacross map area and adjacent parts of the Taylor Mountain map areas contain mid-Cretaceous felsic volcanic rocks. Preservation of these volcanics, along with plutons of comparable age, suggest complicated uplift and exhumation of the landscape since the mid-Cretaceous. Locally present late Cretaceous and Paleogene-Eocene volcanic rocks and porphyry intrusions are commonly located near high-angle faults, suggesting a genetic link between faulting and younger magmatism.

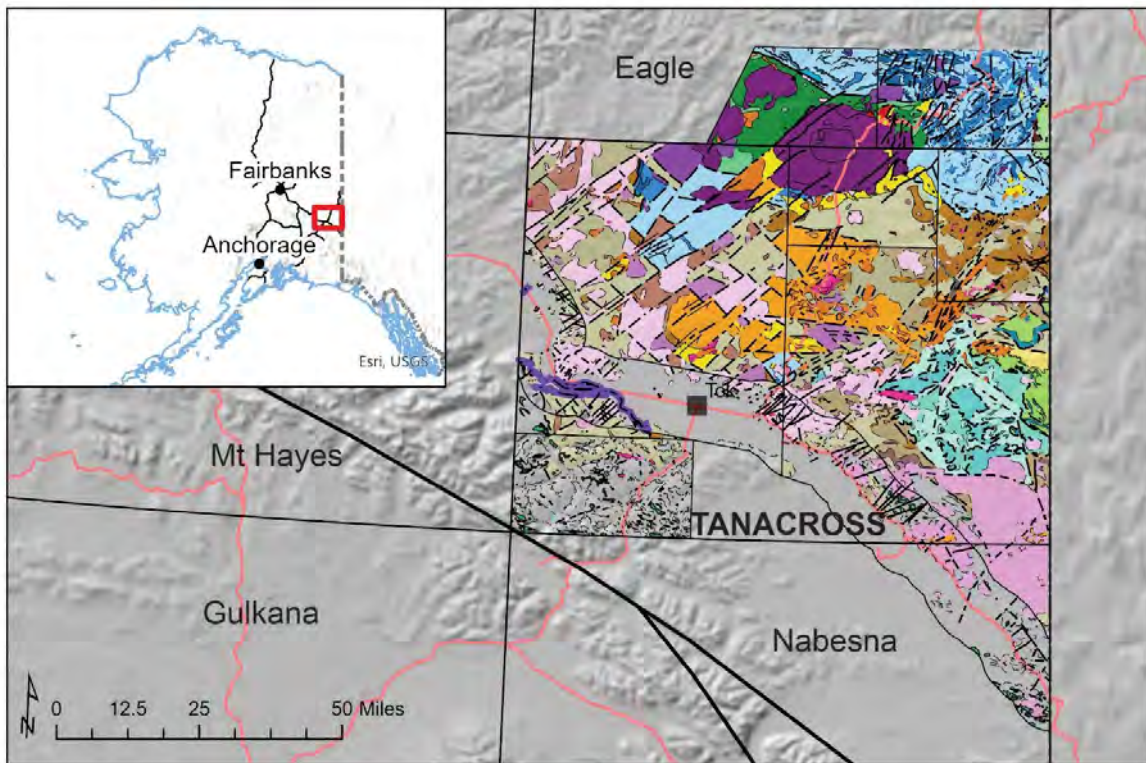


Figure 1. Map showing the location of DGGs geologic mapping progress.