CTG 2017

Abstracts and Program

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The Canadian Cordillera Array is coming soon!

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The Canadian Cordillera Array is a bold initiative to install a Cordilleran-scale open data network with the goal of holistically examining the Earth system from the core to the magnetosphere. Building on the scientific momentum of other North American large Earth systems research and data collection initiatives (e.g. Lithoprobe (1984 to 2004) and EarthScope (2004 to 2018)), the vision for CCArray is to install a network of telemetered observatories; in the Canadian Cordillera to address a broad range of scientific, technological and societal issues. Workshops over the past year have explored imaging, lithospheric and upper-mantle structure, improving understanding of earthquake dynamics and tsunami hazards, extending critical zone science (region from tree canopy through the soil into bedrock – the port of Earth critical for life), permafrost studies, space weather and improving numerical weather modeling. Enhanced monitoring networks would contribute to studies of glacial isostatic adjustment – the ongoing response of the Earth to past ice mass change – and contribute to understanding of Earth rheology and structure. CCArray will be comprised of a network of sensors. Each site will include one or more of the following: broadband seismometers (including ocean bottom seismometers in the Beaufort Sea and eastern Pacific Ocean), Global Naviagation Satellite System (GNSS) equipment, meteorological systems (including barometers), permafrost monitors, atmospheric gas sensors, shallow borehole temperature and moisture sensors, riometers, gravimeters and magnetometers. The CCArray represents the initial component of a planned future pan-Canadian Earth observation network; and may be able to leverage EarthScope instrumentation currently installed in eastern Alaska and northwestern Canada. Like Lithoprobe, funding will be allocated to other supporting geosciences, with the intention of examining deep controlling processes and their connections between surface geology and deep structures in the crust and upper mantle. An important legacy will be an enhanced long-term monitoring capability across Canada. Here we present a summary of some of the potential applications of such a network, expanding upon integrated research results that have emerged out of the US EarthScope program together with outcomes from a series of workshops and planning meetings held across Canada and the US over the past year.

Geochemistry and isotopic character of Precambrian granitoid suites across the Nolan-Zemlak domain boundary, west-southwest Rae craton: testing the possibility of a cryptic internal suture zone

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The Nolan-Zemlak domain boundary in Saskatchewan, a high-strain zone in the WSW Rae craton, has been proposed to represent a cryptic Arrowsmith-related suture marking collision between a 'proto-Rae' craton, characterized by ~2.6 Ga granitoids of the Nolan domain to the north and an older continental block underlying the Zemlak-Beaverlodge domains to the south comprising ~3.0 Ga granitoids and two distinctive early Paleoproterozoic suites (~2.5, ~2.3 Ga). A regional-scale geochemical-isotopic study aims to constrain the igneous petrogenesis of suites across this boundary and test this hypothesis. The oldest (~3.0 Ga) granitoid rocks, located within Beaverlodge domain, have arc-like geochemical signatures, TDMs older than 3.0 Ga and slightly positive ƐNdt values. The Nolan domain, immediately north of the proposed suture, contains weakly deformed, ~2.6 Ga Bt-Hbl-bearing granite-granodiorites with arc-like characteristics, TDMs ranging from 2.89 to 2.83 Ga, and slightly positive ƐNdt values. The Nolan domain granitoids show a progressive southward increase in strain and are in abrupt contact, along a major mylonite zone, with a distinctive unit of highly magnetic Hbl-Bt- gneissic granodiorites of the Zemlak domain, dated at 2517 ± 4 Ma. This rock type and similarly-aged quartz diorite to the east have arc-like geochemistry but are distinct from both the ~3.0 Ga and ~2.6 Ga (Nolan) granites with, a metaluminous character, low Th, TDMs from 2.96-2.86 Ga and slightly negative ƐNdt values. The ~2.3 Ga granites are restricted to the Zemlak and Beaverlodge domains, and have syn- to post-collisional geochemical affinity with more highly negative εNdt values (with TDMs of 3.06-2.87 Ga). The youngest suite of ~1.9 Ga anatectic leucogranites intrudes all older rocks and stitches the Nolan-Zemlak boundary; it yielded the most highly negative εNdt values and TDMs of 3.31-2.84 Ga. A large body of ultramafic-mafic (pyroxenite-gabbro) entrained within mylonitic rocks along the Nolan-Zemlak boundary, is relatively highly fractionated, has a TDM of 2.83 Ga and an ƐNdt value of +0.3 calculated at 2.52 Ga.

In summary, the ~2.6 Ga (Nolan) and ~3.0 Ga suites show the most juvenile ƐNdt values, and hence lowest degrees of crustal influence, which might be expected of terranes originally generated as independent crustal blocks. The younger ~2.5 to ~1.9 Ga granitoids show increased crustal involvement, with dramatic increases for the 2.3 Ga and ~1.9 Ga suites. This boundary separating the ~2.6 Ga and ~2.5 Ga suites may represent an Arrowsmith-age suture or, the ~2.5 Ga Zemlak may have been locally emplaced and related to more distal subduction.

Structural-kinematic relations across the Nolan-Zemlak domain boundary, west-southwest Rae craton

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Recent works in the Rae Province of the Canadian Shield have revealed that its western margin has a longer-lived history than originally thought. As such, the highly strained Nolan-Zemlak domain boundary has been proposed to represent a cryptic suture related to 2.5-2.3 Ga Arrowsmith orogenesis. This collision involved a 'proto-Rae' craton to the north that includes ~2.6 Ga Nolan domain granitoids, and an older (~3.0 Ga) continental block underlying the Zemlak-Beaverlodge domains to the south. Systematic geologic mapping, microstructural study, quartz c-axis LPO fabric analysis, and future contextual geochronology aims to test this hypothesis and constrain the structural, metamorphic, kinematic, and temporal aspects of this boundary-focused high-strain zone. Fieldwork along a N-S transect of this boundary on Tazin lake has established that the essentially undeformed Hbl ± Bt granites of the Nolan domain, north of the boundary, show a progressive southward increase in strain over 7-8 km. Towards the southern shore of Tazin Lake, these rocks become increasingly mylonitic in character along a 3-4 km wide corridor, where they come into contact with a distinctive unit of highly magnetic Hbl ± Bt granodiorite of the Zemlak domain. Accompanying the increase in strain is the appearance of lit-par-lit leucosomes and local map-scale bodies of a distinctive pink leucogranite. Mylonitic foliation dips moderately to steeply NNW and SSE and associated stretching lineations plunge shallowly to the ENE and WSW; rare kinematic indicators indicate sinistral displacement. A series of ENE- to NE-trending topographic lineaments run subparallel to this mylonite zone, along which the ductile foliation is overprinted by a strongly chloritized cataclasite and irregular zones of brecciation. Kinematic indicators in these more brittle zones of opposed (dextral) sense support the inference of a separate, reactivation phase of movement, rather than a ductile to brittle continuum in fault zone evolution. Subsequent petrographic and associated LPO study has reinforced the inference of two distinct stages of deformation: an earlier, high-T (upper amphibolite-grade) event recorded in the mylonitic rocks and a later lower T (greenschist-grade) reactivation observed in the heavily chloritized cataclasites. In thin section, mylonitic Nolan granitoids are characterized by continuous quartz ribbons anastomosing around 1-2 cm K-fsp porphyroclasts. The latter display 'core-mantle' structure with intact cores and highly recrystallized margins along with sectored myrmekitic overgrowths. Together these reinforce the inference of relatively high-T (upper amphibolite facies) and aforementioned kinematic interpretations. While some quartz c-axis patterns from along the boundary show ~500-600^{O}C prism-[a] and [c] slip system predominance, a number of samples show evidence of a much lower temperature (~400-500^{O}C) strain with a predominance of rhomb and prism-[a] active slip systems. This suggests influence of the younger greenschist-grade overprint. Future work will aim to more fully evaluate the nature and timing of respective deformational events using a combination of contextual U-Pb geochronology on zircon and titanite, coupled with 40Ar-39Ar geochronology on hornblende and biotite in the same rocks.

A structural investigation of the Thelon and Judge Sissons faults, northeast Thelon basin, central Rae domain, Nunavut

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The Thelon and Judge Sissons faults provide a unique opportunity to study a long-lived, post-orogenic Paleoproterozoic fault zone that preserves ductile to brittle structures, as well as an important hydrothermal fluid system. These faults are located along the southern margin of the northeast Thelon Basin in the central Rae domain and were investigated through detailed structural mapping and examination of drill core. The Thelon and Judge Sissons faults are ENE-trending and can be traced upwards of 100 km or more along strike. Individual fault strands have well-developed damage and core zones, which vary from < 1 to 15 m in width, and are characterized by multiple generations of quartz veins and breccias. The veins host a variety of primary growth (chalcedonic, comb, zoned, cockade), recrystallization (moss), and replacement (bladed) textures. The two faults initiated as dextral ductile to brittle-ductile shear zones as suggested by the presence of preserved lozenges of mylonite within the fault zones and along their margins. Early ductile to brittle-ductile movement along the faults overprints ca. 1810 Ma granite of the Hudson Intrusive suite, and is followed by two distinct brittle deformation events: (1) a prominent dextral strike-slip event bracketed between ca. 1780 Ma and ca. 1720 Ma, which displaces the Schultz Lake Intrusive Complex upwards of 14 km and is characterized by near horizontal slickenlines with step and tool mark kinematic indicators on steeply-dipping fault planes; and (2) a dextral oblique-slip event, which is loosely constrained between ca. 1667 Ma and ca. 1267 Ma and is observed as oblique (pitch of 50°) slickenlines overprinting earlier horizontal slickenlines along fault planes. The prominent brittle dextral strike-slip movement created a Riedel shear array comprising NNW-trending sinistral R' shears, E-trending dextral R shears, NE-trending dextral P shears, and NW-trending T veins. These structures are present within and adjacent to the Thelon and Judge Sissons faults. As a result, an extensive fracture and fault network was created that allowed extensive fluid migration into and along these faults during slip events. After the Thelon Formation was deposited, late oblique-slip events along these fault zones reactivated this complex structural and hydrothermal fluid flow network, which led to the creation of unconformity-type uranium deposits in the area.

Dating fault gouge: a critical review and case studies

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Fault gouge forms within the damage zone of brittle faults during frictional slip. The gouge is a product of mechanical communition of wall rock materials and growth of new, clay-sized minerals. Fault gouge, much like the fault zone itself, forms a cumulative record of the fault's slip history. When gouge is collected from core or at the Earth's surface, it may thus contain detrital materials from one or more wall rocks, and authigenic clays from one or more slip events. Any K-bearing materials within the gouge, whether detrital or authigenic, accumulate daughter radiogenic ^{40}Ar over geological time. However, these materials can also partially or fully lose ^{40}Ar by thermal diffusion during the fault's evolution. Thus the challenges in interpreting fault gouge ages are many.

Because of the small size of the materials in gouge, our ability to separate and characterize the individual materials of different sources is limited to grain size separations. A typical approach to dating fault gouge is to perform one to several grain size separations, characterize each using X-ray diffraction, scanning electron and/or transmission electron microscopy, and then date the size fractions using K-Ar or encapsulation Ar/Ar methods. Case studies from Canadian and other field areas provide opportunities to compare these approaches to dating fault gouge, and highlight some of the successes and challenges in interpreting results.

Nature and relative timing of deformation along the northern Beniah fault zone in the Point Lake area, central Slave Province, N.W.T.

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The Northwest Territories Geological Survey has undertaken a reconnaissance structural mapping initiative to study the northernmost extent of the Beniah Fault Zone in the Slave Craton, Northwest Territories. The study area is at Point Lake, approximately 340 km north-northeast of Yellowknife, along the Coppermine River system. Lake access allowed for multiple transects across the Beniah Fault Zone.

The Augustus Granite is the oldest recognized unit in the study area and forms part of the Point Lake Basement Complex (PLBC). Locally, the PLBC ranges in age from ca. 3257 Ma to 2660 Ma. Several exposures of Central Slave Cover Group (CSCG), represented by quartzite, banded iron formation, ultramafic rocks, and associated metasedimentary rocks, are preserved in fold hinges above the basement and below the volcanic belt. In multiple localities, a sequence of unnamed mafic volcanic rocks older than the CSCG exists. The majority of volcanic and associated supracrustal rocks in the Point Lake area belong to the post-CSCG Peltier Formation. Higher in the stratigraphy, bimodal volcanism is preserved in the Samandré-Beauparlant Formation. An extensive package of turbidites of the Contwoyto Formation overlies this. All of these units are unconformably overlain by a package of polymict conglomerate, arenite, and siltstone known as the Keskarrah Bay Formation. Large volumes of granite were intruded at ca. 2625 to 2590 Ma. The youngest rocks in the area are Proterozoic mafic dykes.

Deformation was observed along a transect through the Beniah Fault Zone and surrounding areas. The oldest recognized deformation event heterogeneously affects rocks of the Augustus Granite, PLBC, and pre-CSCG volcanic rocks. This protracted event involved initial mylonitization of the rock, local injections of leucosome that were also mylonitized, folding with a steep northeast-striking axial plane, and finally, injection of a second leucosome. The original, high-strain mylonitic fabric appears to have been subsequently recrystallized at lower pressures and temperatures. A second discrete mylonitization event overprints the high-grade, recrystallized mylonite and affects all rock types exclusive of the Proterozoic dykes. This mylonitization forms parallel-sided belts that strike north-south and are sub-vertical. Leucosome was not produced during the second mylonitization, indicating a lower temperature deformation. Following these two discrete mylonitization events, regional folding in three phases affected the Keskarrah Bay Formation and all older units. The first phase produced isoclinal folds and a schistosity, and reoriented pre-D1 fabrics. The second phase of folding produced tight folds with steeply dipping axial planes striking northeast-southwest. Finally, the third phase of folding produced open to gentle folds with northwest-southeast striking, steeply dipping axial planes.

Deformation of forearc basin during oblique arc-continent collision in Taiwan: insights from 3D sandbox modeling

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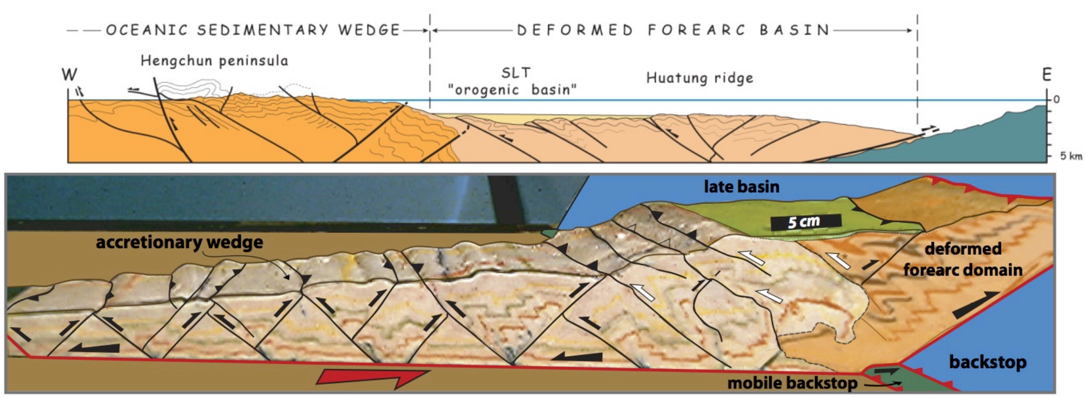
Deformation and progressive subduction of the upper-plate basement during arc-continent collision may result in gradual deformation of the forearc basin modifying structural pattern of the area. Gradual steps in deformation of foreland basin can be analyzed south of Taiwan, where incipient continental collision occurs between the Luzon arc and the China continental margin. Structural interpretation of the offshore area south of Taitung suggests double-vergent thrusts developing in deformed forearc basin between the volcanic arc and oceanic sedimentary wedge of the Hengchun Peninsula. Forearc domain involves the Huatung Ridge, uplifted and back-thrusted onto the Luzon arc, and the Southern Longitudinal Trough an orogenic basin where foreland-vergent thrusts predominate. Oblique (73 degree) component of the arc-continent collision results in strike-slip displacement occurring along the foreland-vergent thrusts.

The impact of forearc subduction on structural kinematics in deformed foreland basin was studied in 3D sandbox modeling of oblique arc-continent collision reproducing settings of Hengchun Peninsula – Huatung Ridge transect. Two velocity discontinuities were introduced in the model: one associated with the displacement of a plastic sheet, corresponding to the kinematics of the main subduction zone that controls deformation of the accretionary wedge, and other - with the retreat of a rigid PVC plate, simulating subduction of forearc basement. Continuous sedimentary supply was provided in the forearc basin area between the building-up accretionary wedge and the rigid backstop (arc). Incipient forearc subduction (displacement of the PVC plate) results in the growth of newly formed thrust wedge in front of the arc. Sedimentary cover in the orogenic basin between accretionary wedge and the thrust wedge remain undeformed. As forearc subduction continues, foreland-vergent thrusts of the thrust wedge progressively propagate in the orogenic basin. After the complete forearc subduction (and retreat of the PVC plate) occurs, structures of deformed forearc basin are thrust over the rear part of accretionary wedge resulting in emplacement of out-of-sequence thrusts. A strike-slip component of displacement along the thrusts in accretionary wedge accommodates oblique shortening during the arc-continent collision.

Forearc subduction analysis of Taiwan orogen and 3D sandbox modeling provides a better understanding of stress and strain partitioning between accretionary wedge and deformed forearc basin during oblique arc-continent collision.



Detachment folds and thrust folds

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Two contrasting styles of deformation and related fold-thrust interaction can be distinguished in the thin-skinned fold and thrust belt forming the central Alberta Foothills and Front Ranges. Paleozoic carbonates form thick competent beams, which are cut by east verging thrust faults with stair-case trajectories (ramps and flats). In contrast, the overlying Mesozoic and Cenozoic strata show much more folding above detachment zones (detachment folds).

These two contrasting styles of deformation can be reconciled by the notion that thrust-ramps in competent units (such as the Paleozoic carbonates) are localized by a buckling instability in the layered succession in an early stage of buckle-folding. Thrust faults in the overlying Mesozoic and Cenozoic units form in a later stage of the buckle-folding process, whereby these faults ramp through the fore-limbs of tight folds (described as fault-propagation folds or as thrust folds). Consequently, the prominent process in these layered strata is buckling, whereby thrust faults initiate at buckling instabilities. Buckle folds can be modified by fault-bending at a later stage, after thrust faults formed (Langenberg, *in prep*).

A sequence of events is suggested, whereby detachment buckle folds are formed first. Subsequently, this process would allow for modification of the folds by propagating thrust faults (thrust folds).

Modeling by Liu and Dixon (1990) showed that the threefold fold classification of Jamison (1989) is part of a continuum. I propose a twofold classification of fault related folds consisting of Detachment Folds and Thrust Folds. Fault-bend Folds are considered a variety of these folds.

Jamison, W.R. (1987): Geometric analysis of fold development in overthrust terranes; Journal of Structural Geology, v.9, pp.207-219.

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Regional to outcrop scale – faults in magnetic data

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The interpretation of airborne magnetic data of the Search II Project area in central British Columbia (Geoscience BC, 2017) provides a regional perspective for the location of first-order structures in an area where the geology of various arc terranes and major porphyry intrusives associated with mineral deposits are often obscured by valley floor sediments. The distribution of intrusive bodies and their relation to fault structures in the Canadian Cordillera is of explicit interest due to the presence of intrusion-related porphyry deposits (Logan & Mihalynuk, 2014; Nelson & Kyba, 2014). In this study, we address the distribution of faults as interpreted from airborne magnetic data and correlate the ages and orientations of structures with alteration patterns and intrusive lithologies. The offset of marker units in the magnetic data also indicates possible slip direction on faults. Relative age relationships can be established by identifying offsets and terminations at fault intersections.

The fault interpretation of the magnetic data revealed that four distinct fault generations dominate the structural character of the area. Northeast-striking dextral faults, north-northwest striking sinistral faults, west-northwest striking sinistral faults and north-northwest striking dextral faults each represent a distinct tectonic event characterized by unique local shortening and extension directions.

Integration of magnetic data, showing intrusives, and radiometric data, showing alteration, highlights which fault generations are associated with magmatic or hydrothermal activity. Potassic alteration, inferred from Th/K ratio from an airborne gamma-ray spectrometer survey shows preferential correlation with north-northwest and west-northwest striking faults. These same fault orientations are also the dominant orientations of faults that intersect and are peripheral to intrusive bodies, as interpreted from the airborne magnetic data. Faults with both alteration signature and spatial association with plutons, strike mostly west-northwest and east-northeast, indicating that faults of this orientation likely played a key role in the localization of magmatic activity.

Field control gives much better insight into fault slip direction, style of faulting, and the change in magnetic susceptibility from fault processes. The orientation of second-order faults and extension veins support the regional interpretation of dextral slip sense on north-northwest striking faults. These faults are locally associated with a low in the regional magnetic data. Ground magnetic susceptibility measurements show that in the study area, the greatest decrease in susceptibility was in areas of brecciation and cataclasite formation. However, it was noted that not all alteration and fault features create a decrease in susceptibility. Fault gouge in the centre of a several meter-wide shear zone had a higher susceptibility than surrounding felsic tuffs and porphyritic intrusive rocks.

Geoscience BC, 2017. Map 2017-03-10. Magnetic Gradient and Radiometric Survey. Search Project Phase II. British Columbia – 2016.

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Nelson, J., Colpron, M., 2007. Tectonics and Metallogeny of the British Columbia, Yukon and Alaskan Cordillera, 1.8 Ga to present. *in* Goodfellow, W.D., (ed..), Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods: Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, p. 755-791.

The importance of structural mapping in ore deposits - a new perspective on the Howard's Pass Zn-Pb district, Northwest Territories, Canada

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The Howard's Pass district of the Selwyn Basin in eastern Yukon and western Northwest Territories, Canada, includes a total of 15 sediment-hosted Zn-Pb deposits and is one of the largest undeveloped Zn-Pb district in the world.

Understanding the structure is crucial for future exploration efforts and new discoveries. The current genetic model holds that syn-genetic mineralization, exhaled during the Silurian, was deformed while sediments were still water-saturated, and although deformed again into an open syncline during the Mesozoic Cordilleran orogen, the distribution of the ore was not significantly affected. Based on recent structural mapping of the entire district, it is proposed here that the map pattern is primarily controlled by thrusting, not simply by folding, and forms a duplex structure. Imbricated thrusts root into a flat-lying detachment surface, termed the Howard's Pass décollement, which forms the floor thrust of the duplex and displays significant ductile strain. Above this floor thrust, a series of imbricated thrust faults disrupt both mineralization and stratigraphic succession. Sulfide minerals (galena, sphalerite, and pyrite) are concentrated and remobilized along a pressure-solution cleavage, which is well developed in zones of high strain. The duplex is capped by a flat-lying upper detachment (roof thrust) above which less shortening has been accommodated. It is suggested here that the duplex and associated fabrics (pressure-solution cleavage, transposition, folds and faults) formed 250-300 Ma after deposition of sediments, during Jurassic-Cretaceous layer-parallel shortening of the Cordilleran orogen, which significantly affected the distribution of the mineralization.

District-wide geodynamic controls on porphyry style mineralization in the Stewart district, northwestern British Columbia: the role of reactivated basement structures

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Most Cu-porphyry deposits are generated in volcanic arc environments under broad contractional stress regimes marked by crustal thickening, surface uplift and rapid exhumation (Sillitoe, 2010). Recent regional and detailed mapping studies in the Stewart exploration district of NW BC suggests that the supergiant Cu-Au Mitchell-Snowfield deposit instead formed in an Early Jurassic pull-apart basin associated with strike-slip faults (Nelson and Kyba, 2014; Febbo, 2016). Furthermore, the reactivation of basement structures is proposed to have exerted a fundamental control on the location of such extensional basins and mineral deposits (Febbo, 2016). To test this model, detailed characterization of sedimentation and structure was completed in the 2017 field season for two separate deposits in the Stewart district: the Big Bulk Cu-Au porphyry deposit and the Red Mountain Cu-Au porphyry deposit. 1:10 000 property-scale stratigraphic and structural mapping focused on: (1) the distribution of orogen-parallel and -transverse structures spatially associated with these deposits, (2) mapping the sedimentary rock record adjacent to faults and transverse to faults, with focus on regional and local stratigraphic marker horizons within which deposits were emplaced, and (3) recognition of potential reactivation in the rock record where basement structures control strain and porphyry localization. Classification of geometry, kinematics of faulting, and vein orientations was completed to evaluate the possible control of directional stress on pluton emplacement. Rocks were sampled for lithogeochemistry, geochronology, petrography and microstructural analysis. In concert with this, stratigraphic columns and sections have been completed to evaluate along-strike variation in depth of emplacement and structure of the deposits. Completion of the proposed integrated compilation of structural, stratigraphic, and geochronological data of these deposits will provide greater insight into the mechanisms responsible for this extensive, mineral-rich zone. If our data supports the supposition of porphyry emplacement in pull-apart basins, a new exploration model for porphyry deposition could be implemented.

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Deformation and hydrothermal alteration interplay in the Eastern Highlands shear zone, Cape Breton Highlands, Nova-Scotia

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The Eastern Highlands shear zone (EHSZ) is located on Cape Breton Island where it separates rocks of the Bras-d'Or and Aspy terranes within Ganderia in the Appalachian accretionary belt. It records late Silurian to Early Devonian shear with east-over-west kinematics (D_1) that may correspond to the accretion of Avalonia during the Acadian orogeny. Previous work on the structure also noted a second deformation event (D_2) with oblique dextral and west-over-east kinematics with unknown significance. We present new mapping and preliminary analysis of the EHSZ that contribute to our understanding of the later stages of deformation and their interplay with hydrothermal alteration.

A psammite unit and associated meta-conglomerate are the westernmost rock units deformed in the EHSZ. The foliated Roper Brook diorite crops out east of the metasedimentary rocks in the northern segment of the shear zone. A massive to gneissic granite, commonly bearing evidence of potassic alteration, forms the easternmost unit of the EHSZ. Further south, near Ingonish River, a rhyolite with tuff layers may represent the extension of this unit along strike.

D_1 and D_2 deformation events are marked by C/S/C' fabrics, sigma- and delta-type clasts observed in all units forming the EHSZ. Crosscutting relationships between D_1 and D_2 fabrics was observed in one location in the field. In a key sample located on the eastern side of the EHSZ, muscovite is only associated with D_2 shear fabrics, thus restricting potassic alteration to this deformation event. Additionally, a N-S zone of altered granite cataclasite and stratabound, pervasive alteration has been observed on the eastern edge of the EHSZ. This deformation is attributed to a third brittle-ductile deformation event, D_3, with east-side-down kinematics.

The D_2 deformation events is interpreted to have occurred sequentially after D_1 along a retrograde pressure-temperature path during exhumation. Based on the mineralogy and style of deformation, the potassic alteration is inferred to have occurred concurrently with D_2. The brittle-ductile, east-side-down D_3 event is associated with hydrothermal chlorite + amphibole alteration but there are no indications of whether it is related to late fault re-activation or has occurred during a later stage of the retrograde path. Future work will attempt to quantify the strain associated with the D_1 deformation event, date the timing of D_2 deformation and associated hydrothermal minerals through a combination of U-Pb monazite petrochronology and $^{40}Ar/^{39}Ar$ dating of mica and/or amphibole. This project provides an opportunity to reconstruct the post-orogenic reactivation of the EHSZ and the associated magmatic-hydrothermal processes that may have contributed to the mineral endowment of the orogen.

Neoproterozoic rift faults in the Purcell Mountains of southeastern British Columbia

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There are more than 20 well-exposed extensional faults in the Purcell Mountains to the west of Invermere in southeastern British Columbia that show clear evidence for activity during the Neoproterozoic rift events that preceded the breakup of the Rodinia supercontinent. Geological investigation of these faults provides information about multiple periods of fault activity that started during deposition of the upper part of the Mount Nelson Formation and continued before and during deposition of the Windermere Supergroup. The exposed structures provide opportunities to study details of the geometries of the rift faults, the geometries of inversion structures that formed during younger contractional reactivation of the faults, and the details of the syn-rift strata.

The oldest documented rift faults formed during deposition of a diamictite succession present within the Mount Nelson Formation. Traditionally the Mount Nelson has been considered to be the uppermost part of the ca 1.47 to ca. 1.3 Ga Purcell Supergroup, but the local presence of diamictite of possible glacial origin in the succession, and results from detrital zircon analyses, indicate it is likely of Neoproterozoic age. The uppermost sequence of the Mount Nelson Formation, a succession of sandstone and shale that overlies the Mount Nelson diamictite, exhibits substantial syndepositional thickening toward an extensional fault in one location, indicating that these strata were deposited within a hanging wall half-graben during active extension.

The Toby Formation is a diamictite succession present at the base of the Windermere Supergroup, and has long been considered to be the rift succession of the Windermere rift. Many of the extensional faults in the Purcell Mountains display changes in the erosion level below the sub-Windermere unconformity, with deeper levels of erosion in the footwalls as compared with the hanging walls of the faults. There are no clear-cut examples where the Toby Formation thickens across Neoproterozoic faults, and in fact there are several faults that offset sub-Windermere strata but are truncated by the sub-Windermere unconformity. This leads to an unexpected conclusion: the most significant Neoproterozoic extensional faulting in the region apparently occurred during the period represented by the sub-Windermere unconformity (after Mount Nelson deposition and before Toby deposition).

There are three faults that cut the Toby Formation and are truncated at an unconformity at the base of the overlying Horsethief Creek Group. At one location two of these faults bound a small horst block where a cap carbonate interval that overlies the Toby diamictite has been removed by erosion prior to Horsethief Creek deposition; the cap carbonate is present on the down-dropped sides of the two faults. Pronounced thickness and facies changes in Horsethief Creek Group deep water strata take place across several other syndepositional extensional faults.

Most of the extensional faults are northwest-striking, southwest-side-down faults, but northeast-side-down and north-side-down faults are also present. Fault dips, when corrected for Mesozoic folding, range from near-vertical to less than 40 degrees. Some faults have listric shapes in cross-section. Several faults have well developed extensional fault propagation folds associated with them.

Solid-state sintering as a lithification mechanism in volcanic conduits

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We present results from an experimental study designed to constrain the conditions and mechanisms responsible for lithification of volcanic fault gouge at Mount St. Helens (MSH).

From 2004-2008 MSH produced seven lava spines that were each mantled by a carapace of volcanic fault gouge – a fine crystal-rich rock powder containing little to no glass, created by fracturing and cataclasis at the conduit-wall rock interface (Cashman et al., 2008; Kennedy et al., 2009). Notably, the gouge in the carapaces was variably consolidated. Textural analyses of natural samples suggest the gouge was 'lithified' during transport to the surface (Fig. 1a), and that melting did not significantly contribute to lithification (Ryan et al., 2017). This indicates there is a previously unidentified solid-state lithification process occurring in the MSH volcanic conduit. Based on these analyses, we have proposed 'hot pressing' as the new lithification process (Ryan et al., 2017).

We hypothesize that hot pressing is driven be diffusion of atoms between crystalline particles, analogous to solid-state sintering processes used to manufacture ceramics, and diffusional creep in dense solids (Rahaman, 2003; White, 1965). To test this hypothesis we have conducted experiments designed (1) to check whether solid-state sintering is possible at conditions expected in a volcanic conduit, and (2) to constrain the temperature-pressure-time conditions necessary to substantially densify the initially granular experimental material. In these experiments we compact natural gouge from MSH at high temperatures (700-900°C) under either differential or isostatic pressures (15-70 MPa) for extended times (10-60 hours). These experimental conditions were chosen because they can be expected within the upper conduit at volcanoes that produce lava spines.

Using this experimental methodology, we have created a suite of variably consolidated experimental products. The density of the materials increases with temperature and applied pressure. These experimental results seem to show that hot pressing (i.e. solid-state sintering) is not only possible at conditions expected within the volcanic conduit, but also occurs rapidly, producing dense material in tens of hours.

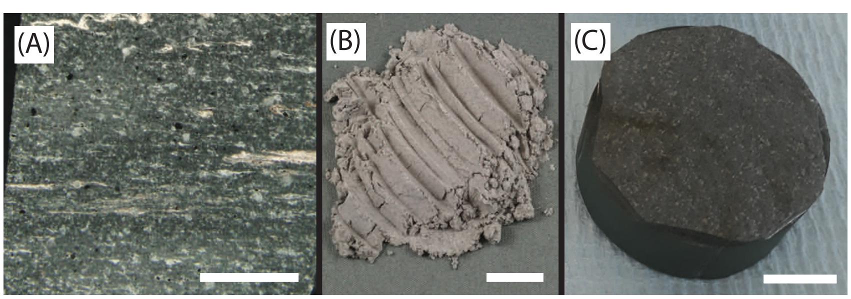

Figure 1: (A) Close up of completely lithified MSH conduit fault gouge. (B) Sieved MSH unconsolidated gouge used for experiments. (C) Cylinder of gouge hot pressed at 800°C and 70 MPa isostatic pressure for 60 hours. Scale bars are 1 cm.

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Kennedy LA et al. (2009) *Am Mineral* 94, 995.
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Rahaman MN (2003) *Ceramic Processing and Sintering* 875 p., New York: Marcel Dekker.
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Late-orogenic cross-folds in the Ottawa River gneiss complex, western Grenville Province: shear-induced sheath folds or products of superimposed deformation?

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Kilometre-scale, noncylindrical, upright to inclined cross-folds dominate the map pattern in the western Ottawa River Gneiss Complex (ORGC), southwest Grenville Province. Principally developed in orthogneiss, they are post-peak Ottawan structures that occur in both allochthonous and parautochthonous units and also distort the Allochthon Boundary. Most examples have linear to oval map patterns, but some have a box style with branching axial traces. In principle, two possible origins for these structures are: (i) refolding of prograde, thrust-related structures, or (ii) sheath folds, of which only half or less is preserved at the present erosion level.

Sheath folds are defined as noncylindrical structures with highly-curved hinge lines and 3D-apical angles of 20° to 90°. Shear-induced sheath folds form in multi-layer sequences with low to moderate viscosity contrasts, and km-scale examples are typically recapitulated by m- to dm-scale counterparts. Moreover, they are pervaded by L~S mineral-shape fabrics.

In this presentation, we describe three lines of field evidence to distinguish between possible origins (i) and (ii). First, the absence of m- to dm-scale sheath folds in much of the ORGC implies a corresponding absence of km-scale structures. Second, average strain levels in many km-scale cross-folds are at least an order of magnitude lower than required for sheath folding. The third line of evidence involves a comparison of the styles of natural and experimental sheath folds with those of two representative major upright cross-folds in the ORGC, the box-style Moon River synform (MRS) and the oval Sparrow Lake basin (SLB).

The apical angle of the MRS is approximately 135°, implying that, if it is a sheath fold, half or more of it has been removed by erosion. However, we have found no evidence for sheath folds in surrounding rocks to support this interpretation. Moreover, its hinge zone is characterized by L>>S fabrics, and the limb regions by S>>L fabrics. Metre-scale sheath folds do occur in one section of the hinge zone, but are restricted to rocks with L>>S fabrics, suggesting they formed by local constrictional strain. Regarding the SLB, its map shape is not a useful criterion in this regard, since it resembles both a remnant of an experimental sheath fold and Ramsay's fold-interference patterns 2 and 1-2. However, the subhorizontal hinge line and L>>S mineral-shape fabrics in the hinge zone are more readily explained by superimposed folding.

In conclusion, both the low to moderate levels of average strain and the general scarcity of dm- to m-scale cross-folds with sheath forms are difficult to reconcile with a sheath-fold origin for their hosting km-scale cross-folds. Additionally, the structural styles and shape fabrics of the well-studied MRS and SLB differ significantly from natural shear-induced sheath folds and their kinematic and dynamic models, collectively leading us to prefer the interpretation that the noncylindrical geometry of all km-scale cross-folds in the ORGC is a net result of superposed folding.

The Evolution of the Southern Asian margin: P-T-t Paths from the Hindu Kush, Chitral (NW Pakistan)

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This study aims to better understand the role of the inherited Asian crustal structures and thermal regime in the development of large-scale Himalayan dynamics. It specially aims to unravel the geological characteristics of the southern Asian margin prior to its collision with India and the generation of the Himalaya and the associated Tibetan plateau.

The goal of this study is to reappraise the formation and exhumation of metasedimentary rocks from the Chitral region of the Hindu Kush range (North Pakistan), which preserve evidence of the tectonic evolution of the Himalaya–Karakoram–Tibet orogeny that predates the Himalayan subduction/collision history. Combined classical geothermobarometry, phase equilibria modelling, in situ U-Th/Pb monazite geochronology, and garnet and monazite trace element analysis allow us to elucidate the pressure–temperature–time evolution of three adjacent garnet + staurolite-bearing micaschists and three sillimanite + anatexite bearing micaschists.

Garnet in staurolite-bearing micaschists has a complex zonation which records multiple growth stages. Inferred P–T paths have been successfully predicted from thermodynamic modelling for each sample. Most paths outline an increase in temperature combined with a decrease of the pressure during garnet growth. While garnet cores crystallized in a staurolite-free environment, garnet rims crystallized in equilibrium with staurolite. Moreover, garnet in one sample shows a discontinuous overgrowth recording a last stage of crystallization after staurolite-breakdown characterizing a decrease in pressure–temperature conditions. Garnet in sillimanite-bearing micaschists shows a homogeneous composition, only recording the peak of metamorphism at supra-solidus conditions (consistent with the observed textural evidence for partial melting). Monazites dated in the analysed samples yield a variety of Mesozoic and Cenozoic age populations, which can be linked to the different garnet growth stages previously characterized in each sample.

The pressure–temperature–time paths obtained for the different samples from the Chitral region provide important constraints on the main deformation, magmatic and metamorphic events along the southern margin of Eurasia. These include the accretion of the Hindu Kush–SW Pamir to Eurasia during the Late Triassic, followed by the accretion of the Karakoram terrane in the Early Jurassic. Younger Jurassic and Cretaceous ages record the development of an Andean-style volcanic arc along the southern Eurasian margin, which ended with the docking of the Kohistan island arc and the emplacement of the Kohistan–Ladakh batholith during the Late Cretaceous. The initial Eocene collision of India with Eurasia was followed by widespread high- temperature metamorphism and anatexis associated with crustal thickening within the Himalaya system in the Late Oligocene and Early Miocene.

The Wager shear zone, northwestern Hudson Bay, Nunavut: new mapping and initial structural characterization

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The inferred Paleoproterozoic Wager shear zone (WSZ) is located on the northwestern coast of Hudson Bay, Nunavut. It extends west approximately 450 km from Southampton Island, across Roes Welcome Sound, through Wager Bay and farther inland. It was first recognized during reconnaissance-scale mapping conducted in the 1960s and further defined through targeted mapping carried out in the late 1980s and early 1990s. The detailed timing, kinematics and magnitude of displacement across the WSZ, however, have not been explored, leaving its regional significance and potential correlation with other structures largely unknown. To help address this knowledge gap, new geological mapping was conducted during the summer of 2017 to delineate the boundaries of the shear zone by defining a strain gradient, to characterize its various components, and to collect specimens for petrographic, microstructural and geochronological analyses. At the outcrop scale, the shear zone is characterized by a steep, east-west trending mylonitic foliation and a sub-horizontal mineral-stretching lineation with abundant dextral shear-sense indicators. A northward increasing strain gradient across the southern boundary of the WSZ is up to 2–3 km wide, whereas the equivalent along the northern boundary appears to be more abrupt, generally less than 250 m. Rocks outside of the shear zone preserve evidence of earlier (Archean?), largely sinistral, deformation. Detailed analytical work, as well as compilation of new and historical data, is now underway to help unravel the complex structural history of the area and investigate the potential relationship between the WSZ and Paleoproterozoic (and possibly older) regional tectonic events.

Slip zone versus damage zone micromechanics, Arima-Takasuki Tectonic Line, Japan

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The Arima-Takasuki Tectonic Line (ATTL) of southern Honshu, Japan is defined by historically active faults and multiple splays producing M7 earthquakes. The damage zone of the ATTL comprises a broad zone of crushed, comminuted and pulverized granite/rhyolite containing cm-scale slip zones and highly comminuted injection veins. In this presentation, prior work on the ATTL fault rocks is extending to include microstructural characterization by transmission electron microscopy (TEM) from recent trenching of the primary slip zone, as well as secondary slip zones. This is necessary to adequately characterize the extremely fine-grained material (typically less than 1 m) in both damage and core zones. Damage zone material exhibits generally random textures[3] whereas slip zones are macroscopically foliated, and compositionally layered, notwithstanding a fairly homogeneous protolith. The latter reflects fluid-rock interaction during both coseismic and interseismic periods. The slip zones are microstructurally heterogeneous at all scales, comprising not only cataclasites and phyllosilicate (clay)-rich gouge zones, but also Fe/Mn pellets or clasts that are contained within gouge. These structures appear to have rolled and would suggest rapid recrystallization and/or growth. A central question related to earthquake recurrence along existing faults is the nature of the gouge. In both near-surface exposures and ongoing drilling at depth, “plastic” or “viscous” gouge zones comprise ultra-fine-grained clay-siliciclastic particles that would not necessarily respond in a simple frictional manner. Depending on whether the plastic nature of these slip zones develops during or after slip, subsequent focusing of slip within them could be complicated.

Canadian Tectonics Group Workshop Schedule - Sunday October 15th - EME 1121

	Time	Presenter	Title
Sesson 1	09:00	Langenberg	*Detachment folds and thrust folds*
	09:20	Root	*Neoproterozoic rift faults in the Purcell Mountains of southeastern British Columbia*
	09:40	Konstantinovaskaya	*Deformation of forearc basin during oblique arc-continent collision in Taiwan : insights from 3D sandbox modeling*
	10:00	Boggs	*The Canadian Cordillera Array is coming soon!*
	10:20	**Poster Introductions**	
	10:30	**Break and Posters**	
Sesson 2	11:00	Schwerdtner	*Late-orogenic cross-folds in the Ottawa River Gneiss Complex, western Grenville Province: Shear-induced sheath folds or products of superimposed deformation?*
	11:20	Hunter	*A Structural Investigation of the Thelon and Judge Sissons faults, northeast Thelon Basin, central Rae Domain, Nunavut*
	11:40	Knox	*Nature and relative timing of deformation along the northern Beniah Fault Zone in the Point Lake area, central Slave Province, N.W.T.*
	12:00	Martel	*The importance of structural mapping in ore deposits - a new perspective on the Howard's Pass Zn-Pb district, Northwest Territories, Canada*
	12:20	**Lunch and Posters**	
Sesson 3	01:30	Ryan	*Solid-state sintering as a lithification mechanism in volcanic conduits*
	01:50	Lenauer	*Regional to outcrop scale – faults in magnetic data*
	02:10	White	*Slip Zone versus Damage Zone Micromechanics, Arima-Takasuki Tectonic Line, Japan*
	02:30	Kellett	*Dating fault gouge: a critical review and case studies*
	02:50	**Wrap-up**	

Posters	10:30 - 11:00 & 12:20 - 1:30	Langenberg	*Detachment folds and thrust folds*
		Cloutier	*Geochemistry and isotopic character of Precambrian granitoid suites across the Nolan-Zemlak domain boundary, west-southwest Rae craton: testing the possibility of a cryptic internal suture zone*
		Deane	*Structural-kinematic relations across the Nolan-Zemlak domain boundary, west-southwest Rae craton*
		McIntyre	*District-wide geodynamic controls on porphyry style mineralization in the Stewart district, northwestern British Columbia: The role of reactivated basement structures*
		Piette-Lauziere	*Deformation and hydrothermal alteration interplay in the Eastern Highlands shear zone, Cape Breton Highlands, Nova-Scotia*
		Therriault	*The Wager shear zone, northwestern Hudson Bay, Nunavut: new mapping and initial structural characterization*
		Soret	*The Evolution of the Southern Asian Margin: P-T-t Paths from the Hindu Kush, Chitral (NW Pakistan)*