Structural controls on the Mitchell Cu-Au porphyry: effects of porphyry alteration on deformation style and strain localization.

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The Mitchell Au-Cu-Mo porphyry deposit is part of the Kerr-Sulphurets-Mitchell (KSM) camp located near Stewart BC. The deposit is hosted in early Jurassic Mitchell intrusions that are contemporaneous with Unuk River Formation volcanic rocks of the Hazelton Group (Stikine Terrane). The deposit is deformed by both brittle and ductile deformation associated with the Cretaceous Skeena fold and thrust belt, and regionally, strain is localized into the deposit relative to areas outside of the porphyry system. The Mitchell thrust fault offsets the upper portion of the deposit by approximately 1600 m. The deposit (owned by Seabridge Gold) hosts 1740 million tonnes at 0.61 g/t Au, 0.17% Cu and 58 ppm Mo based on a 0.5 gold-equivalent gram per tonne cutoff. The offset portion of the porphyry (the Snowfield deposit) has a combined measured and indicated resource of 1370 million tonnes at 0.59 g/t gold, 0.1% Cu and 85 ppm Mo based on a 0.3 gold-equivalent gram per tonne cutoff. The deposit has undergone two phases of folding: 1) F₁ folds plunge steeply to moderately to the west, with an east striking, steeply north dipping axial surface. F₁ folds range from tight to isoclinal in phyllic altered rocks to gentle folds in K-feldspar altered rocks; 2) F₂ folds are gentle, steeply plunging with north-northwest striking, steeply east dipping axial surfaces that cut F₁ folds. The deposit is variably strained, with the intensity of deformation directly correlated with the intensity and type of porphyry alteration. As such, fabric intensity and fold wavelengths vary with host rock alteration type. Within the phyllic and argillic alteration zones, Cu-Au bearing stockwork veins are tight to isoclinally folded, and are associated with a well-developed axial planar cleavage. Folds in the veins are formed by a buckling mechanism and solution transfer processes are widespread. In the chlorite-quartz and quartz-K-feldspar alteration zones, where the competence contrast between quartz veins and host rock is low, folds are gentle to open and are associated with a spaced cleavage. Brittle-ductile conjugate strike-slip faults, found at the cm to metre scale, cut F₁ folds and are cut by F₂ folds and strike: 1) east-northeast and dip 80° to the north with a dextral shear sense and 2) east-northeast and dip 80° to the north with a sinistral shear sense. Flattening and folding strongly control the distribution and morphology of mineralized quartz veins and high-grade breccias. Brittle thrust faults cuts both ductile deformation events and dissect the original deposit along the Mitchell thrust, transporting the Snowfield deposit to the southeast. A ‘Basal thrust’ offsets the deposit an unknown distance at depth and is located ~950 m below the Mitchell thrust fault. Re-Os (vein molybdenite) provides a mineralization age of 190+ 0.8 Ma for the deposit: An Ar-Ar (muscovite) age of 110.2 +2.3 Ma is reported for the Mitchell thrust which offsets the deposit. We propose that all deformation recorded in the deposit occurred between the onset of the contraction related to the Skeena thrust Belt (~ 120 Ma) and 110.2 Ma. We develop a model for the localization of strain in the Mitchell deposit and compare this to other deformed porphyry deposits.
Unconformity-type uranium deposits are one of the most sought after uranium deposit types due to their high grades averaging 1% U₃O₈ with local mining grades greater than 20% U₃O₈ within the McArthur and Cigar Lake deposits of the Athabasca Basin. Unconformity-type uranium deposits are situated at or proximal to the angular unconformity between late Paleoproterozoic, intracratonic, sandstone-dominated sedimentary basins and Archean to Paleoproterozoic tectonically-reworked and metamorphosed metasedimentary and metavolcanic belts. The three main unconformity-type uranium districts in the world are hosted within the Athabasca and Thelon basins in Canada, and the McArthur Basin in northern Australia. Other than their spatial setting, unconformity-style deposits are characterized by low temperature (150° to 220°C) hydrothermal mineral assemblages dominated by extensive clay alteration envelopes proximal to the mineralized zones. The structural controls on mineralization vary throughout the different deposits in each district, and between the different unconformity-type districts themselves. Overall, the mineralization is closely associated with complex episodic brittle to semi-brittle faulting and associated fracturing and brecciation, however, the primary fault kinematics within the different deposits range from compressional, transpressional, strike-slip, and combinations thereof. The overall orientation and geometry of the individual ore deposits can be correlated to specific kinematic components of the controlling fault structures. At a deposit scale, structural controls include perturbations along the faults such as flexures and step-over relations along fault traces, as well as fault splay intersections. Segmentation of the main controlling fault by subsidiary tear faults is typical in many deposits. At an ore lense-scale, mineralization controls include R and T type extensional structures, as well as fracture networks and breccias related to fault damage zones. Rheological contrasts in the basement rocks, including the presence of quartzite or plutonic bodies in the vicinity of the ore-hosting fault zones, as well as the orientation of the main basement rock fabric also bear strong control on the location, geometry, and grade of the ore bodies.

The Tatiggaq Zone is an unconformity-related uranium showing within the northeast Thelon Basin. It is located within Neoarchean Woodburn Lake group metasedimentary rock that was intruded by granite and syenite of the Paleoproterozoic Hudson Intrusive Suite. The area is cut by two ENE-trending dextral strike-slip fault zones, named the Judge Sissons and Thelon faults, as well as subsidiary E-trending dextral faults, NW-trending sinistral faults, and NE-trending faults. These faults are interpreted to represent R, R’, and transpressional faults related to dextral strike-slip faulting at ca. 1.83 to 1.76 Ga. Extensive, multiphase quartz-healed brecciation, ultracataclasites with shearing, and quartz vein stockworks with intriguing epithermal-style textures characterize the main fault conduits. The steeply-dipping uranium mineralization is situated in the hanging-wall to these main structures within the subsidiary fault network.

Diagnosis and formation of hydrothermal breccias in hydrothermal systems

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Analysis of structurally modified epithermal or porphyry systems is commonly hindered by a lack of well-bedded host sediments in volcanic/plutonic terranes and by the inherently irregular geometry of hydrothermal systems. Without reference to an originally horizontal, planar fabric, interpretation of a deformation history has no starting point. A method for analyzing vein geometry and vein system symmetry is presented as a tool for structural analysis of epithermal or porphyry systems and host terranes.

An example is presented from the Stewart Gold-Copper Project, a high-sulphidation epithermal prospect located in the Burin peninsula of Newfoundland. The Stewart Project is characterized by a zone of strong quartz–pyrophyllite ± alunite advanced argillic alteration, hosted in greenschist facies felsic volcanic rocks of the Neoproterozoic Marystown Group. No well-defined bedding or way-up indicators are present in the host felsic volcanic stratigraphy. Two generations of tectonic fabrics ($S_1$ and $S_2$) and locally tight $F_1$ folds overprint the hydrothermal alteration system. Three vein sets (Types 1–3) with distinct mineralogy and mutually orthogonal symmetry axes are also present. Type 1 Quartz veins are interpreted as hydrothermal veins related to the advanced argillic alteration system and pre-date $D_1$ deformation ($S_1$ and $F_1$).

The symmetry axis of the Type 1 vein system is interpreted to have maintained its geometric relationship with the causative hydrothermal system. This symmetry axis thus defines the overall plunge of the system and may define a vector to a porphyritic core. In the absence of a reliable stratigraphic datum or way-up criterion, vein symmetry axis can be a useful structural tool for exploration targeting.
Structures exert controls on both the formation, location and subsequent tectonic modification of volcanic-hosted massive sulphide deposits (VMS). VMS deposits form at, or immediately below, the seafloor by the precipitation of metals from hydrothermal fluids that migrated upwards along syn-volcanic faults and fissures within and along the walls of larger subsidence structures. Thus, identifying the presence of these early faults and subsidence structures is important for VMS exploration. Subsidence structures may be characterized by coarse breccias that are localized along their faulted walls, by thick deposits of aerially restricted volcaniclastic rocks, and by swarms of syn-volcanic dikes and sills. Faults are also present within subsidence structures where they are characterized by abrupt changes in volcanic lithofacies, by strong alteration (e.g., epidote-quartz-chlorite alteration), and by syn-volcanic dikes that occupy the faults. These early faults are primary zones of weakness that are commonly reactivated during subsequent tectonic modification thus obscuring their early syn-volcanic origin.

Because VMS deposits consist of weak ductile sulphide minerals, they can be strongly modified during deformation. Most sulphide minerals are ductile at temperatures of at least 100°C - 200°C below those of most rock types, except carbonates, but they can be slightly stronger than their clay-altered host rocks at low metamorphic rocks. At high metamorphic grades, the ductility contrast between sulphide minerals and their host rocks decreases and their rheological behavior becomes similar. Internal structures that are indicative of tectonic deformation of VMS lenses include sulphide breccias (also called durchwebegung structure), sulfide layering, folding and layer transposition, asymmetrical strain shadows around rigid clasts, and piercement structures in the wallrocks of sulphide lenses. On the scale of a deposit, tectonic modification of the ore lenses may be expressed by the elongation of ore lenses parallel to a regional stretching lineation, the thickening of ore lenses in the hinge of regional folds, thrust-stacking of the VMS lenses, and by complete transposition of the deposit. Primary metal zoning in sulphide lenses is generally robust during deformation and remobilization. Thus metal zoning can be used to reconstruct the primary geometry of a deposit that has been strongly deformed, folded and transposed. Examples of deformed VMS deposits from Proterozoic to Paleozoic orogenic belts will be discussed with emphasis on deposits from the prolific Flin Flon Belt in Manitoba and Saskatchewan.
Magmatic Ni-Cu massive sulphide deposits consist of weak sulphide minerals, including, in order of increasing strength, chalcopyrite, pyrrhotite and pentlandite. Because Ni-Cu massive sulphide deposits are typically weaker than their host rocks, strain partitioning results in strong deformation of the deposits as high strain zones and shear zones. However, the strong deformation is usually masked by post-deformation recrystallization and annealing of the sulphide minerals, but several structures can provide evidence for the strong deformation. These include piercement structures, sulphide breccia or durchwebegung texture, infilling of fractures by weaker sulphide minerals cutting through strong inclusions, ductile flow of sulphides into the hinges of mesoscopic drag folds, the formation of pentlandite “eyes” or porphyroblasts that overprint a tectonic layering, and the boudinage and folding of competent (quartz/calcite?) veins, rock fragments, and dikes within the deposits. Piercement structures form by ductile flow of the weak massive sulphides into brittle fractures in the more competent wall rocks. During deformation, rock fragments are plucked from the wall rocks and entrained within the ductilely flowing sulphides forming sulphide breccias. Flattening of the fragments during deformation can produce a foliation and stretching lineation that are coplanar and colinear to the foliation and lineation, respectively, in the deformed wall rocks. The foliation and lineation in massive sulfide ore can also form by tight folding and transposition of dikes and veins cutting though the ore lenses, and the oriented growth and/or rotation of unequant metamorphic silicate minerals such as amphibole and biotite. Pyrrhotite-pentlandite-chalcopyrite ore can revert to a metamorphic monosulfide solid solution (MSS) during upper greenschist facies metamorphism and at higher temperatures. Thus, the ore can deform as a homogeneous MSS, which with decreasing temperatures, will exsolve pentlandite along grain boundaries of elongate flattened pyrrhotite grains as “eyes” or porphyroblasts that overgrow the tectonic foliation. Most of these features occur in deformed contact-style Ni-Cu-PGE magmatic deposits in the South Range of the Sudbury impact structure in Sudbury, Ontario. During the Penokean Orogeny, the South Range was cut by reverse shear zones that preferentially followed weaker massive sulphides ore lenses. The latter will be used as examples to discuss the development of tectonic structures in deformed massive Ni-Cu sulphide deposits.
Structural and tectonic controls on Archean gold mineralization: examples from the Abitibi-Wawa Subprovince of the Superior Province

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Young-Davidson and Hemlo gold deposits occur in the Abitibi-Wawa Subprovince of the Superior Province. The Young-Davidson deposit is an intrusion-related lode-gold deposit that at least in part is structurally controlled. It is associated with the development of the Cadillac–Larder Lake deformation zone and hosted in a syenite of ~2679 Ma. Three main generations of veins are identified in the syenite: V1 quartz-ankerite veins, V2 quartz-pyrite veinlets and V3 quartz-carbonate veins. The major phase of gold mineralization is associated with V2 veins. Gold mineralization and vein emplacement appear to have occurred during shearing and the syenite acted as a mechanical trap due to competency contrast.

The Hemlo deposit is a disseminated and replacement style gold deposit that is spatially associated with a stratigraphic contact. The protolith is mainly a fragmental rock and a barite horizon occurring at the contact. The contact and the fragmental rock at the contact probably served as mechanical traps and the barite horizon as a chemical trap. The deposit is located in the Hemlo shear zone and mineralization occurred during shearing, before mid-amphibolite-facies peak metamorphism. Mineralization was occurring at ~2677 Ma and most likely had started earlier. Mineralizing fluids probably had a magmatic source, interpreted to be related to the 2682–2677 Ma granodioritic (sanukitoid) plutons abundant in the vicinity.

In spite of the obvious differences, the two deposits share many similarities. Both are genetically related to shear zones and late mantle-derived intrusions that are of similar ages, and the associated shear zones have similar kinematic history and probably have similar ages. The two deposits appear to share a common tectonic origin and their different characteristics may be due to variation in local geological settings. In particular, we suggest that the gold deposits, the intrusions and the hosting shear zones all developed within a regime characterized by synchronous vertical and horizontal tectonism at the late stages of Archean cratonization. They were all possibly linked to a range of processes associated with the accretionary growth and stabilization of the craton, in particular slab break-off and the associated extensional orogenic collapse following terrane accretion.
Structural geology: a key to mineral deposit studies in deformed terrain

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Structural geology has played and will continue to play a key role in mineral deposit studies and mineral exploration in deformed terrain. Many mineral deposits are structurally controlled, both at the regional and deposit scales. The ore bodies and/or the host rocks are often deformed, whether the deposits were originally structurally controlled or not. Structural study is necessary for understanding the current geometry and the kinematic history, for restoring the geometry and thus the spatial relationships among different lithological units/structures at different stages of the geological history (in particular at the time of mineralization), and for understanding the relationships among various geological events (e.g. alteration/mineralization, deformation, sedimentation, metamorphism, magmatism, etc.). All these will help to understand the genesis of the deposits concerned and identify favourable locations for mineralization. In this introductory talk, these general points are discussed using examples from various parts of Canada.
Veins as tectonites in high strain zone settings.

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Veins develop on a number of scales during the evolution of high strain zones, from macroscopic vein-fracture arrays from centimetres to hundreds of metres, to micro-veins associated with porphyroclasts. Most represent a brittle response to stress, part of the evidence for transient permeability, and mass-transfer during deformation. Under general shear the initial orientation of vein-arrays relates to the instantaneous strain ellipsoid, but progressive deformation sees a continuous rotation of all material lines that do not lie parallel to the eigen vectors (where vorticity = 0). While veins originate as a passive response to strain, during subsequence progressive deformation the role of veins and related wall-rocks has a more complex relationship to strain. Recrystallization of vein material can produce strain hardening, while the original vein-fill may be a focus for strain partitioning. Wall-rock alteration may produce strain softening especially associated with carbonate and phyllosilicate growth, and again control strain partitioning. Fragmented vein-fills can behave as competent boudins, or small porphyroclasts, which themselves control further vein formation, reflecting control over transient permeability. Brittle responses to strain generally represent late stage evolution in high strain zones, but brittle features can form during overall ductile deformation in response to local perturbations in fluid pressure and strain rates. These brittle responses can range from the fracturing of porphyroclasts and boudin, to cataclastic dikes with pseudotachylite. Examples of all these complex relationships are examined from the Gill Lake area, Nunavut; Heath Steele mine, northern New Brunswick; the Clarence Stream high strain zone, southern New Brunswick; and the Lynn Lake area, Manitoba. The Gill Lake area displays sequential veins in deformed granitoids reflecting a cooling hydrothermal system; Clarence Stream exhibits brittle episodes during the development of mylonites; the Lynn Lake area illustrates the effects of wall-rock alteration on strain partitioning; while Heath Steele illustrates mass-transfer effects in massive sulfides.
Structural setting of possible IOGC-type mineralization in deformed Carboniferous rocks, southern NB.

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The Partridge Island Block (PIB) in the Saint John area of southern New Brunswick is part of a late Devonian-early Carboniferous terrane recently recognized in the Appalachians of southern New Brunswick. Its framework is a sequence of basaltic and felsic volcanic rocks and related red mudstone-siltstone-sandstone, intruded by a suite of leucotonalite-alkali granite with earliest Tournaisian ages. The PIB is the a detached part of the larger Cobequid Highland block of Nova Scotia. The PIB has a complex tectonic relationship with adjacent Appalachian terranes, partly across major strike-slip high strain zones, partly overthrust onto the middle to late Carboniferous cover (especially the mid-Carboniferous Ball's Lake Formation and Pennsylvanian Lancaster Formation), and itself overthrust by the Cambrian Saint John Group.

The Cobequid Highland zone in Nova Scotia hosts extensive IOGC-type mineralization, and this distinctive mineralization is also seen in the PIB, and elsewhere in the coastal strip around Saint John and to the southwest toward Maces Bay and Point Lepreau. Most of this mineralization is expressed as ubiquitous hematite veins (often with specularite), but around Coleson Cove, Lorneville and east of Saint John harbour, true IOGC-type veins carry quartz-siderite±hematite±copper sulfides. The host rocks for most of this mineralization are the mid- to upper Carboniferous Balls Lake and Lancaster formations, and vein arrays display a genetic relationship to the thrusts and shear zones that bound the PIB, formed during late Pennsylvanian deformation. This period of mineralization is at least 30 million years later than the last igneous activity in the PIB.
Structural control of potash ore bodies fall naturally into two distinct categories. The majority of North American potash deposits occur in relatively flat lying regional basins which have been structurally altered by the development of evaporate karst features, including wash outs and collapse of overlying formations. Also, migrating fluids have, in places, resulted in the selective removal of potash minerals with the retention of halite and associated insolubles to form features known as “salt horses”. All of the features described above can have a major influence on the logistics and economics of developing and mining a potash ore body, and the distribution of these structures can impact the viability of any operation.

The potash deposits in eastern Canada differ from the large continental deposits. They are typically the result of deposition in small, rapidly subsiding half-grabens, resulting in variable bed thicknesses, syndepositional slumping, salt withdrawal from margins and diaperic thickening, with associated dissolution of potash on the crests of these structures. Later, regional compression resulted in the development of nappe structures, isoclinals recumbent folding, sheath folds, intraformational breccias and a strong foliation within the potash and associated carnallite. All these features have an impact, both positive and negative, on the mining of these deposits.

In eastern Canada a number of these structurally complex potash deposits have been explored throughout the Maritimes Basin. Most of these deposits have been found to be of limited size, low grade and non-commercial, with the exception of southern New Brunswick where three potash mines have been developed. These underground mines allow the detailed structural control of potash ore bodies to be examined “in outcrop”; something that is not possible from surface mapping and drilling. This presentation will focus on these unique evaporate structures.
Structural controls on gold mineralisation in the Trans Hudson Orogen with a specific focus on the New Britannia Mine, Snow Lake, MB.

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Orogenic gold deposits are usually associated with quartz vein systems, which are broadly coeval with deformation, metamorphism and magmatism in compressional and transpressional environments during continental collision. The 1.9 – 1.8 Ga Trans Hudson Orogen (THO) in Saskatchewan and Manitoba comprises a series of lithotectonic domains, including the La Ronge, Glennie, Lynn Lake, Flin Flon, and Snow Lake domains. These domains exhibit different styles of orogenic gold deposits which reflect a change in tectonic regime, metamorphic grade and timing of gold mineralisation from west to east across the THO. The deposits are associated with shear zones at higher metamorphic grade, and fault zones at lower metamorphic grade within transpressional to thrust-and-fold belt settings.

Shear zone hosted gold mineralisation at mid to upper amphibolite facies metamorphism is the predominant style of gold deposit in the La Ronge (Komis deposit and Roxy showing), Glennie (Seebee deposit) and Lynn Lake domains (Burnt Timber and MacLellan deposits). The deposits are associated with oblique-extensional (Komis) or shear veins (Seebee and Burnt Timber) associated with major orogen-parallel shear zones. The shear zones exhibit a steeply plunging stretching lineation, together with dextral shear sense indicators on horizontal surfaces, suggesting dextral transpression. Many gold deposits in the western Flin Flon Domain (e.g. Rio deposit) formed at sub–greenschist grade conditions within a conjugate system of brittle-ductile faults.

In the Snow Lake domain, gold deposits formed at mid-amphibolite grade temperatures during the formation of regional thrust faults and late transcurrent faults and shear zones. The North Star deposit displays two styles of gold mineralisation and shows evidence for remobilisation of gold along reactivated faults. The New Britannia mine which is the most significant past producer of the THO exhibits varying styles of mineralisation: i) the main mine is associated with a fault breccia style mineralisation associated with a potential splay or transfer fault from the main thrust fault, ii) other deposits on the property are located at lithological contacts (Boundary, Birch and No. 3 zones) where a fault intersects the hinge of the main regional fold, or iii) they are located along early thrust fault contacts (Bounter zone).