New Models for Mineral Exploration in British Columbia: Is There a Continuum Between Porphyry Molybdenum Deposits and Intrusion-Hosted Gold Deposits?

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Introduction

There has been little research into, or exploration for, molybdenum deposits in Canada or elsewhere since the early 1980's. There are numerous poorly understood, relatively under-explored molybdenum deposits and occurrences in the Canadian Cordillera. There are geochemical similarities between porphyry molybdenum deposits and "intrusion-hosted" gold deposits in the Cordillera. Although there is no gold in the Adanac deposit itself, placer gold is currently being mined on the lower reaches of Ruby Creek below the deposit. The close proximity of these two mineral occurrences raises the possibility that the Adanac molybdenum deposit may by the roots of a hydrothermal system that produced molybdenum and gold. This scenario is consistent with mineral zonation in other intrusion-hosted gold deposits (Thompson et al. 1999). Understanding the association, or lack thereof, between the gold and molybdenum in this area is an important step toward focusing further exploration in the Cordillera for both of these deposit types.

The first goal of this research is to determine the place of the Adanac deposit within the spectrum of molybdenite deposits. The second goal of the research is to compare the Adanac molybdenum deposit to intrusion-hosted gold deposits in the North American Cordillera and to determine whether there are geochemical similarities between Adanac and these deposits.

Geologic Setting

The Adanac molybdenum deposit is in northwest British Columbia near the town of Atlin (Figure 1). The geology of the Atlin area was mapped by Aitken (1959) and the regional setting of the deposit is discussed by Christopher and Pinsent (1982). The area is underlain by serpentinites, limestones, basalts, and shales of the accreted Cache Creek Terrane. It is Pennsylvanian and Permian in age and weakly metamorphosed. These rocks are intruded by two younger batholiths, the Jurassic Fourth of July and the Cretaceous Surprise Lake Batholith.

The Adanac deposit occurs in the western margin of the Surprise Lake Batholith (Figure 2). It occurs at the head of Ruby Creek, under the floor of an alpine cirque. Here, porphyry domes intrude the batholith, and mineralization occurs as a sub-horizontal stockwork of veins above these porphyries. The mineralization and intrusions are cut off to the north by the Adera Fault, which also defines the southern boundary of the Fourth of July Batholith.

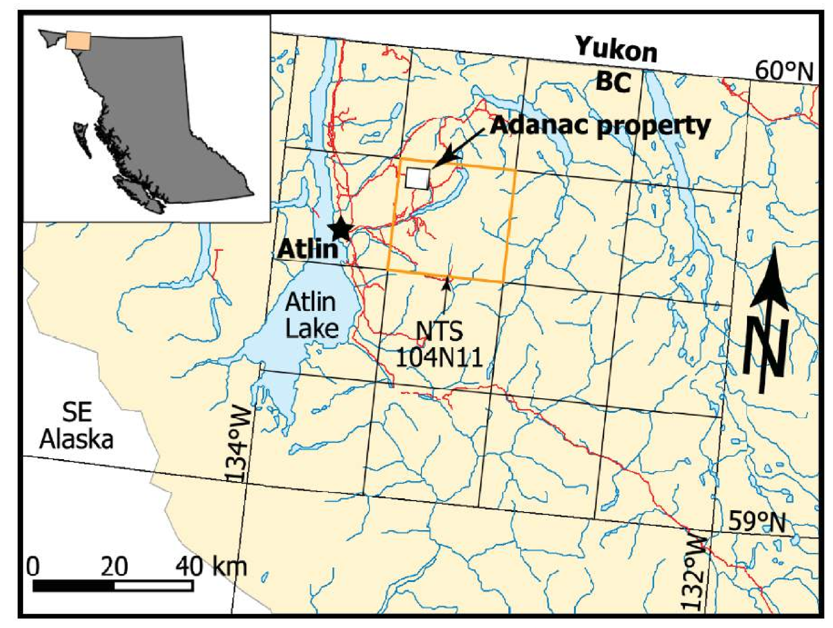


Figure 1. Location map for the Adanac molybdenum deposit.

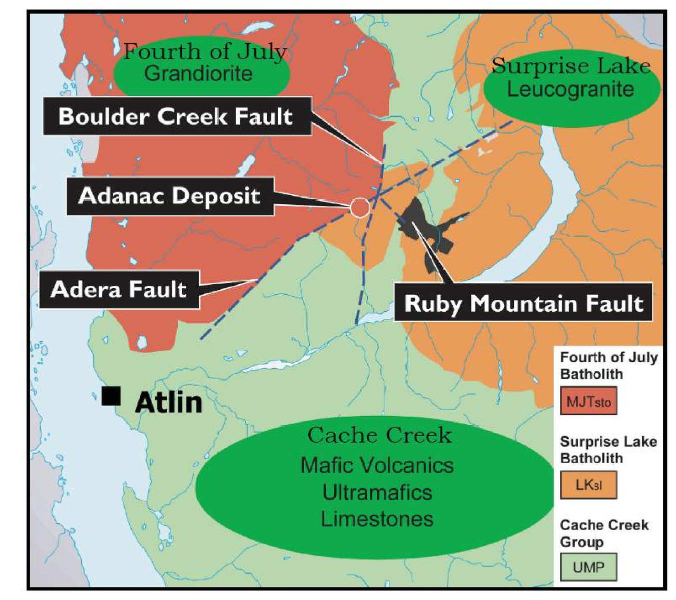


Figure 2. Generalized regional geology of the Adanac deposit. Modified from Aitken, 1959.

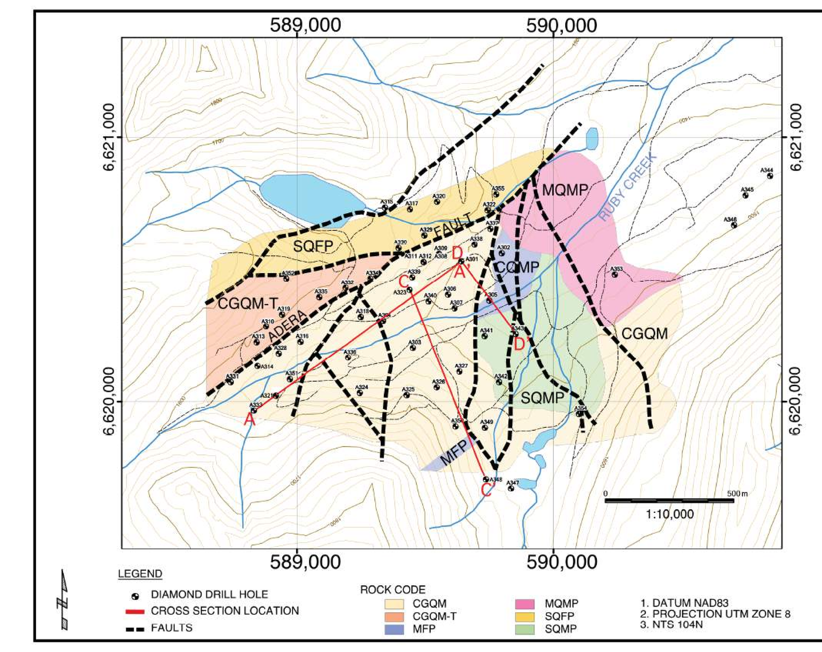
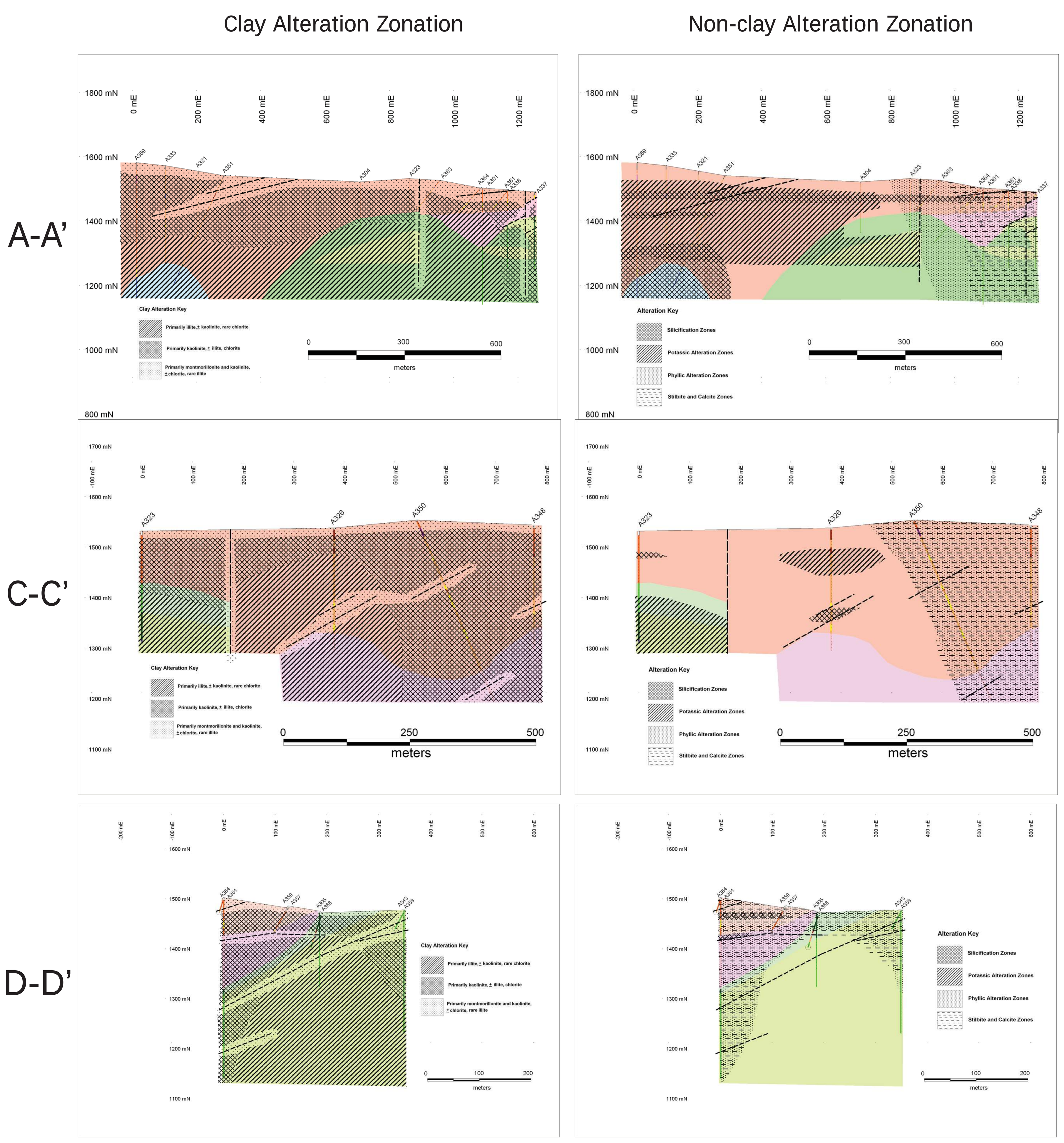
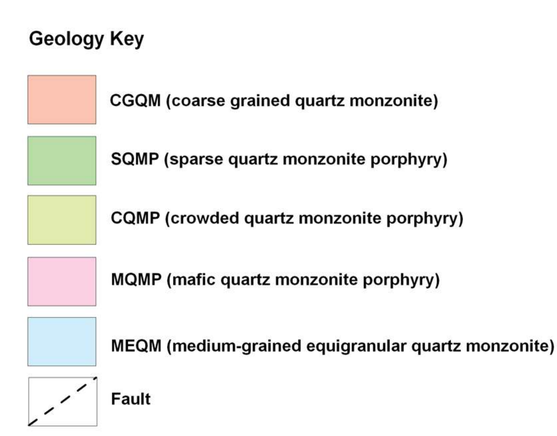
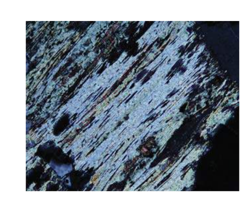


Figure 3. Surface geology of the Adanac deposit showing drill hole and cross section locations. Modified from Christopher and Pinsent, 1982.

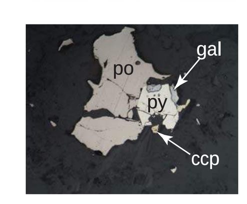
Clay Alteration Zonation / Non-clay Alteration Zonation







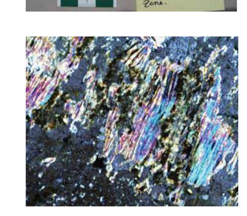
Silicification of biotite. Thin section photo, 20x, crossed polars.



Common opaques in silicified zones. Pyrrhotite (po), pyrite (py), chalcopyrite (ccp), and galena (gal). Thin section, 20x, reflected light.

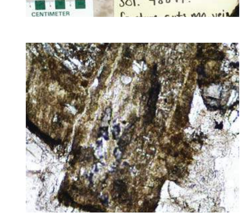
Surface of feldspar in potassic alteration zone. Note light brownish dustings, which are weak clays. Thin section photo, 10x, plane light.

Feldspar flooding in drill core.

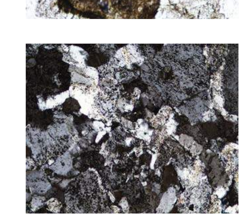


Sericite altered chlorite near a QSP vein. Thin section photo, 10x, crossed polars.

Vuggy stilbite-filled fracture (brown crystals in open fracture) in drill core.



Montmorillonite in thin section. Montmorillonite is the dark colored material replacing the feldspars. 10x, plane light.



Illite or kaolinite in thin section, on feldspars. 10x, crossed polars.

Hydrothermal Alteration

Characteristics of hydrothermal alteration at Adanac:

Alteration characteristics were determined from 35 polished thin section analyses and 22 X-ray diffraction analyses of clay altered and fresh rocks. Sample locations were determined based on drill holes re-logged over summer 2007 with a focus on alteration. Non-clay alteration and zonation is discussed below followed by a description of alteration characteristics. These alteration zones are listed in paragenetic order based on cross-cutting relationships seen in drill core. Clay alteration and associated zonation is discussed last.

Alteration Zonation

The zoning of alteration at Adanac is moderately well pronounced. High silica, or silicification zones, occur at depth on the western end in cross section A-A'. Areas of silicification in this area are common and may extend for up to 6 feet in drill core. Silicification extends to all other areas in the cross sections as patchy zones that form sill-shaped bodies traceable from one drill hole to the next. They do, however, become less frequent and smaller (one foot) away from the deeper western end. Silicification zones appear to drape over and extend the MEQM intrusion on the west, and drape over the SQMP and CQMP intrusions to the east. Potassic zones occur above the main silicification zones on the western end of A-A' and coincide with the upper sill-shaped bodies of silicification. Potassic alteration also occurs inside the SQMP and CQMP in the central area of A-A'. The main potassic zone consists either of 1-3 feet of pink feldspar flooding (near complete replacement of original mineralogy) or a high frequency of potassic envelopes around veins. The quartz-sericite-pyrite (QSP or phyllic) alteration zone appears in the eastern portion of A-A', and in the southern portions of the deposit, represented in cross sections C-C' and D-D' on the right hand side. The stilbite-calcite zone overprints the phyllic zone further to the east in cross section A-A', and is entirely coincident with the phyllic zone in the southern portions of the deposit. Neither the phyllic or stilbite-calcite zones appear in deeper, fresher portions of the SQMP and CQMP intrusions in cross section D-D'.

Alteration Characteristics of Adanac Compared to other Porphyry Molybdenum Deposits:

Most porphyry molybdenum deposits have a potassic core, a quartz-sericite-pyrite zone, and outer and upper argillic and propylitic zones (Westra and Keith, 1981). Calc-alkaline type deposits have poorly developed potassic zones compared with alkalic or alkali-calcic type porphyry molybdenum deposits. Alkalic and alkali-calcic deposits are also more likely to have high silica cores, or silicification zones. At Climax, alteration zones are more complex and intense, because the deposit formed from multiple intrusions which caused overprinting of alteration zones (White et al., 1981). Alteration at Climax does, however, include a high silica core in the deepest parts of the intrusion, below mineralized areas. Above silicification and straddling the deepest (and youngest) intrusion is both the potassic zone and the youngest blanket of mineralization. Outward from this core of intrusion and mineralization are the argillic (kaolinite and montmorillonite), QSP, and propylitic zones. Because this pattern of alteration is so similar to Adanac, it is likely that the core (mineralizing intrusion) of the deposit is closest to the western end of cross section A-A', and perhaps is the MEQM.

Silicification is characterized by the addition of quartz and opaque minerals, typically pyrite. Silicification occurs as patchy zones that extend for one foot to several feet in drill core. Quartz is seen in thin section replacing feldspars and biotite or chlorite. Opaque minerals include, in paragenetic order from oldest to youngest, 1) magnetite 2) pyrite 3) pyrrhotite-molybdenite-galena 4) sphalerite- chalcopyrite-galena. These minerals are found disseminated and in veins. Magnetite commonly replaces biotite or chlorite and pyrite replaces the magnetite and biotite or chlorite. All other sulfides replace magnetite or pyrite, in the orders listed above. Pyrite and magnetite are the most abundant opaques. About 1/3 of the biotite is altered to chlorite or (less commonly) sericite. Sericite also occurs on feldspars. Epidote is sometimes seen as disseminated fine grains. Clay alteration occurs as dustings on feldspars but does not destroy textures. XRD analyses suggest this is likely illite.

Feldspar flooding, or potassic alteration, is characterized by added fresh pink feldspar, that occurs as replacement zones extending to several feet in drill core, or as envelopes around quartz veins. Secondary biotite occurs in the floods, and is noticeably fresh. Secondary biotite is 2-3 mm in size up to 5cm. It is characterized by shredded, anhedral textures and crystal sizes that are larger than primary biotite. In thin section, pyrite is typically absent, but magnetite may be present. There is some dusty clay alteration on feldspars which is most likely illite. Several samples displayed fluorite that appeared to be cogenetic with rock-forming minerals. There are abundant euhedral calcite grains in most samples, which appear to be cogenetic with potassic alteration.

The phyllic, or quartz-sericite-pyrite (QSP) zone is characterized in hand sample by 1-3mm sized veinlets or fractures filled with quartz, sericite, and pyrite, with sericite and pyrite also extending into 1-6cm envelopes around the veins or fractures. This area commonly displays greenish or bluish hues in hand sample. In thin section there is an increased amount of clay alteration in this zone compared with silicified and potassic alteration zones, with feldspars typically having centers that are texturally destroyed. The alteration of biotite to chlorite is more common than in silicified and potassic zones as well. Clay minerals in the QSP zone are dominated by kaolinite, with chlorite and illite being common.

The stilbite-calcite zone is characterized in hand sample by 2mm to 3cm-sized fractures that are filled with calcite and stilbite + fluorite. These fractures are seen to cut all other alteration types. Fractures may be completely filled with calcite and stilbite or sometimes are open and contain only vuggy, euhedral stilbite. Rocks also display a greenish or bluish hue, similar to the QSP alteration. Fluorite is also present with this stage of alteration, as it occurs as vein fill along with both calcite and stilbite. In thin section, stilbite is confined to veins and fractures, but both calcite and fluorite are seen in adjacent wall rock. Clay alteration in this zone is similar to that in QSP zone. Clay alteration has increased relative to fresher rocks and zones of silicification and potassic alteration. Centers of feldspars are destroyed texturally, displaying clays in their place. These clays are primarily kaolinite, with chlorite and illite being common as well.

Clay zonation: Phyllosilicate alteration minerals identified include illite, kaolinite, chlorite, and montmorillonite. Rocks that show no apparent clay alteration in hand sample, or that are silicified or feldspar flooded, show minor clay patches on feldspars in thin section. Textural features within the feldspars are still visible. These rocks are dominated by illite; contain less kaolinite and chlorite; and montmorillonite is absent. Because these rocks show no evidence of fracturing or gouge, it is assumed that only early primary fluids passed through these rocks, and therefore illite is the dominant clay product of these fluids. Further away from the zones containing abundant silicification and feldspar flooding, the rocks begin to display a greenish or bluish hue. Feldspars become increasingly texturally destroyed in the centers. Areas outside of fresher rocks and silicified or potassic zones are dominated by kaolinite, with chlorite and illite being common, and montmorillonite absent. Kaolinite and chlorite therefore are the main clay products of late primary hydrothermal fluids. Faults, or rock that exhibits gouge or crumbling in the drill core, have a dirty olive green or brown appearance. In thin section, the feldspars are texturally destroyed and contain black, white, and dark brown patches. These rocks are always dominated by montmorillonite and kaolinite, commonly contain chlorite, and less commonly contain illite. These rocks almost certainly allowed groundwater fluids to pass through them, and montmorillonite may be the product of these fluids based on its presence exclusively in faults.

Geochemistry of Adanac in Comparison with other Deposits

Geochemistry of Adanac compared with other molybdenum deposits:

Major element geochemistry was determined for ten samples of fresh rock; one from each major lithology in the deposit; using ICPMS. Normative mineral amounts were calculated using the CIPW (Cross et al., 1903) method. Using the IUGS system of classification (Streckeisen, 1973), all rocks in the suite are granites (Figure 4). An alkali-lime index at 50 wt% SiO_2 was calculated, meaning the rocks are further classified as alkalic (alkalic = alkali-lime index <51 wt% SiO_2).

Published literature on porphyry molybdenum deposits broadly outlines two basic types of deposits, the "granite" and "quartz monzonite" types (White et al., 1981). Westra and Keith (1981) recognized that these two basic types can be separated based on the K_2O content at 57.5 weight% SiO_2. A natural dividing line occurs between those deposits with K_2O content of less than 2.5% and those with contents above that. Molybdenum deposits with a K_2O content of less than 2.5% are classified as "calc-alkaline" quartz-monzonite types. These deposits have low F values (0.1-0.25%); lower molybdenite grades (0.25%); little Sn; and W present as scheelite. Source plutons have between 100-350 ppm Rb, and 100-800 ppm Sr (Figure 5). Those deposits with K_2O contents above 2.5% are broadly referred to as the Climax type of deposit. Such deposits are associated with alkali-calcic to alkalic granites, and are enriched in F (0.5- >5%) and Sn. Rubidium content of the source plutons is typically 200-800 ppm, with less than 125 ppm Sr. The molybdenite grades are typically higher (>0.30% MoS_2) than the QM type, and W is present as wolframite.

Using the Westra and Keith classification model, the Adanac deposit fits well with other Climax-type deposits. The K_2O content was calculated at greater than 2.5%. All rocks at Adanac are alkalic granites. Tungsten in the deposit is present as wolframite. The deposit is enriched in F, typically containing between 0.2 and 1%. Figure 5 illustrates how the $K_2O_{57.5}$ value for Adanac and other deposits is consistent with the Rb vs. Sr data in dividing porphyry molybdenum deposits based on geochemistry.

Geochemistry of Adanac in comparison to intrusion-hosted Au deposits:

Intrusion-hosted Au deposits occur in the North American Cordillera in the Tombstone-Tungsten magmatic belt, in the Tintina gold province of Alaska and Yukon. These deposits are associated with reduced granites and granodiorites of the type that commonly host W or Sn porphyry or skarn deposits (Thompson et al., 1999). These Au deposits are not always typical porphyry deposits, i.e., with Au being found in a multidirectional stockwork of quartz veins within the intrusion itself. The gold may be up to 3km away from the associated intrusion, hosted in tension veins or skarns. The associated metals and trace elements are Bi, W, As, Sn, Mo, Te, and Sb. The Au itself is correlated at the deposit level with Bi and Te, while As, W, and Mo typically occur in deeper parts of the system, or may occur in separate zones away from the intrusion. It is a reasonable question to ask, considering Adanac's close proximity to placer gold operations, whether or not some of this placer gold was originally hydrothermal and related to the same event as the molybdenite. Geochemical investigations of Adanac and intrusion hosted gold deposits, however, have revealed some important differences. Intrusion-hosted Au deposits in the North American Cordillera (Fort Knox, Dublin Gulch, Donlin Creek, and Scheelite Dome, to name a few) are commonly associated with more reduced types of magmas than are Climax-type porphyry molybdenum deposits. These deposits are associated with ilmenite-series magmas while Adanac, based on thin section studies, clearly has abundant magnetic magnetite and no ilmenite. Strontium contents of these mineralizing plutons (>1000 ppm) tend to be a bit higher than Climax-type molybdenum deposits (<125 ppm) as well. For example, the Deadman pluton, a large pluton in the Yukon that is part of the Tombstone suite, has elevated Sr (600-3500 ppm) (Flanders et al, 2006).

Hallmark trace element signatures for intrusion-hosted Au deposits are not present at Adanac. Even while the Au zones and W-Mo zones are separate in porphyry Au deposits, with W and Mo typically being closer to the intrusion, it is not uncommon to find some Au in veins in the intrusion itself. In addition, it is common for veins in intrusions hosting these Au deposits to have anomalous Bi, Au, As, and Sb. These anomalies are orders of magnitudes higher than the values seen at Adanac. Scheelite Dome, for example, has early intrusion-hosted W veins, while the main Au mineralization occurs outside and adjacent to the mineralizing stock (Mair et al, 2006). These W veins contain 10-100 ppm Au and around 600 ppm As. There is almost no gold (<0.1 ppm) at Adanac and As is generally background, usually between 1 and 60 ppm. Even in the tungsten trenches peripheral to the molybdenite zone at Adanac, where one might hope Au to begin to increase with distance from the intrusion, Au is only 0.6 ppb and As is <0.5 ppm. While Bi, Te, and Sb are all less than 0.5 ppm in the W veins at Scheelite Dome, values of all three elements increase in gold-bearing tension veins within the mineralizing intrusion to 200-1000 ppm Bi, 20-50 ppm Te, and 60-800 ppm Sb. Bismuth at Adanac occasionally hits higher values (up to 130 ppm), but only rarely; typically Bi is in the range of 3 to 30 ppm. Antimony rarely is up to 30 ppm, clearly below the values for the gold deposits. There are no data for Te at Adanac.

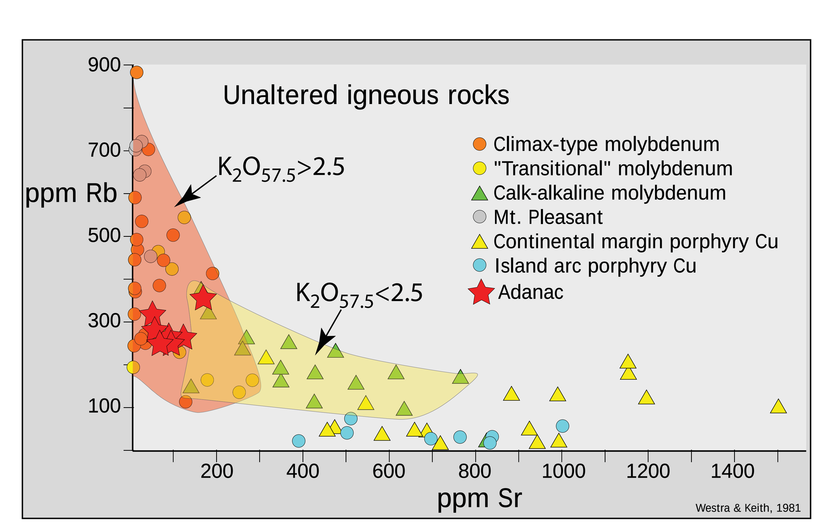


Figure 5. Graph showing Rb and Sr values for various types of porphyry deposits, including copper porphyries and a tungsten-molybdenum porphyry (Mt. Pleasant). The $K_2O_{57.5}$ value fields are superimposed on the graph. As their $K_2O_{57.5}$ value would indicate, rocks at Adanac fall within the field of Climax-type deposits. Modified from Westra and Keith (1981) to include Adanac.

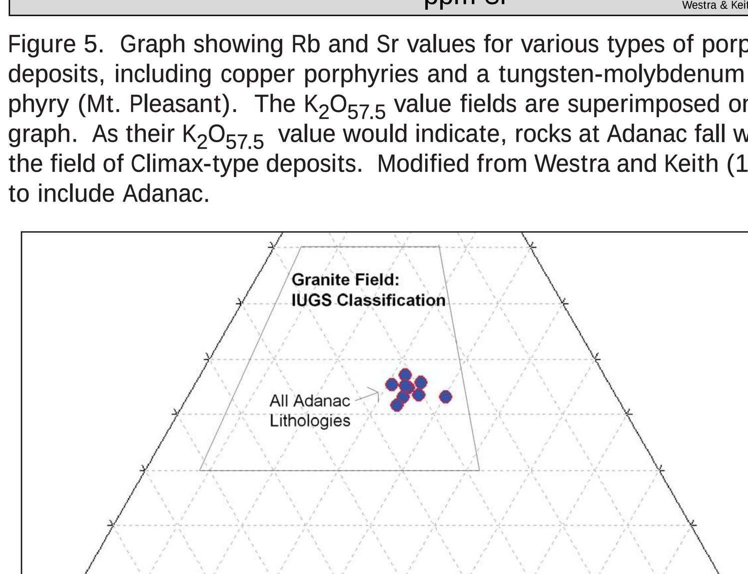


Figure 4. Ternary plot showing the IUGS rock classification scheme. All Adanac rocks plot in the granite field.

Conclusions

The Adanac porphyry molybdenum deposit falls into the category of a Climax-type deposit on the basis of geochemistry of Rb, Sr, and $K_2O_{57.5}$. The host rock is a peraluminous, high-F, alkalic granite. Hydrothermal alteration characteristics and zonation patterns are consistent with a Climax-type deposit as well, having well defined zones of silicification, potassic alteration, QSP alteration, and argillic alteration.

Based on preliminary studies of intrusion-hosted Au deposits in comparison with Adanac, placer gold on the lower reaches of Ruby Creek may not be related. However, it is still possible that there may be unexplored areas in the immediate vicinity of Adanac (1-3 km) that display more geochemical similarities to intrusion-hosted Au deposits than to Adanac.

Geochronologic measurements over the coming year will more clearly elucidate the timing and duration of both magmatic and hydrothermal mineralization events. Broader comparison of Adanac to other molybdenite deposits as well as intrusion-hosted Au deposits will allow us to further refine our genetic and tectonic models for both deposit types in the Canadian Cordillera.

Ongoing Work

Ongoing work for this project includes a geochronologic study of both the mineralization and magmatic events, a microprobe study of trace element content in biotites, further investigation of connections between local placer gold operations and the Adanac porphyry molybdenum deposit, and finally, a summary regional exploration model.

The first aspect of the geochronologic study is the dating of mineralization events using Re-Os isotopes in molybdenite from various samples throughout the deposit. In conjunction with mineralization dates, the timing of magmatic events will be determined using U-Pb isotope ratios in zircons. It is hypothesized that deeper lithologies on the southwest end of the deposit (MEQM) will yield ages closest to mineralization.

We intend to further investigate the connection between molybdenite and intrusion-hosted Au deposits. This will proceed on two fronts. First, we will continue to compile data for both other molybdenite deposits and intrusion-hosted Au deposits to determine what the similarities and differences are between these two deposit types in the Cordillera. Second, on a more local scale, we plan to compare initial Os isotope signatures of local placer gold with Os signatures from magnetite in the same vein with molybdenite at Adanac. If the signatures are similar, it may be postulated that hydrothermal system(s) of the same age in the same area are responsible for both Au and Mo mineralization.

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