Early Jurassic porphyry(?) copper (-gold) deposits at Minto and Williams Creek, Carmacks Copper Belt, western Yukon

Reza Tafti and James K. Mortensen[1]
Mineral Deposit Research Unit, Earth & Ocean Sciences, University of British Columbia[2]

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ABSTRACT

The Minto and Williams Creek copper (-gold) deposits in western Yukon are hosted by variably deformed Early Jurassic (198-197 Ma; U-Pb) plutonic rocks and to a lesser extent strongly metamorphosed supracrustal rocks. These rocks are pendants and schlieren within slightly younger (197 Ma; U-Pb), intermediate-composition intrusive phases of the Granite Batholith. Chalcopyrite and bornite are disseminated and also occur as stringers in these rocks. Alteration muscovite associated with late quartz-feldspar-epidote veins gives a 182 Ma Ar-Ar age. Geobarometry on post-mineral intrusive phases in the area indicate that they were emplaced at a depth of >9 km. Hornblende geochemical studies of plutonic and meta-plutonic host rocks at Minto and Williams Creek indicate that they formed in a continental magmatic arc setting. Cu/Au ratios and field observations indicate that supergene mobility of copper was more extensive at Williams Creek than at Minto. Our results indicate that the two deposits represent variations on typical copper (-gold) porphyry deposits.

RÉSUMÉ

Les gisements de Cu (-Au) de Minto et de Williams Creek dans l'ouest du Yukon sont encaissés dans des roches plutoniques (198-197 Ma; U-Pb) du Jurassique précoce variablement déformées et dans une moindre mesure dans des roches supracrustales fortement métamorphisées. Ces roches constituent des enclaves dans des phases intrusives de composition intermédiaire légèrement plus jeunes (197 Ma; U-Pb), du Batholite de Granite. La chalcopyrite et la bornite sont disséminées et forment également des filonnets dans ces roches. La muscovite d'altération associée aux filons tardifs de quartz-feldspath-épidote donne un âge de 182 Ma selon la méthode Ar-Ar. L'analyse géobarométrique de phases intrusives postérieures à la minéralisation indique que leur mise en place a eu lieu à plus de 9 km de profondeur. Des études géochimiques de la hornblende contenue dans les roches plutoniques et méta-plutoniques encaissantes aux gisements de Minto et de Williams Creek indiquent qu'elles se sont formées dans un arc magmatique continental. Les rapports Cu/Au et les observations sur le terrain indiquent que la mobilité supergène de Cu a été plus étendue au gisement de Williams Creek qu'à celui de Minto. Selon les résultats que nous avons obtenus, les deux gisements représentent des variations de gîtes porphyriques de Cu(-Au) typiques.

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[1] *jmortens@eos.ubc.ca*

[2] *6339 Stores Road, Vancouver, British Columbia, Canada V6T 1Z4*

INTRODUCTION

The north-northwest-trending, informally named 'Carmacks Copper Belt', in west-central Yukon (Fig. 1) contains the Minto deposit (Yukon MINFILE 2002, 115I 021 and 022, Deklerk, 2002) and the Williams Creek (Carmacks Copper) deposit (Yukon MINFILE 2002, 115I 008, Deklerk, 2002), which is located approximately 50 km to the southeast of the Minto deposit. Several other copper (± gold) occurrences, some of which have been drilled (e.g., the Stu; Yukon MINFILE 2002, 115I 011, Deklerk, 2002), are also present in the area between these two deposits. The Minto deposit was discovered in 1971 and contains approximately 9 million tonnes of ore with an average grade of 1.73% Cu, 0.48 g/t Au and 7.5 g/t Ag (Deklerk, 2002). The Williams Creek (Carmacks Copper) deposit contains published reserves of approximately 15.5 million tonnes at 1.01% Cu (Deklerk, 2002). The nature and origin of the two deposits are poorly known because both deposits are deformed, metamorphosed, deeply weathered, variably oxidized by meteoric waters, and poorly exposed. Original lithological and contact relations are generally only exposed in exploration trenches, road cuts and drill core. Previous workers have assigned these deposits to various different deposit types, including metamorphosed volcanogenic massive sulphide deposits, metamorphosed redbed copper deposits and deformed copper-gold porphyries (e.g., Pearson, 1977; Sinclair, 1977; Pearson and Clark, 1979). Exploration for additional mineralized zones of the Minto or Williams Creek type in the region has been hampered by the lack of genetic or exploration models for the deposits. The purpose of the current project is to gain a better understanding of the nature of copper (-gold) deposits and the main host rock units in the Minto and Williams Creek deposit areas. This information will form the basis for new genetic and exploration models for copper (-gold) deposits in the Carmacks Copper Belt. During the 2002 and 2003 field seasons, the authors examined and sampled surface exposures of the Minto Main Zone, host rocks for the mineralized rock zones exposed in new cuts in the vicinity of the camp and along the access road at Minto, and exposures of the No. 1 and No. 12 zones at Williams Creek, as well as core from

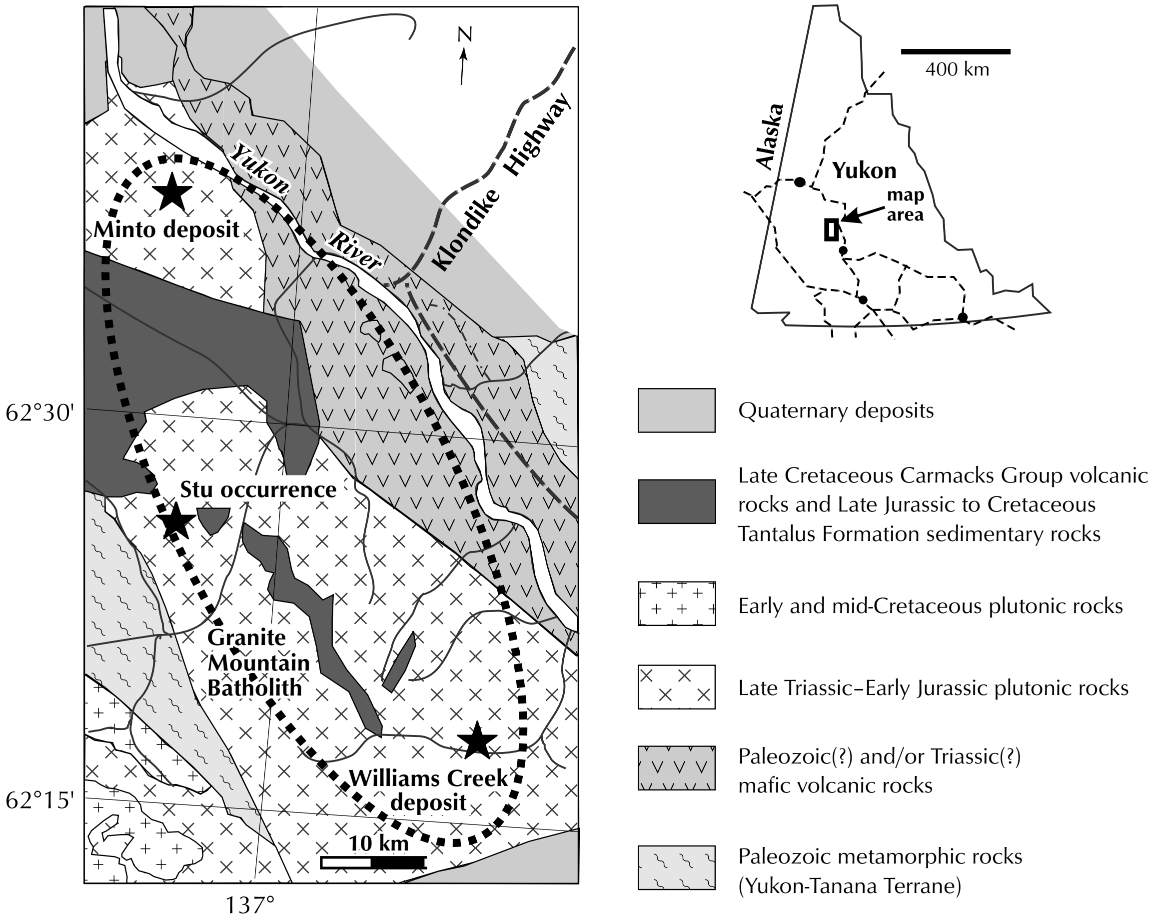

Figure 1. *Map showing the location and regional geological setting of the Minto and Williams Creek deposits and the Stu occurrence (Yukon MINFILE occurrences, Deklerk, 2002; geology simplified from Gordey and Makepeace, 1999). The Carmacks Copper Belt is outlined by the heavy dashed line.*

several drill holes at Minto and Williams Creek and the Stu prospect. This work included documenting the nature of contact relationships between rock units, and detailed sampling for petrographic, geochemical and geochronological studies. Magnetic susceptibility measurements were also taken on representative samples of the main lithological units to help constrain interpretations of ground and airborne magnetic surveys.

PREVIOUS WORK

The Williams Creek deposit was discovered by J.G. Abbott in 1970 (Abbott, 1971), who recognized that the copper was contained mainly within lenses of gneissic and amphibolitic rock (interpreted to be metasedimentary in origin) that were surrounded by unmineralized intrusive rocks. Abbott (1971) noted some similarities between the Williams Creek deposit and typical porphyry copper deposits. Sinclair (1977) carried out geological mapping in the vicinity of the Minto deposit, as well as reconnaissance-level geochemical studies of intrusive rocks in the area. Pearson (1977; see also Pearson and Clark, 1979) completed a Master of Science thesis focused on the Minto deposit, which included petrographic, mineralogical and geochemical studies, as well as a limited amount of sulphur isotope work on the sulphide minerals at Minto. A 1:250 000-scale geological map of the Carmacks map sheet was published by Tempelman-Kluit (1984). The detailed geology of the Minto and Williams Creek deposits is described in numerous unpublished mineral assessment reports prepared by various company geologists. A low-level airborne magnetic and radiometric survey was flown over the entire Minto-Williams Creek area by the Geological Survey of Canada and the Yukon Geology Program in 2001 (Shives et al., 2002). No geological interpretation of this new geophysical data set has yet been published.

REGIONAL SETTING

Three main lithological assemblages underlie the Minto-Williams Creek area. Intermediate to felsic intrusive and meta-intrusive rocks of the early Mesozoic Granite Batholith underlie much of the area and are interpreted to be intrusive to the Yukon-Tanana Terrane (Fig. 1; Gordey and Makepeace, 1999). The batholithic rocks are in fault and/or intrusive contact with an unnamed package of altered mafic volcanic rocks to the northeast, and are unconformably overlain by sedimentary rocks and volcanic flow rocks of the Late Cretaceous Tantalus Formation and Late Cretaceous Carmacks Group, respectively. Copper and gold at Minto and Williams Creek are hosted by deformed and metamorphosed rafts and pendants of older intrusive rock units and supracrustal rocks contained within the Granite Batholith. Regional structure is poorly understood because outcrop is very sparse (<1% exposure; Fig. 2), and the area is unglaciated and deeply weathered. In addition, there is a lack of detailed geological mapping in this area. However, some significant steep faults have been recognized in the area (e.g., the DEF fault at Minto; see later discussion).

GEOLOGY OF THE CARMACKS COPPER BELT

Much of the Minto-Williams Creek area is underlain by intrusive and meta-intrusive rocks. Stained slabs and thin section petrography together with field observations were used to differentiate between different intrusive phases in the area. Sample modes have been calculated for representative stained slabs using digital image analysis methods, as described by Duncan (1999). Based on modal analysis, ten distinct intrusive phases were identified in the Minto and Williams Creek area (Mortensen and Tafti, 2003). Compositions range from granodiorite to quartz monzodiorite to diorite. Quartz diorite and diorite are more common at Williams Creek than at Minto. These rocks are equigranular to porphyritic, and massive to moderately foliated. The porphyritic phases contain phenocrysts of K-(potassium) feldspar, plagioclase and/or quartz. In some instances the K-feldspar phenocrysts range up to 3 cm long. Post-mineralization granitic pegmatite and aplite dykes are widespread in the area, especially at Minto.

Microscopic studies of the intrusive rocks indicate that biotite occurs as the main mafic mineral in all phases. Hornblende is present in dioritic and quartz dioritic intrusive rocks and locally in the granodioritic phases. Euhedral to subhedral epidote and allanite are present in some of the unfoliated intrusive phases (Fig. 3). Much of this epidote is clearly part of the original mineral assemblage of the rock and is therefore considered to be 'magmatic' epidote (see later discussion). Quartz, K-feldspar and plagioclase (oligoclase) are present in all intrusive phases. Plagioclase is subhedral and very locally displays growth zoning. Zircon, titanite and apatite are the main accessory minerals, and are present in all of the intrusive phases. Euhedral garnet (almandine) occurs locally in some of the intrusive phases (especially the

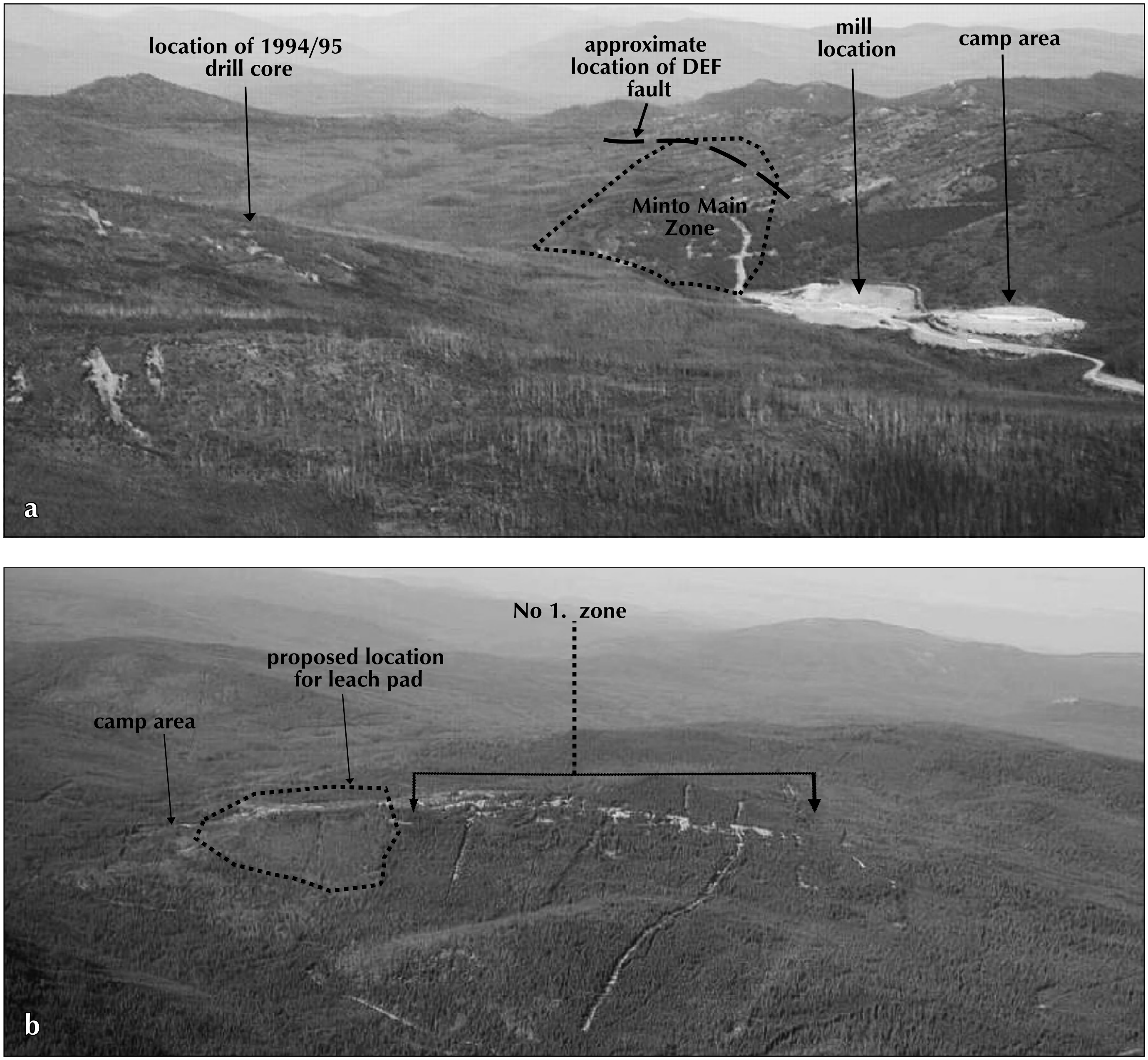

Figure 2. (a) *Aerial view of the Minto deposit area (looking northwest) showing the approximate location of the DEF fault and the Main Zone.* ***(b)*** *Aerial view of the Williams Creek deposit (looking west) showing the No. 1 zone and the proposed location for leach pad.*

foliated granodiorite at Minto) and ranges up to 0.7 cm in diameter. The main opaque mineral is magnetite and locally ilmenite. Biotite and hornblende have locally been partially altered to chlorite and secondary epidote. This alteration is more extensive in the more strongly foliated rocks. Some late calcite veinlets are also present.

The immediate host rocks for copper- and gold-mineralized rock can be divided into three types: 1) biotite-rich gneiss and quartzofeldspathic gneiss (main ore hosts at Minto and Williams Creek); 2)'siliceous ore' at Minto and rarely at Williams Creek; and 3) fine-grained 'amphibolite' and biotite schist at Williams Creek. The petrography of the host rocks is discussed in more detail in a later section.

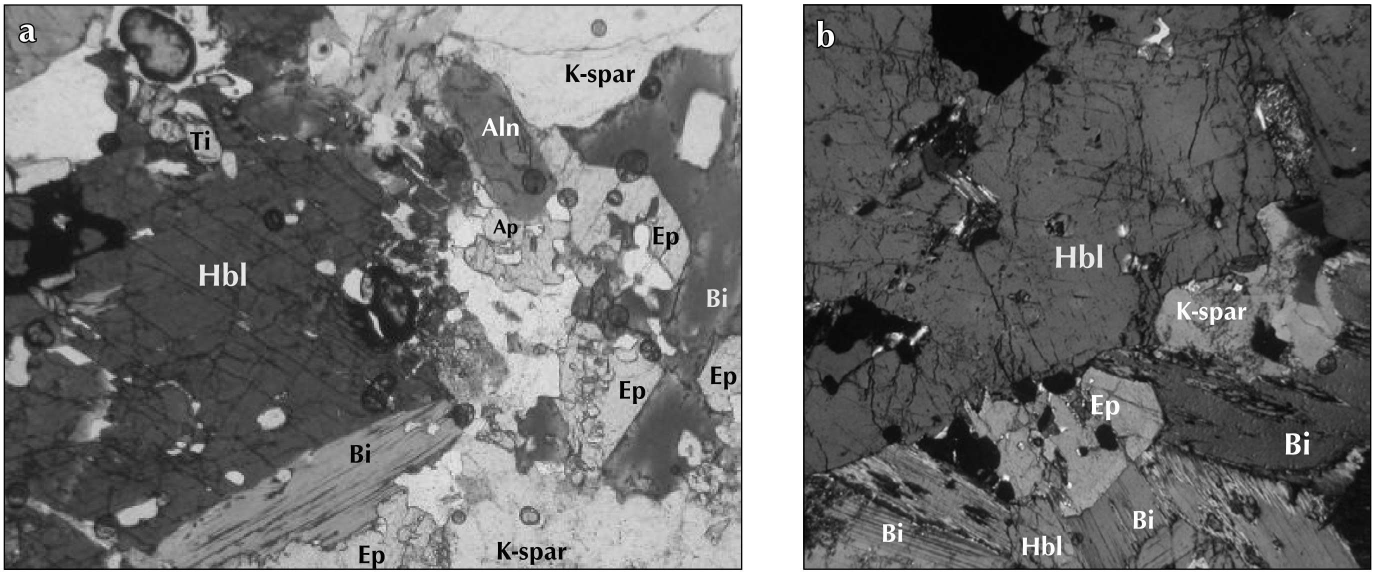

Figure 3. *Photomicrographs of massive K-feldspar-phyric granodiorite at Minto.* ***(a)*** *Sub-euhedral grains of epidote (Ep) and allanite (Aln) are present; plane-polarized image, field of view is 3 mm.* ***(b)*** *Subhedral epidote (Ep) showing zoning; cross-polarized image, field of view is 2 mm. Bi = biotite; Ap = apatite; K-spar = potassium feldspar; Hbl = hornblende; Ti = titanite.*

CONTACT RELATIONSHIPS AND STRUCTURAL GEOLOGY

The structural evolution of the Minto and Williams Creek areas, and the nature and origin of the foliation(s) within the various rock units are critical for understanding the genesis of the two deposits. Alignment of K-feldspar phenocrysts in the porphyritic granodiorite of the Granite Batholith is ascribed to magmatic flow. It is likely that some alignment of mafic minerals and mineral aggregates, and potentially the formation of mafic schlieren observed locally within the batholith, may have also occurred during emplacement of the intrusion. However, petrographic studies of the intrusive rocks show that they have been affected by at least two distinct phases of foliation development. Feldspar phenocrysts (mainly plagioclase) in the main phase of porphyritic diorite and quartz diorite at Williams Creek are typically strongly recrystallized in both the massive and foliated phases. Many of the moderately to strongly foliated phases show features of strong recrystallization and strain in quartz and plagioclase grains, which indicate tectonic deformation and metamorphism at biotite grade (300-400°C). Field relationships and drill core intercepts show that this foliation is cut by massive to slightly foliated intrusive phases (Fig. 4) and by several generations of aplitic dykes. Ductile deformation has also affected some of the late dykes that cut the massive intrusive rocks (Fig. 5). The foliation in orthogneiss units is parallel to the foliation of amphibolite/biotite-schist wall rocks at Williams Creek, which indicates they were deformed together (Fig. 6). There are numerous cases of small-scale, ptygmatically

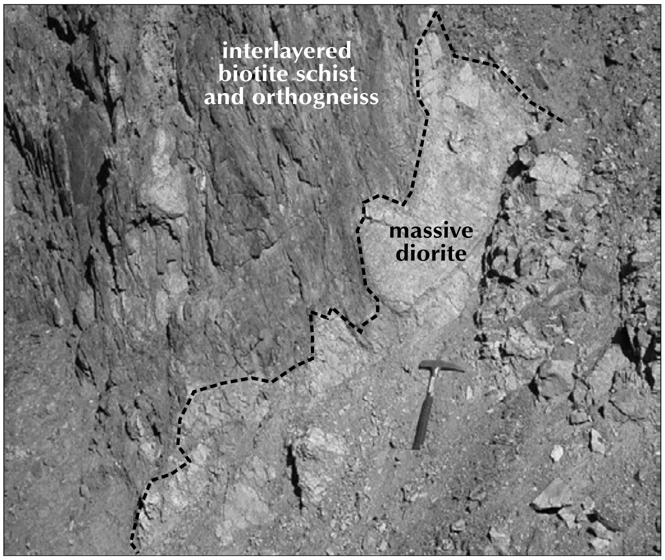

Figure 4. *Sharp contact between interlayered biotite schist and orthogneiss, and massive, post-mineralization diorite in the hanging wall of the No. 1 zone at Williams Creek (bulk sampling trench 91-20).*

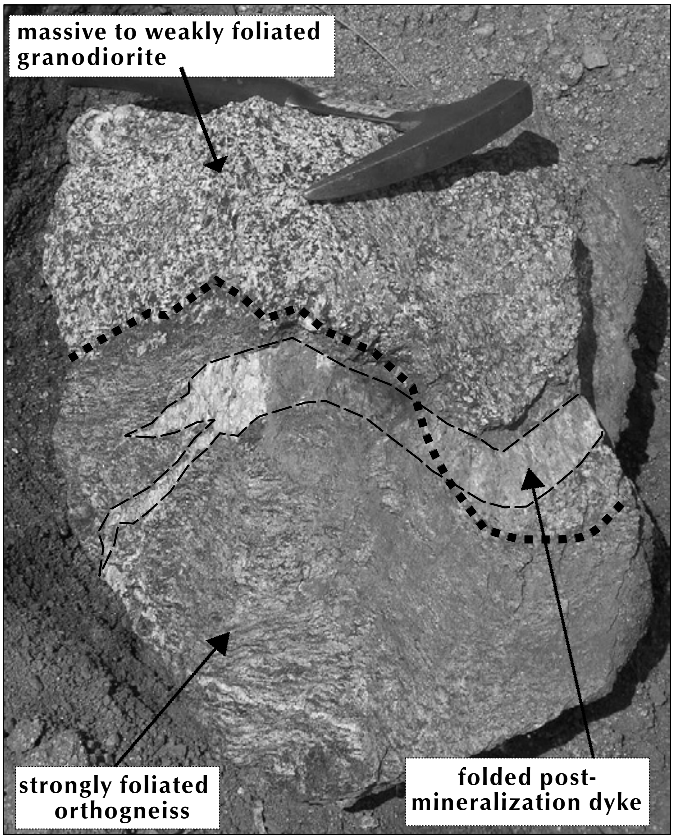

Figure 5. *Contact between a well foliated orthogneiss and a massive K-feldspar-phyric granodiorite at Minto. The small dyke cuts the main body of granodiorite and cuts across the foliation of the orthogneiss. The contact between the massive granodiorite and the orthogneiss, as well as the small dyke and the foliation in the orthogneiss, are folded into gentle open folds.*

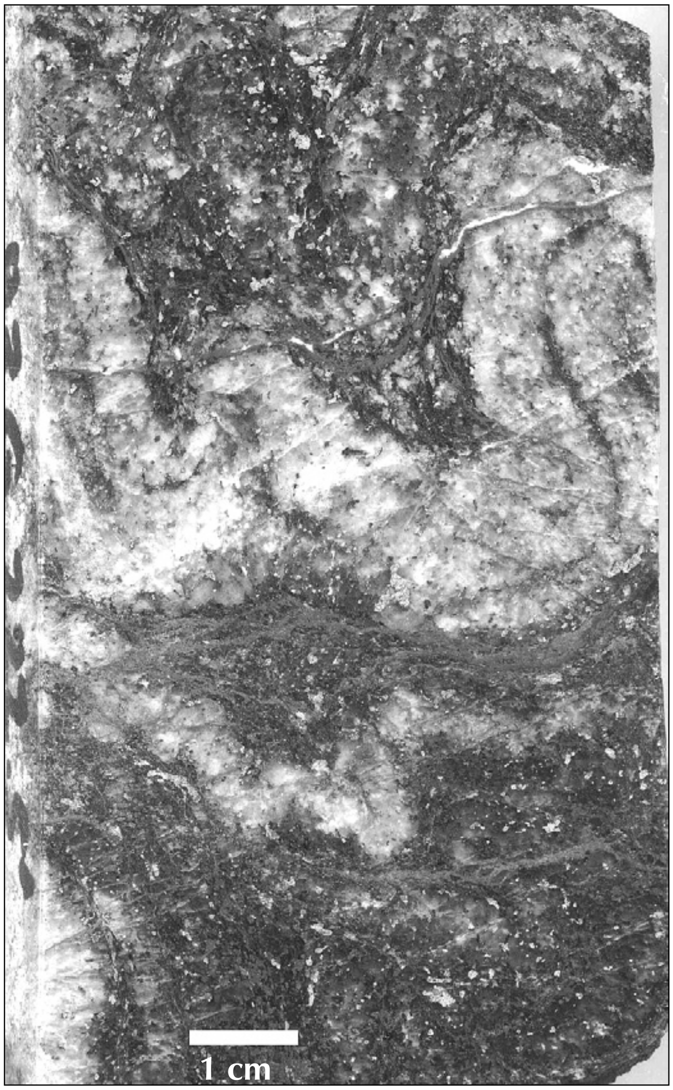

Figure 7. *Slab of strongly deformed, mineralized orthogneiss with ptygmatically folded aplitic dyke.*

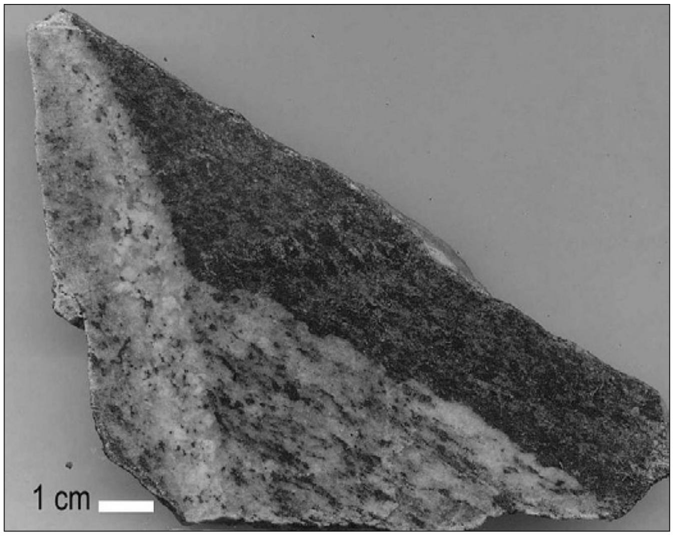

Figure 6. *Interlayered biotite schist and orthogneiss that are cut by a granodiorite dyke. Foliation in both the schist and orthogneiss is parallel, indicating that they were deformed at the same time.*

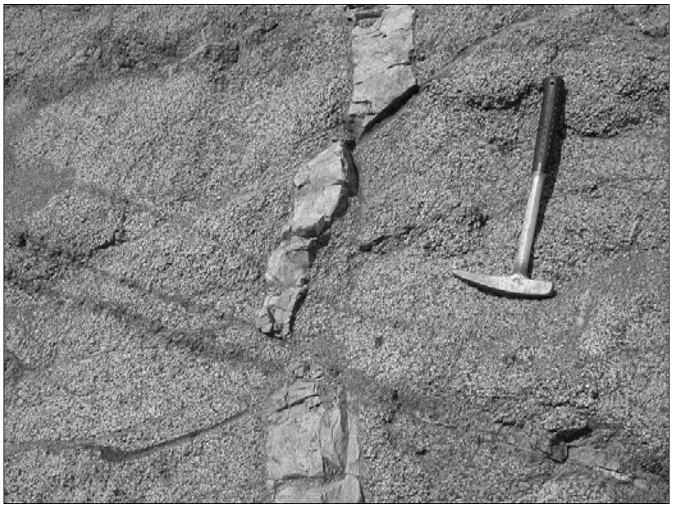

Figure 8. *Small-scale conjugate fault sets displacing a late aplite dyke at Minto.*

folded aplite/pegmatite dykes within strongly deformed orthogneisses (Fig. 7).

Late, post mineralization, brittle faults at several different orientations have been identified in the area, including the east-west-trending DEF fault that forms the northern boundary of the Main Zone at Minto (Fig. 2a). In some instances (e.g., Fig. 8), the brittle faults form conjugate sets. These young brittle faults have facilitated deep circulation of surface water and oxidation of the hypogene sulphide minerals and their host rocks, including the pervasive hematization noted throughout parts of the Minto deposit. In addition, substantial block rotation has occurred at Minto, at least locally. This is evidenced by the tilting of younger sedimentary units (probably Late Jurassic to Cretaceous Tantalus Formation) south of the Main Zone at Minto by up to 60° (bedding/core angles as low as 30° in vertical drill hole 99-01). Such late fault block rotation may in part account for the anomalously shallow dips of the dominant foliation in gneissic host rocks in the Minto Main Zone. The difference between the mainly subhorizontal dip of foliation at Minto and the much steeper (up to vertical) dips at Williams Creek may also be due to large-scale block rotation.

GEOCHRONOLOGY

Preliminary uranium-lead (U-Pb) zircon ages of 194 ± 1 Ma and 192 Ma were reported by Mortensen and Tafti (2003) for a mineralized and strongly foliated granodiorite from Minto and massive porphyritic quartz diorite of the Granite Batholith at Williams Creek, respectively. A detailed U-Pb and Ar-Ar (argon) dating study of the two deposits and their host rocks is now underway. The recent work has demonstrated that the intrusive rocks in this area have very complex U-Pb systematics, with multiple ages of zircon inheritance and significant post-crystallization lead-loss. We have obtained U-Pb zircon and/or titanite ages for the following samples:

- fine-grained granitic orthogneiss at Williams Creek (197.3 ± 1.5 Ma; zircon);
- K-feldspar-phyric granodiorite at Williams Creek (197.3 ± 1.5 Ma; zircon);
- plagioclase-phyric diorite at Williams Creek (197.3 ± 1.5 Ma; zircon);
- mineralized garnetiferous orthogneiss at Minto (197 ± 2 Ma; zircon);
- K-feldspar-phyric granodiorite at Minto (192 ± 2 Ma; titanite);
- post-mineralization granitic dyke at Minto (195 ± 1 Ma; zircon).

Although field relationships clearly show that the massive phases of the Granite Batholith are younger than the foliated and mineralized intrusive phases, they are actually very similar in age.

Two samples of coarse muscovite from selvages, developed adjacent to late quartz-feldspar-epidote veins at Minto that are associated with strong bleaching and K-feldspar alteration, gave Ar-Ar plateau ages of 182 ± 1 Ma. These veins are observed to cross-cut pegmatite and aplite dykes that locally contain miarolitic cavities and must therefore have been emplaced at relatively shallow levels. We therefore interpret the Ar-Ar ages to date the latest hydrothermal event that affected the Minto area.

GEOBAROMETRY AND GEOTHERMOMETRY

The aluminum-in-hornblende geobarometer of Anderson and Smith (1995) was used in combination with the amphibole-plagioclase thermometer of Blundy and Holland (1990) to determine the depth and temperature of emplacement of some of the intrusive phases in the study area. McCausland et al. (2002) previously reported surprisingly great depths of emplacement of intrusive rocks in the Williams Creek area based on aluminum-in-hornblende geobarometry. Our results show that the latest intrusive phases in the Minto and Williams Creek area formed at depths of more than 9 km. The presence of euhedral to subhedral epidote that is interpreted to be magmatic in origin in some of these samples is consistent with a pressure during crystallization of at least 6 kbar (corresponding to depths of ~18-20 km; e.g., Zen and Hammarstrom, 1984).

Crystallization temperatures for several of the intrusive phases were calculated using amphibole-plagioclase thermometry. The resulting temperature estimates of 720°C to 840°C are surprisingly low for intrusive rocks with granodioritic to dioritic compositions. Model temperatures for intrusive rocks from throughout the Minto and Williams Creek area were also calculated using zircon saturation geothermometry (Watson and Harrison, 1983). This method yields similar and in some cases even lower magmatic temperatures than those obtained from the amphibole-plagioclase equilibria. The significance of these consistently low temperature estimates is uncertain at this point.

GEOCHEMISTRY

Major, trace and rare-earth element compositions have been determined for more than 40 samples of mainly unmineralized, foliated and unfoliated intrusive rocks, and 5 samples of amphibolite and biotite schist in the Minto and Williams Creek area. They indicate that most intrusive rock units are subalkaline, and weakly to moderately peraluminous. Concentrations of immobile trace, high field-strength and rare-earth elements are most consistent with generation in a continental magmatic arc. Calculated ferric/ferrous ratios for the samples are between 0.17 to 0.67, which indicate that these are moderately oxidized magmatic rocks. Mineralized rock units are compositionally very similar to the unmineralized phases but appear to be slightly enriched in K and some trace elements. Summary geochemical plots for these samples are shown in Figure 9.

Our results from the Minto and Williams Creek area indicate that intrusive rocks in this area are geochemically very similar to other Late Triassic and Early Jurassic intrusive rocks elsewhere in the Yukon-Tanana Terrane in Yukon and eastern Alaska as described by Mortensen et al. (2000).

COPPER-GOLD DEPOSITS AT MINTO AND WILLIAMS CREEK

Results of the fieldwork and petrographic studies confirm that the main host rocks for both the Minto and Williams Creek deposits are variably deformed plutonic rocks. The Minto deposit is mainly hosted within foliated biotite and quartzofeldspathic orthogneiss (‘quartzofeldspathic ore’), with a lesser amount of copper- and gold-mineralized rock contained within a banded, relatively quartz- rich rock (‘siliceous ore’). The mineralized zones are enclosed by massive to very weakly foliated granodiorite of the Granite Batholith. The main host for the Williams Creek deposit is orthogneiss of dioritic to quartz dioritic composition, and to a lesser extent supracrustal rocks (amphibolite and biotite schist). In surface exposures at Williams Creek (e.g., the bulk sample trenches within the main No. 1 zone), copper is present in both orthogneisses and supracrustal rocks; however, nearly all of the contained copper appears to be as secondary copper-oxide minerals along fracture surfaces, and there is little evidence that significant amounts of hypogene copper sulphide minerals were ever present in these rocks. As at Minto, the mineralized zones and their deformed and metamorphosed host rocks at Williams Creek are enclosed by massive quartz diorite and granodiorite of the Granite Batholith (Fig 4).

Petrographic and field studies of ‘quartzofeldspathic ore’ and biotite-rich gneiss show that these rock types are strongly deformed and metamorphosed intrusive rocks (orthogneiss), and the excess amount of biotite appears to represent secondary (hydrothermal) biotite associated with strong hypogene potassic alteration.

‘Siliceous ore’, which is well developed at Minto and locally present at Williams Creek, is typically thinly banded on a scale of millimetres to 1 cm, with layers consisting mainly of quartz (± K-feldspar) and lesser amounts of magnetite, as well as disseminated bornite and chalcopyrite. These characteristics suggest derivation from a very different protolith than the quartzofeldspathic or biotite-gneiss units. These quartz-rich bands could have been derived from siliceous layers in a thinly bedded supracrustal sequence, or could in part represent completely transposed sets of quartz veins, or both.

Geochemistry and petrography of fine-grained ’amphibolite‘ at Williams Creek (actually mainly biotite schist) indicate that these rocks had a supracrustal protolith, most likely an intermediate or mafic volcanic rock, or epiclastic rock of this composition. The presence

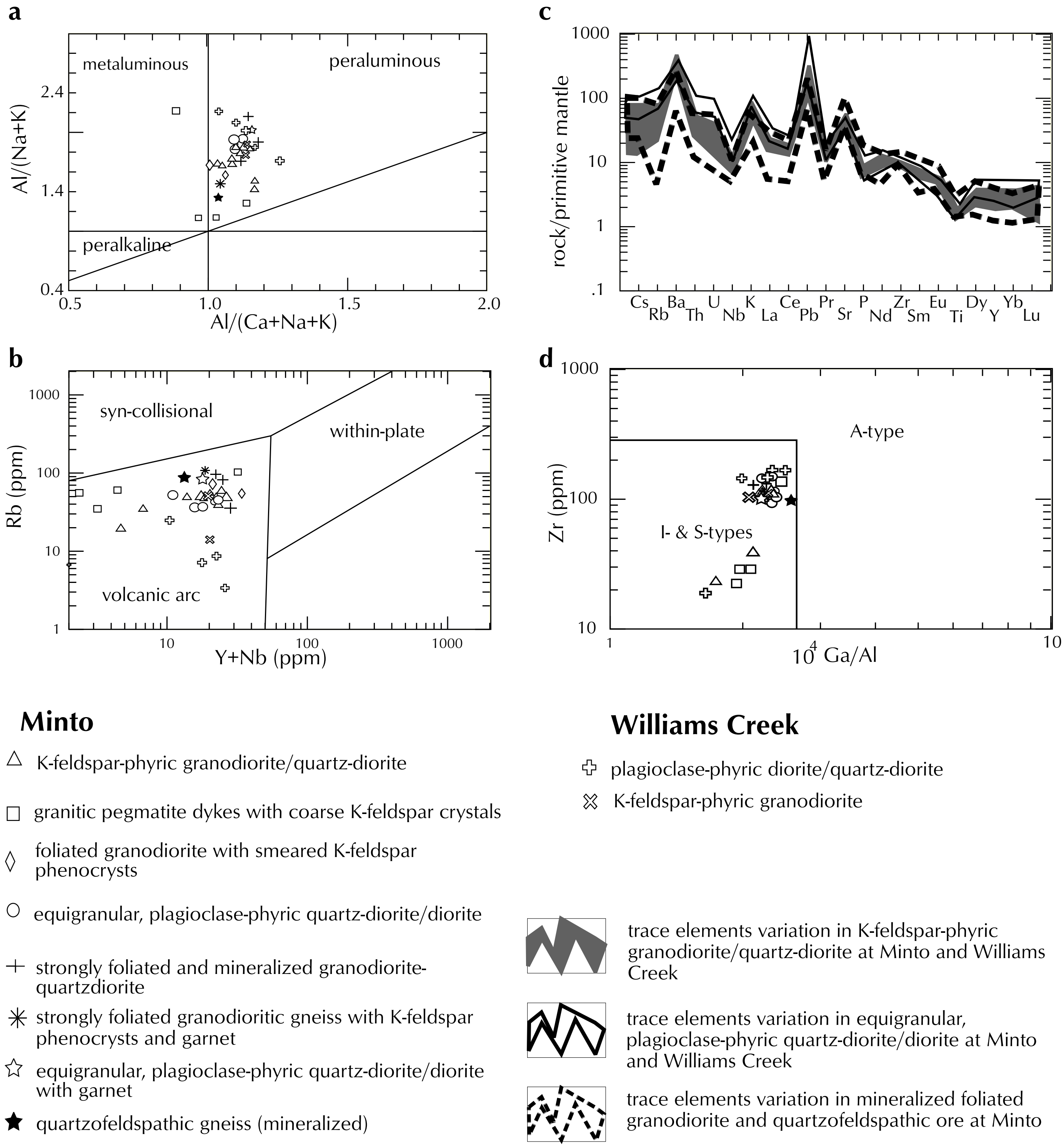

Figure 9. (a) *Shand's index plot (after Maniar and Piccoli, 1989) depicting the dominantly peraluminous nature of the Early Jurassic intrusions at Minto and Williams Creek deposits.* ***(b)*** *Rb versus Y+Nb discrimination diagram indicating a volcanic arc setting for the intrusions at Minto and Williams Creek (Pearce et al., 1984).* ***(c)*** *Primitive-mantle-normalized multi-element plots for different intrusive phases (from Sun and McDonough, 1989).* ***(d)*** *Zr versus Ga 10^4/Al discrimination plot for I-, S- and A-type granites (from Whalen et al., 1987).*

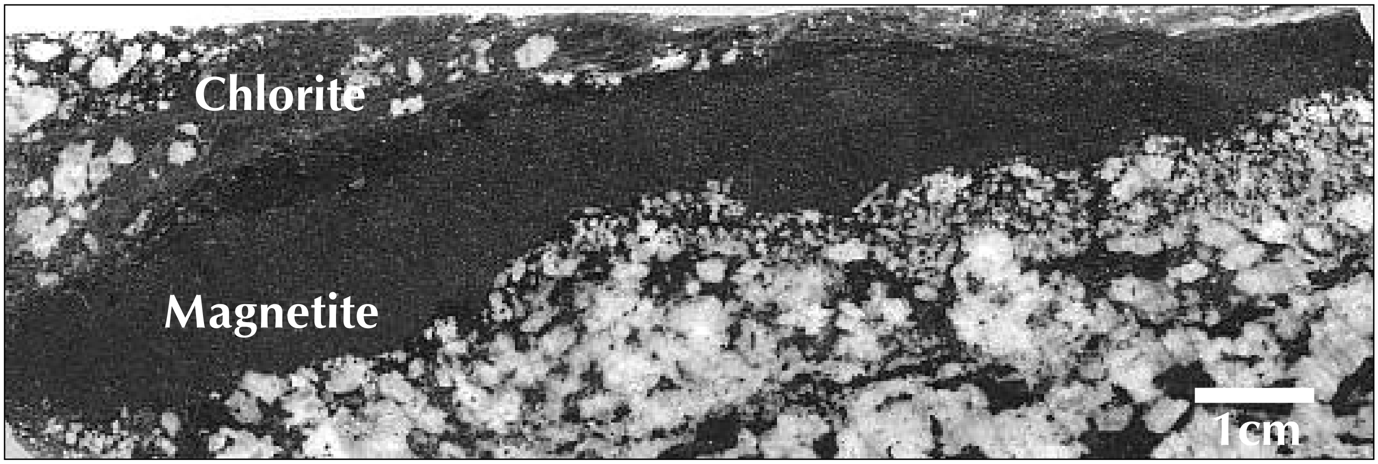

Figure 10. *A 2.5-cm-thick vein of magnetite within weakly foliated quartz diorite at the Williams Creek deposit.*

of banded 'siliceous ore' interlayered with the amphibolite in some drill intercepts at Williams Creek may support the sedimentary origin suggested above for the 'siliceous ore'. Observed field relationships indicate that these supracrustal units were wall rocks to early intrusive phases and that the intrusive rocks and their wall rocks were mineralized during a single hydrothermal event.

Chalcopyrite, bornite and very minor pyrite are the main hypogene sulphide minerals observed at Minto and Williams Creek. These minerals are disseminated in host rocks and locally occur as narrow, discontinuous, foliaform stringers. In some instances chalcopyrite and/or bornite form bands or blobs up to 2 to 3 cm long. Mineralization occurred prior to the ductile deformation that has affected the host units. With the exception of rare, fine grains of chalcopyrite and/or bornite that appear in some of the late dykes (attributed to late remobilization of the sulphide minerals), copper sulphide minerals are always hosted by strongly deformed rock units. In biotite-rich rocks (particularly 'biotite gneiss ore'), sulphide minerals are closely associated with the biotite. Magnetite is present in all the mineralized rocks in varying amounts and locally comprises as much as 25% of the rock. Magnetite veins up to 2 cm wide are locally associated with massive bornite veins of similar dimensions (Fig. 10).

Petrography and SEM (scanning electron microprobe) studies of mineralized rock samples show that chalcopyrite and bornite are intimately intergrown. Supergene alteration of these hypogene minerals produced secondary copper sulphide minerals such as covellite and chalcocite along rims and fractures, and locally as whole grain replacements. Native copper is also very locally present as narrow veinlets in oxidized zones.

Pyrite is rare in both deposits, and where present is associated with chalcopyrite. In rare instances pseudomorphs of calcite and/or siderite after hypogene pyrite are observed. Anhedral to subhedral magnetite and hematite occur together with the hematite commonly appearing to replace the magnetite. Gold is present both in native form and alloyed with silver (electrum). Silver is also present very locally as silver telluride (hessite). These gold and silver minerals are commonly contained within bornite and rarely form isolated grains. SEM studies show that electrum forms grains up to 150 microns in diameter (Fig. 11). It is uncertain at this time why high-fineness gold coexists with electrum within a single grain; however, it

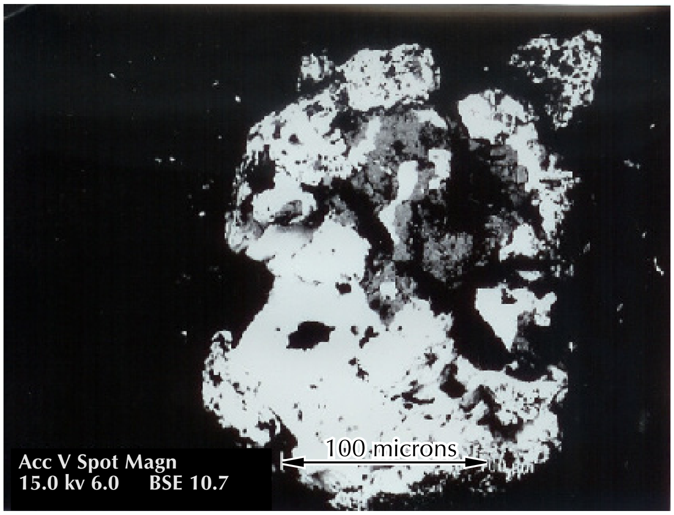

Figure 11. *Scanning electron microscope (SEM) image of an electrum/gold grain mounted on epoxy (black) recovered from a heavy mineral concentrate from 'siliceous ore' at Minto. White portions are gold with relatively high fineness, and the medium grey portions are electrum.*

may indicate that some of the primary electrum has had silver leached out during supergene processes. Molybdenite is very rare; where present it occurs as euhedral hexagonal grains in garnetiferous 'quartzo-feldspathic ore'.

The mineralogy of the 'siliceous ore' is slightly different than that of other mineralized rocks. A significant amount of gold, zinc sulphide (wurzite) and barite occurs in some samples of the 'siliceous ore'.

Pyrrhotite is locally disseminated in some sections of the fine-grained, garnetiferous amphibolite and biotite schist at Williams Creek. The origin of this sulphide mineralization is uncertain; it may represent syngenetic (volcanogenic?) sulphide minerals that were present in the mafic rocks prior to intrusion of the Early Jurassic magmas.

The very limited exposure in the Minto and Williams Creek area makes it difficult to confidently differentiate between the effects of hypogene alteration and later supergene effects. Earthy, and locally specular hematite is commonly observed to replace magnetite; it also stains feldspars along late fractures and fills late fractures. The hematization is commonly accompanied by bleaching of the wall rocks. It appears to be entirely late in the alteration history, and is likely completely unrelated to the mineralizing process. Epidote is commonly associated with hematite on late fractures but also occurs as an earlier, disseminated style of alteration, typically associated with mafic minerals. Chlorite is widespread throughout the Minto and Williams Creek areas. Some chlorite is spatially associated with late faults and breccia zones, where it has pervasively altered the breccia matrix and fragments. However, chlorite also replaces bent and kinked biotite grains that are considered to be part of the hypogene alteration. Clay alteration is pervasive in all of the oxidized zones, especially in the vicinity of late faults and fractures. Biotite in massive intrusive phases is mainly igneous in origin; however, locally secondary biotite is seen replacing primary hornblende in some of the altered but undeformed intrusive phases. In the strongly foliated gneissic zones, biotite has been recrystallized along with the sulphide minerals, and primary textural information relating to its origin is not preserved. However, it appears likely that both primary igneous biotite and a substantial component of hydrothermal (hypogene) biotite were originally present in the rocks, and both were completely recrystallized during the ductile deformation. Relatively coarse-grained sericite is only rarely developed as an alteration phase at Minto and has not yet been observed at Williams Creek. At Minto, sericite is observed both as an alteration envelope around a late epidote-filled vein that cuts massive granodiorite, and also as a narrow envelope surrounding a late aplite and pegmatite dyke. Pervasive, very fine-grained sericite alteration is also locally observed in some of the strongly foliated intrusive rocks.

Although strongly overprinted by supergene effects, we conclude that strong potassic alteration, consisting of development of secondary biotite after primary mafic minerals, and probably minor introduction of secondary K-feldspar, was well developed during formation of the hypogene copper-gold mineralization. Propylitic alteration (chlorite, carbonate and epidote) may have been developed during the hypogene processes; however, this would be largely obscured by subsequent deformation and supergene processes. The general scarcity of widespread pyrite and sericite suggests that hypogene argillic and sericitic alteration may not have been widely developed.

A GENETIC MODEL FOR MINERALIZATION AT MINTO AND WILLIAMS CREEK

As discussed above, hypogene minerology at Minto and Williams Creek consists of chalcopyrite, bornite and magnetite, with only minor amounts of pyrite and very minor molybdenite. Very small amounts of quartz were introduced during hypogene processes, with the possible exception of quartz stockwork that may now be represented by 'siliceous ore' (see previous discussion). Associated hypogene alteration is characterized by abundant secondary biotite and lesser amounts of secondary K-feldspar. These ore and alteration assemblages closely resemble those associated with early stages of mineralization in typical copper (-gold) porphyry deposits (e.g., Einaudi et al., 2003) as well as some iron-oxide-copper-gold-type (IOCG) deposits. Post-ore, very localized quartz veins display alteration envelopes consisting of epidote, minor calcite and rare sericite. A critical consideration in evaluating the resource potential and economics of metal extraction for the two deposits is the nature and extent of supergene modification that has affected them. Supergene effects are characterized by the presence of abundant secondary copper oxide and less abundant secondary copper sulphide minerals, especially at Williams Creek, and by the local presence of abundant hematite and clay (mainly in the vicinity of late steep faults). Within the main No. 1 zone at Williams Creek, as exposed in the bulk sample trenches, nearly all of the contained copper appears to occur in the form of

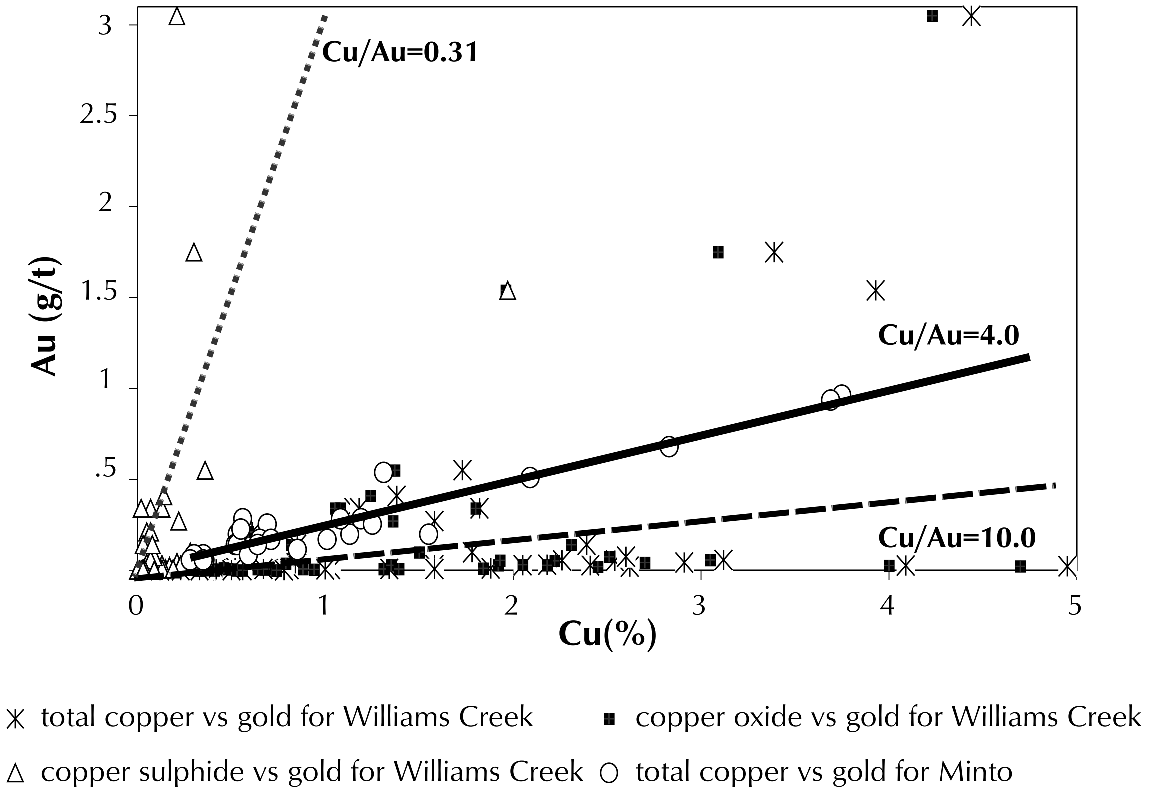

Figure 12. *Gold versus copper plot for the Minto and Williams Creek (No. 1 zone) mineralization. Data from Williams Creek are from three 1981 drill intersections. See text for discussion.*

secondary copper oxide minerals (especially malachite and azurite) coating fracture surfaces, and there is little evidence that significant amounts of hypogene copper sulphide minerals were ever present in the rocks. A plot of total Cu (%) versus Au (g/T) for the two deposits (Fig. 12) shows a slightly lower total Cu/Au ratio for Minto than Williams Creek (~4 at Minto versus ~10 at Williams Creek); however, both ratios are well within the range of typical values for alkaline porphyry copper deposits of British Columbia (Cu/Au = 0.3-15; McMillan et al., 1995). A plot of oxide Cu versus Au for the No. 1 zone at Williams Creek, however, suggests that much of the copper present is in the form of oxide minerals. This data, together with the observation that most of the copper in the No. 1 zone, at least at shallow levels, appears to have been introduced into the host rocks by supergene processes, suggests that the No. 1 zone has experienced strong supergene enrichment. A plot of Cu (as sulphide mineral) versus Au for the No. 1 zone at Williams Creek (Fig. 12) results in a much lower Cu/Au ratio (~0.31), which is unusually low for a typical hypogene porphyry copper deposit. It therefore remains uncertain how much of the copper contained in the Williams Creek deposit represents hypogene grade versus supergene enrichment, and therefore what the true hypogene Cu/Au ratio of the deposit was.

DISCUSSION

Sulphide minerals at Minto and Williams Creek occur mainly disseminated or as foliaform stringers within moderately to strongly deformed intrusive rocks, and to a lesser extent in foliated supracrustal rocks. Sulphide minerals in the deformed intrusive rocks clearly pre-date most if not all of the ductile strain recorded by their host rocks. The sharp contact between unmineralized, massive quartz diorite of the Granite Batholith, which is dated at ~197 Ma at Williams Creek, and the foliated and mineralized rocks demonstrates that the mineralization is older than the Granite Batholith. These observations provide evidence for four distinct events that occurred within a very short time interval in the Minto and Williams Creek area: 1) intrusion of early plutonic rocks into (probably) already deformed supracrustal rocks of the Yukon-Tanana Terrane at 198-197 Ma; 2) mineralization and alteration of these intrusive phases and their wall rocks; 3) ductile deformation of the mineralized rock units; and 4) intrusion of the main, massive, post-mineral phases of the Granite Batholith at ~197 Ma. The very tight age-brackets on these events suggest that they essentially represent a continuum.

Lead isotopic analyses of sulphide minerals and igneous feldspars from Minto and Williams Creek (this study) and sulphur isotopic studies by Pearson (1977) indicate magmatic sources (δ^{34}S ‰ values between –3 and +1) for the metals and sulphur contained in the deposits. The nature of the hypogene mineralization and alteration observed is consistent with the early stages of a typical porphyry system. The lack of evidence for a significant quartz stockwork in either of the deposits is reminiscent of the alkalic copper-gold porphyry deposits in British Columbia (e.g., McMillan et al., 1995), which are very similar in age to the Minto and Williams Creek deposits (Mortensen et al., 1995). The mineralized units were almost immediately intruded by post-mineral phases of the Granite Batholith, and petrographic evidence (presence of abundant magmatic epidote) and aluminum-in-hornblende geobarometry indicates that these post-mineral intrusions were emplaced at depths much greater than those that would permit formation of a porphyry-type deposit (note that Rusk et al. (2002) report a depth of formation of up to 8.5 km for the Butte porphyry-copper deposit in Montana). We suggest that a hydrothermal system had begun to develop a typical porphyry deposit but was shut off when the whole system was buried to depths of >9 km. Therefore, the late stages of hypogene mineralization and alteration that are typically associated with porphyry deposits (phyllic and argillic alteration and widespread introduction of pyrite) could not develop. Late pegmatite and aplite dykes, dated at ~194-196 Ma at Minto, cross-cut the Granite Batholith and locally contain miarolitic cavities, indicating that they were emplaced at a relatively shallow level in the crust; this provides evidence for a regional uplift event following the burial event at ~197 Ma. Sericite and epidote alteration that is associated with these dykes is dated at ~182 Ma (Ar-Ar muscovite), and indicates that hydrothermal fluid circulation had resumed by that time.

We conclude that the Minto and Williams Creek deposits formed during a major period of 'vertical tectonics' that affected this region. Regional scale uplift from mid-crustal depths to very shallow crustal levels at ~186 Ma was demonstrated by field and U-Pb dating studies of the Aishihik Batholith and Long Lake plutonic suite intrusions approximately 70 km to the southwest of our study area (Johnston et al., 1996). There is also evidence for regional-scale crustal thickening throughout large portions of the Yukon-Tanana Terrane in western Yukon and eastern Alaska between ~195 and 185 Ma (e.g., Mortensen, 1990, 1992), which could coincide with the burial of the mineralizing systems at Minto and Williams Creek. The crustal thickening, burial and subsequent uplift of the region must have occurred within an active continental arc setting, since the geochemistry of all intrusive phases emplaced during this interval indicates a strong arc affinity.

A relatively simple, 'arrested porphyry' model for the formation of the Minto and Williams Creek deposits has therefore emerged from our studies. However, many questions are still outstanding. For example, the importance of locally abundant disseminated pyrrhotite (at Williams Creek) and wurtzite (at Minto) of possible syngenetic origin in the amphibolite and biotite schist remains uncertain. Could this mineralization have provided a critical local source of some of the sulphur required for the formation of the hypogene copper ores? This and other problems are still being investigated. Some important exploration implications arise from the study. In particular, the mineral deposits at Minto and Williams Creek have been shown to be temporally and genetically associated with ~198 Ma magmatism. Although Late Triassic to Early Jurassic intrusive rocks are widespread throughout the Yukon-Tanana Terrane in Yukon and eastern Alaska (Mortensen et al., 2000), most of these intrusions appear to be either older (218-202 Ma) or younger (192-185 Ma) than the main mineralized intrusive phases at Minto and Williams Creek. Furthermore, formation of a porphyry deposit requires relatively shallow-level intrusions, and many of the Triassic and Jurassic intrusions contain epidote that is thought to be magmatic in origin, indicating emplacement of the magmas at too great a depth to permit the formation of a porphyry-type deposit. Identification of relatively shallow, ~198 Ma intrusions in western Yukon should therefore be a first-order criteria for exploring other deposits of this type in the region.

Recognition of the extent of supergene enrichment that has affected the Williams Creek deposit in particular has implications for the original dimensions and grade of the deposit. Although we have only been able to examine a small portion of the Williams Creek deposit, our observations suggest that much of the copper contained in the No. 1 zone is in the form of secondary oxide-mineral enrichment, and is not simply hypogene ore that has been oxidized in place.

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