Hydrothermal alteration, mineralization and exploration potential of the Mars alkalic copper-gold-molybdenum porphyry occurrence, Laberge map area (105E/7), Yukon

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ABSTRACT

The Mars property occurs on the southwestern margin of the Teslin Crossing pluton, a composite intrusion of intermediate, alkalic composition that was emplaced into sedimentary rocks of the Middle Jurassic Tanglefoot formation at about 175 Ma. Exposed alteration and mineralization define a northwest-trending zone 2.8 by 1.5 km. New field and petrographic data document a core zone dominated by sodic and magnetite-rich alteration, surrounded by more extensive calc-potassic alteration; each assemblage contains disseminated and fracture-hosted copper-gold mineralization. Subzones of younger quartz veins with strong copper-molybdenum±gold mineralization are widely distributed. Sericitic and propylitic alteration is minor and weakly mineralized. The system has low sulphide mineral content with a high ratio of chalcopyrite to pyrite. Hornfels in the Tanglefoot formation has stronger pyrite-pyrrhotite and also carries copper-gold mineralization. The Mars system is a silica-oversaturated alkalic copper-gold-molybdenum porphyry deposit with strong similarities to the Cadia and Goonumbla deposits in Australia.

RÉSUMÉ

La propriété de Mars est située sur la marge sud-ouest du pluton de Teslin Crossing, une intrusion composite de composition alcaline intermédiaire mise en place dans des roches sédimentaires de la Formation de Tanglefoot du Jurassique moyen vers 175 Ma. L’altération et la minéralisation exposées permettent de définir une zone de 2,8 sur 1,5 km à direction nord-ouest. Les nouvelles données pétrographiques recueillies sur le terrain documentent une zone centrale où domine une altération sodique et magnétitifère entourée d’une altération calco-potassique plus étendue; chaque assemblage renferme une minéralisation de cuivre-or disséminée et logée dans des fractures. La répartition des sous-zones à filons de quartz plus jeunes fortement minéralisées en cuivre-molybdène±or est large. L’altération séricitique et propylitique est mineure et faiblement minéralisée. Le système a une faible teneur en sulfures et affiche un rapport élevé de chalcopyrite à pyrite. La cornéenne dans la Formation de Tanglefoot a une teneur plus élevée en pyrite-pyrrhotite et renferme également une minéralisation en cuivre-or. Le système de Mars est un gîte porphyrique de cuivre-or-molybdène alcalin sursaturé en silice très apparenté aux gisements de Cadia et Goonumbla en Australie.

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INTRODUCTION

The Mars property is located about 65 km north-northeast of Whitehorse, Yukon (Fig. 1). It was first explored for traditional calc-alkalic copper-molybdenum porphyry potential in 1971 (Wark, 1998). Recognition of its gold potential did not occur until the mid-1990s (A. Doherty, internal report by Aurum Geological Consultants, 1996), and the property is now known to host porphyry-style copper-gold-molybdenum mineralization genetically related to alkalic intrusions in the Teslin Crossing pluton (Hart, 1997; Wark, 1998). Major alkalic copper-gold±molybdenum porphyry deposits are globally widespread and include the Copper Mountain/Ingerbelle, Afton-Ajax, Mount Polley, Galore Creek and Mount Milligan deposits in British Columbia (Barr et al., 1976; Lang et al., 1995), Goonumbla/North Parkes (Muller et al., 1994) and Cadia-Ridgeway (Holliday et al., 2002) in New South Wales, Marian and Dinkidi in the Philippines (Wolfe et al., 1999), and Skouries in Greece (Kroll et al., 2002). Many of these deposits are active or former mines, and the economic potential of the Mars property is being currently tested under option by Saturn Minerals Inc.

The Mars property is the only currently recognized example of this deposit type in Yukon, yet it has only received very limited exploration and geological study. This paper first briefly reviews the regional and local geology of the property. It then focuses on new field and petrographic observations on the mineral assemblages and distribution of alteration and mineralization. It concludes with a more specific classification of the deposit and presents an updated exploration model.

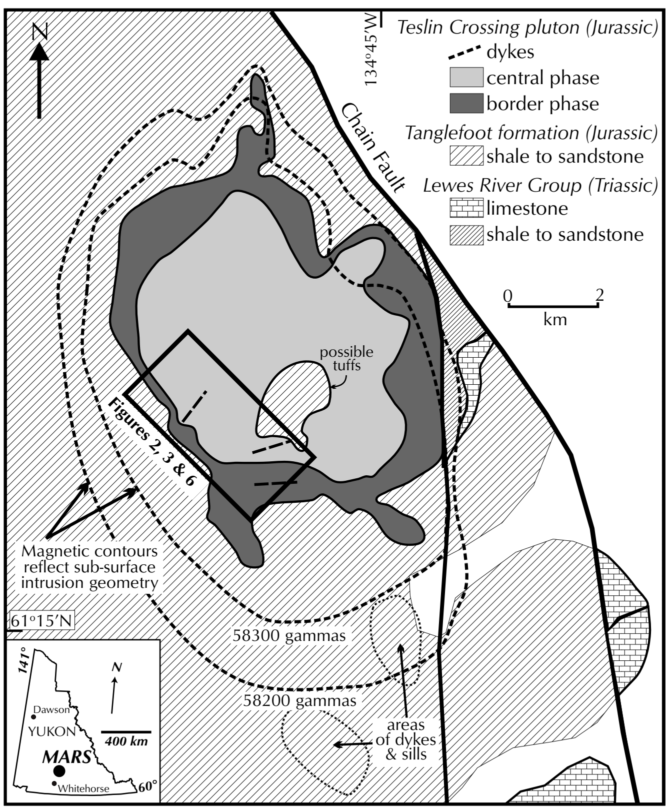

Figure 1. *Geological setting of the Teslin Crossing pluton. Contours of aeromagnetic data suggest that the pluton extends significantly to the south and southwest, beneath the Tanglefoot formation. See text for further discussion. Box shows the location of Figures 2, 3 and 6. Map modified slightly from Hart (1997).*

REGIONAL GEOLOGY

The regional setting of the Teslin Crossing pluton has been discussed in greatest detail by Hart (1997) and Bostock and Lees (1938), who are the sources for most of this summary. The pluton is located within the Stikine Terrane (Stikinia), which accreted to the margin of ancestral North America during the Middle Jurassic. Stikinia consists of an Upper Paleozoic volcanic arc basement overlain by the Lewes River volcanic arc of Middle and Late Triassic age. The Whitehorse Trough developed as a marginal basin during this time, and was infilled by up to 7 km of strata that include Late Triassic volcanic-rich detritus and carbonate of the Lewes River Group, and Jurassic clastic rocks of the Laberge Group. Amalgamation of the adjacent Cache Creek Terrane and accretion to North America resulted in deformation of these rocks during the Middle and Late Jurassic.

The Teslin Crossing pluton (Fig. 1) is an isolated body that was emplaced near the axis of the Whitehorse Trough in the Middle Jurassic. Although the pluton occurs at the approximate centre of a 35-km-long, northwest-trending belt that contains numerous small stocks, sills and dykes, it does not appear to be part of an extensive igneous suite (Hart, 1997), although Gordey and Makepeace (2001) correlate it with the Bryde plutonic suite.

Host rocks to the Teslin Crossing pluton are mostly fissile, black, well-bedded, carbonaceous, variably limey, poorly indurated shale and siltstone with minor, thin, chert-rich sandstone interbeds (Hart, 1997). Tempelman-Kluit (1984) assigned these rocks to the Middle Jurassic Tanglefoot formation, and fossils yield biostratigraphic ages of

Toarcian or Aalenian (Hart, 1997). The rocks occur in a block that is fault-bounded against older rocks; the eastern margin of this block, and of the Teslin Crossing pluton itself, is cut by north and north-northwest faults that form part of the southern end of the Chain Fault (Fig. 1). The sedimentary rocks dip steeply away from their contact with the Teslin Crossing pluton. Volcanic rocks of Aalenian age are found 10 km north-northwest of the pluton and may be temporally associated (Hart, 1997). A poorly exposed roof pendant of hornfels of possible tuffaceous origin (Hart, 1997; Wark, 1998) occurs in the east-central part of the pluton (Fig. 1), but the age and composition of these rocks have not been established.

THE TESLIN CROSSING PLUTON

The Teslin Crossing pluton, although not mapped in detail, generally comprises a central phase bounded by a more mafic border phase, with both units cut by dykes of variable composition and orientation (Fig. 1; Bostock and Lees, 1938; Hart, 1997). The pluton is bounded on the east by strands of the Chain Fault. On the north and west, contacts against host rocks are sharp and steep (Pangman, 1973; Pangman and VanTassell, 1972). The south contact may dip more shallowly, and airborne magnetic data indicate that the intrusion extends well outboard of the exposed contact. The >57 200 gamma magnetic contour indicates a body at least twice the exposed size of 8 by 5 km (Hart, 1997); a large-scale sill geometry has also been suggested but has not been favoured (Hart, 1997). Sedimentary rocks above the buried part of the pluton and adjacent to steeper contacts have been converted to hornfels.

The central phase of the pluton has been described by Hart (1997) as a texturally and compositionally variable suite dominated by a medium to light grey-pink, hornblende-bearing monzonite that contains magnetite, rare biotite and, possibly, pyroxene (Pangman and VanTassell, 1972). The border phase is a grey, texturally variable, crowded monzodiorite to monzonite porphyry; it contains abundant pyroxene, lesser biotite, and locally minor hornblende. Phenocrysts comprise pyroxene and plagioclase. Minor phases of the pluton include younger tan syenite that lacks ferromagnesian minerals, and small zones of hornblende-bearing alkali syenite of uncertain timing. The central and border phases contain abundant xenoliths of hornfelsed Tanglefoot formation, pyroxenite and gabbro. All intrusive phases contain titanite, magnetite, apatite, rutile and zircon.

Swarms of sills have been described from south of the pluton (Hart, 1997; Fig. 1). They are similar to the border phase but are finer grained, locally more mafic, and commonly have a trachytic texture. Trachytic hornblende-feldspar porphyry syenite dykes are common within the pluton. Narrow, less common hornblende-rich mafic dykes are also present; these were described by Pangman and VanTassell (1972) as lamprophyres, but other authors have called them monzonite to monzogabbro (Hart, 1997; Wark, 1998). Dykes within the pluton are reportedly unaltered and unmineralized (Wark, 1998). They strike northeast to east-northeast with nearly vertical dips, whereas sills south of the pluton strike north and dip to the west (Hart, 1997).

Isotopic ages on the Teslin Crossing pluton include four potassium-argon (K-Ar) dates on biotite and hornblende between 164 and 186 Ma (Stevens et al., 1982; Tempelman-Kluit, 1984), and a single uranium-lead (U-Pb) date on zircon of 175.6±2.0 Ma from a sill south of the pluton (Hart, 1997). Geochemical data (Hart, 1997; R.C. Wells, private report to Placer Dome North America Ltd., 1998) from the intrusions indicate a weakly alkalic, metaluminous to locally and weakly peraluminous composition. Normative compositions indicate silica-saturation to weak silica-oversaturation for the central and border phases of the pluton, and a nepheline-normative composition was determined for a pyroxenite xenolith (Hart, 1997).

LOCAL GEOLOGY IN THE PRINCIPAL ZONE OF MINERALIZATION

The area of greatest interest to this study is located on the southwest margin of the pluton and encompasses most of the known alteration and mineralization (Figs. 1 and 2). Only general comments on the area are possible due to the absence of detailed mapping. The area contains mostly border phase that, in part, surrounds an embayment of hornfels of Tanglefoot formation. The central phase is located to the north and northwest of the border phase, but sharp contacts were not observed between them. The roof pendant of hornfelsed, possible volcanic rock, noted above enters the northeastern margin of the area. The area has a northwesterly elongation parallel to the overall orientation of the pluton contact. Many faults are broadly parallel to this contact, but north to north-northeast, northeast and east-northeast faults are also present. Data are insufficient to document movement history or relative timing of the various structures. Many veins trend northwest (see next section), but the predominantly to wholly post-hydrothermal dykes have east-northeast, northeast and north-northeast strikes.

ALTERATION AND MINERALIZATION

Previous work on the Mars property has focused on mineralized 'prospects' (Figs. 2 and 3; Wark, 1998) that include the Cliff, X, Kelly, Pluto, New, Windy Ridge South and Moon Knob zones, as well as the JL, Andrew and TA zones newly discovered by Saturn Minerals. The distribution of these zones and the more recent field work by the authors suggest that larger scale alteration patterns provide a better framework for an improved exploration model. The field and petrographic work of this study have therefore been combined with previous work (Pangman and VanTassell, 1972; Hart, 1997; Wark, 1998) to subdivide alteration into assemblages that have distinct relationships to copper-gold-molybdenum mineralization. The main types of alteration are: 1) hornfels; 2) potassium- and potassium-calcium silicate; 3) sodium-silicate; 4) magnetite; 5) silica, including swarms of quartz-sulphide veins; 6) propylitic; and 7) sericite. These assemblages cover a northwest-trending area at least 2.8 by up to 1.5 km that is open in most directions, and is broadly coincident with copper values in soils of >100 ppm (Fig. 3). The distribution of individual alteration types is shown schematically in Figure 3, but work is not yet sufficient to fully define either the boundaries of any of the zones or the complete mineralogical associations that they represent.

HORNFELS

Contact metamorphism formed in Tanglefoot formation adjacent to the Teslin Crossing pluton, prior to the onset of hydrothermal activity related to copper-gold-molybdenum mineralization. Hornfels extends for at least a few hundred metres away from the southwestern contact of the pluton, but its full extent is concealed by alluvium. Major and minor minerals include biotite, quartz, plagioclase, potassium feldspar, pyrite and pyrrhotite, with local traces of chalcopyrite. Some intervals have returned highly anomalous copper and gold values, which have been related petrographically to later potassium-calcium-silicate, sodium-silicate and/or magnetite-bearing alteration and veins.

POTASSIUM- AND POTASSIUM-CALCIUM-SILICATE ALTERATION

Potassium-feldspar is the most widespread and, on average, the earliest alteration mineral. The most common expression of this alteration is envelopes of potassium-feldspar around tight, planar fractures or narrow veinlets that contain potassium-feldspar, actinolite, calcite, and rare quartz and biotite. These veinlets locally contain traces of pyrite and chalcopyrite. In many parts of the system these veins are widely spaced (up to a few per metre), but they are also commonly found in higher densities where they are associated with stronger pervasive alteration and higher concentrations of pyrite and chalcopyrite. This type of alteration encompasses the entire area of mineralization, and according to Hart (1997) may extend well beyond the boundaries shown in Figure 3. The veins commonly have the appearance of altered joints and lack preferred orientations; this may indicate formation as a high-temperature, possibly deuteric event consistent with their early timing. Pervasive biotite-dominated alteration is not common. A siliceous breccia with a biotite-rich matrix was observed at Moon Knob (see "Silica-rich alteration" section).

SODIUM-SILICATE ALTERATION

Sodium-silicate alteration occurs in the central and eastern parts of the mineralized area, but distribution of the alteration is very poorly defined (Fig. 3). Limited evidence suggests that it overprints potassium-silicate alteration, and is cut by magnetite-bearing veins. The assemblage is dominated by incipient to intensely pervasive albite. In some locations, diffuse veinlets of albite and albite-quartz were observed. Disseminated pyrite and chalcopyrite are more abundant than is typical of potassium- and potassium-calcium-silicate alteration zones.

MAGNETITE ALTERATION

An extensive zone in the southeastern part of the property contains abundant veinlet-hosted and pervasive magnetite alteration (Fig. 3), but to the northwest it is less common and its distribution is more erratic. Veins are dominated by magnetite, commonly contain minor biotite and/or quartz, and typically have prominent potassium-feldspar envelopes. They range from hairline fractures to > 0.5 m in width, and wider examples can extend for at least tens of metres along strike. Veins range from planar to sinuous, and contacts with host rock can be sharp or diffuse. There is a general and locally strong relationship

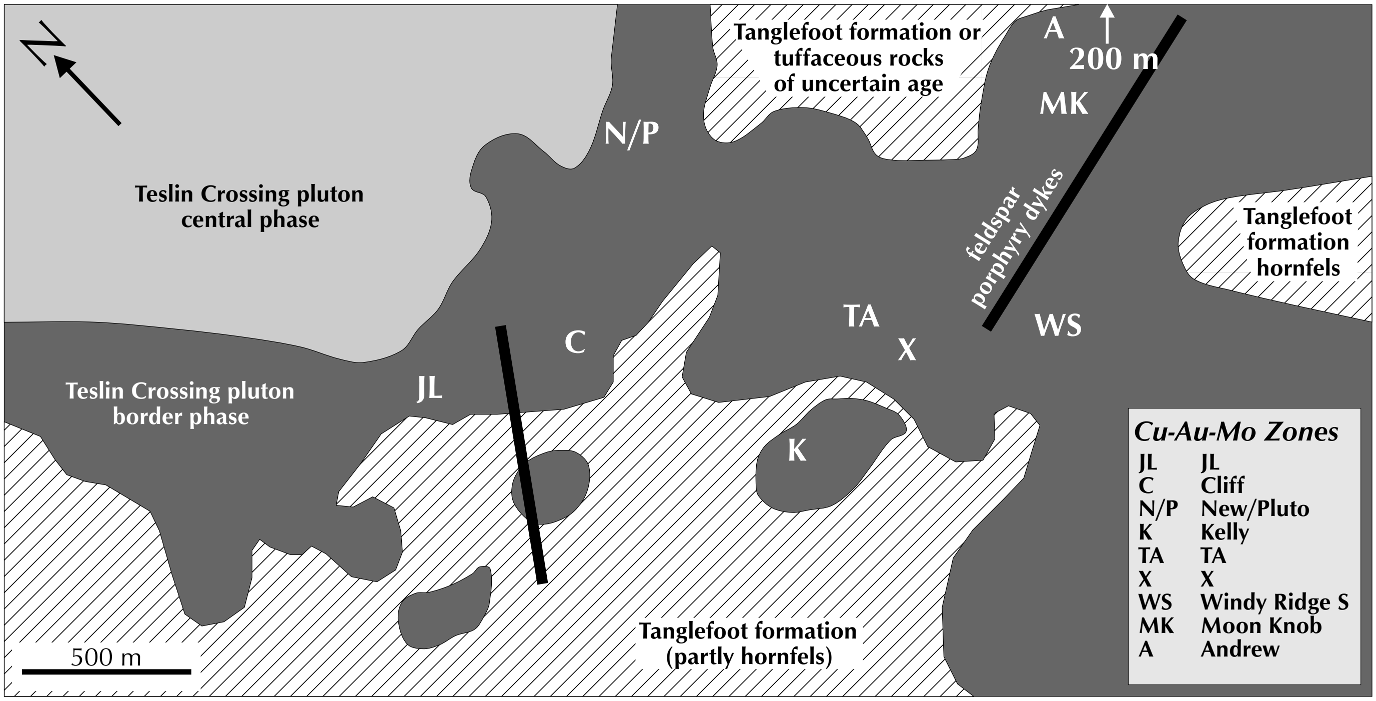

Figure 2. *Geology of the Mars study area. Note the rotation of the map from north, and that the Andrew zone is located about 200 m northeast of the edge of the map. Geology modified from Wark (1998). Location of this figure is shown as outline on Figure 1.*

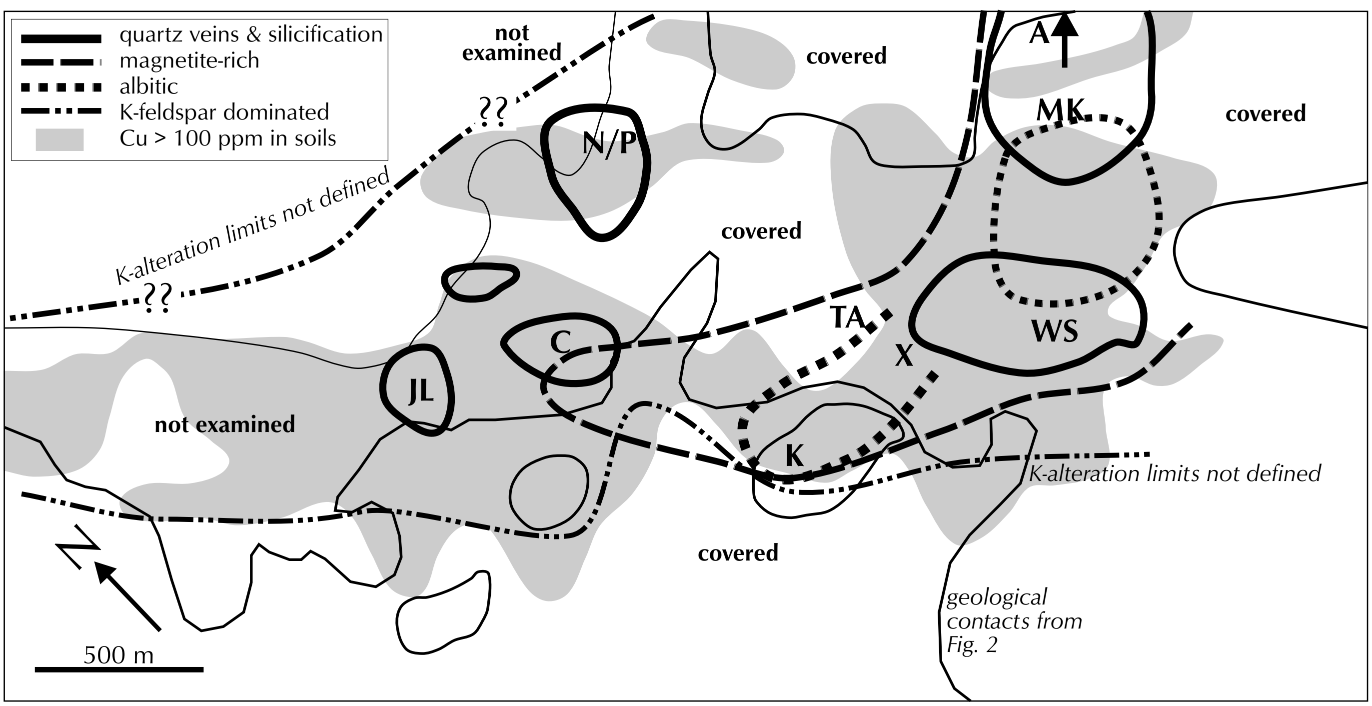

Figure 3. *Distribution of alteration assemblages in the Mars magmatic-hydrothermal system. Boundaries for alteration zones are not fully defined, as discussed in the text. Grey area outlines Cu-in-soils values > 100 ppm (Wark, 1998). Geological contacts from Figure 2 have been retained for reference, but patterns have been deleted. Mineralized zones as in Figure 2. Location of this figure is shown as outline on Figure 1.*

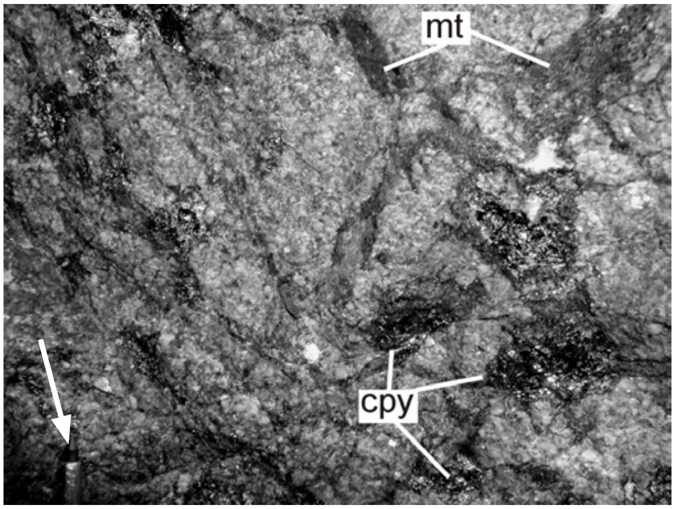

Figure 4. *Photograph illustrating the relationship between magnetite alteration and sulphide minerals. Host rock is the moderately albitized border monzodiorite phase cut by wispy magnetite veins (mt; dark, irregular features). The bright zones within the magnetite zones are coarse clots of chalcopyrite (cpy). Sample is from the Kelly zone. Arrow points to scriber at bottom left for scale.*

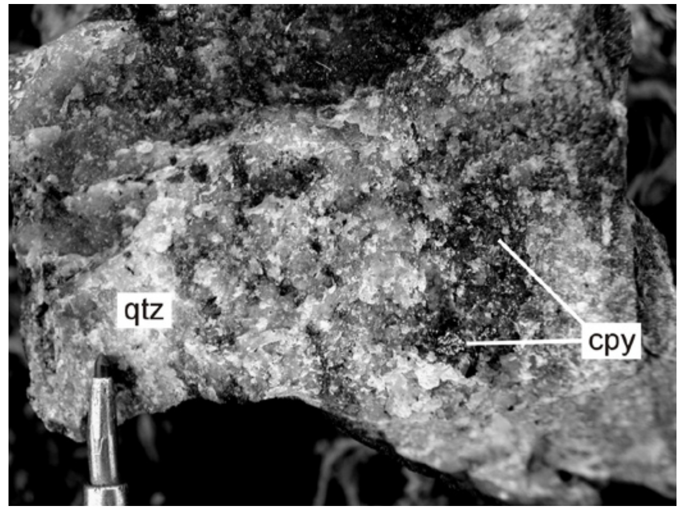

Figure 5. *Photograph of a quartz-sulphide mineral vein from the Moon Knob zone. The entire sample is quartz vein (qtz), and a vuggy, open space texture is evident. Chalcopyrite (cpy) is abundant in this sample, particularly in the dark, vuggy area at right-centre. Sample is about 7 cm across.*

between magnetite alteration and copper-gold mineralization (but not with molybdenum). Some samples with among the highest grades of copper and gold in the system are associated with magnetite alteration (R.C. Wells, private report to Placer Dome, 1998), where it contains both chalcopyrite and bornite (Fig. 4). Elsewhere, magnetite alteration either lacks or has an unclear association with copper-gold. It is probable that magnetite alteration comprises more than one sub-stage.

SILICA-RICH ALTERATION

Silica-rich alteration is widespread (Fig. 3) and is characterized by sulphide mineral-bearing, quartz-rich veins (Fig. 5). Many veins contain later interstitial or cross-cutting calcite, and minor magnetite, actinolite and/or chlorite are common. Sulphide minerals are almost ubiquitous but are very irregularly distributed within individual veins; they include chalcopyrite, lesser pyrite and molybdenite, and reportedly trace galena (R.C. Wells, private report to Placer Dome, 1998). Many veins lack envelopes, but others have silicified or narrow potassium-feldspar envelopes. Quartz veins range from hairline fractures to >30 cm in width. Wider veins are steeply dipping and have a preferred northwest orientation; they are commonly related to high densities of narrower veins that form conjugate splays off the main vein. The veins initially filled open space (Fig. 5), but the quartz in many is strongly undulose and recrystallized, suggesting that weak, post-precipitation deformation has been widespread. A small (< 3-m exposure) hydrothermal breccia on Moon Knob contains transported fragments of silicified hornfels and intrusive rock in a matrix of biotite, quartz, pyrite, bornite, magnetite and chalcopyrite. Quartz veins cut potassium-silicate, potassium-calcium silicate, sodium-silicate and magnetite-rich alteration.

PROPYLITIC ALTERATION

Propylitic alteration was observed only locally, and mostly in the northwestern part of the system where it is very restricted in both extent and intensity. The most common manifestation is veinlets with various combinations of epidote, albite, actinolite, chlorite, quartz, carbonate and hematite. Veins of this type cut potassium-feldspar bearing veins, but relationships to other alteration types were not established.

SERICITE ALTERATION

Sericite is widespread, and no definite pattern of distribution has been recognized. Most occurs as a weak, selectively pervasive replacement of feldspar in intrusive rocks affected by potassium- and potassium-calcium-silicate alteration, to which it may be temporally related. No additional information is available.

MINERALIZATION

The copper-gold-molybdenum mineralization at the Mars property is widely distributed (Figs. 2 and 3). At the current level of exposure, the overall sulphide mineral concentration in intrusive host rocks is low (up to a few but mostly < 2%) and the ratio of chalcopyrite to pyrite is high. Pyrrhotite is found only in veins located close to the outer contact of the pluton where it is proximal to hornfels. Bornite is common in areas affected by magnetite alteration, but is also present in other alteration types. Molybdenite is found mostly in late quartz-sulphide mineral veins where it is associated with some of the highest concentrations of chalcopyrite on the property. Gold occurs in native form and is associated with chalcopyrite, bornite and pyrite (R.C. Wells, private report to Placer Dome North America Ltd., 1998). Historical sampling has not been systematic, but many surface rock chip and grab samples exceed 1% Cu, 1 g/t Au and/or several hundred ppm Mo. The PGE potential of the property has not been tested, although these metals are commonly present in alkalic copper-gold porphyry deposits (Thompson et al., 2001; Kroll et al., 2002). Hornfels contains several percent disseminated pyrite, lesser pyrrhotite, and trace chalcopyrite; where copper-gold mineralization is more strongly developed, it can be related petrographically to an overprint by other alteration types and/or veins.

INTERPRETATION AND EXPLORATION MODEL

The characteristics of the Mars magmatic-hydrothermal system are compatible with the alkalic copper-gold porphyry model (Barr et al., 1976; Lang et al., 1995). These deposits include silica-undersaturated, silica-saturated and silica-oversaturated sub-types, based on the modal or normative composition of the associated alkalic intrusions and, to a lesser extent, on alteration (Lang et al., 1995; in review). The Mars system should be considered a silica-oversaturated alkalic copper-gold porphyry deposit on the basis of: 1) abundant quartz-sulphide veins and siliceous alteration; 2) widespread, but weak, sericite alteration; 3) the quartz-normative composition of the intrusions (Hart, 1997; R.C. Wells, private report to Placer Dome North America Ltd., 1998); and 4) the presence of strong molybdenum mineralization. Important examples of silica-oversaturated alkalic copper-gold-molybdenum deposits that share many similarities with Mars include Goonombla/North Parkes (Muller et al., 1994) and Cadia-Ridgeway (Holliday et al., 2002) in Australia, and Skouries in Greece (Kroll et al., 2002), all of which are active mines.

Classification of the Mars property as a *silica-oversaturated* alkalic copper-gold porphyry deposit has implications for exploration potential and methods. Silica-oversaturated systems contain, on average, a greater tonnage of mineralization than other alkalic copper-gold porphyry types. Magnetite-bearing potassium-silicate alteration in silica-oversaturated alkalic deposits is commonly an important environment for ore, but more critically, a substantial proportion of mineralization is typically related to sheeted or stockwork quartz-sulphide veins. This contrasts sharply with the nearly complete absence of quartz-sulphide veins in other types of alkalic copper-gold porphyry deposits, in which disseminated mineralization hosted by pervasive, magnetite-bearing potassium-feldspar and/or biotite alteration is the norm.

The exploration significance of these patterns to mineralization in silica-oversaturated alkalic systems generally, and to observations at Mars more specifically, is evident in a reinterpretation of induced polarization (IP) data (Fig. 6). The initial interpretation of the IP results by Wark (1998) focused on chargeability highs. These are concentrated at the southwestern contact of the pluton and clearly indicate the distribution of sulphide-rich hornfels; copper-gold mineralization has been documented within the hornfels and it indeed comprises a viable exploration target. Alkalic copper-gold systems are, however, typified by a low overall sulphide mineral concentration with a high ratio of chalcopyrite and/or bornite to pyrite (Lang et al., 1995; in review), and IP chargeability highs are correspondingly less important as indicators of ore than in sulphide-rich deposits such as calc-alkalic copper-molybdenum porphyry systems. Figure 6 shows an excellent correlation between IP resistivity highs and exposed zones of quartz-sulphide mineral veins. The resistivity anomalies are much larger than, and have northwest trends parallel to the preferred orientation of, the exposed zones of quartz-sulphide mineral veins. The resistivity highs are therefore

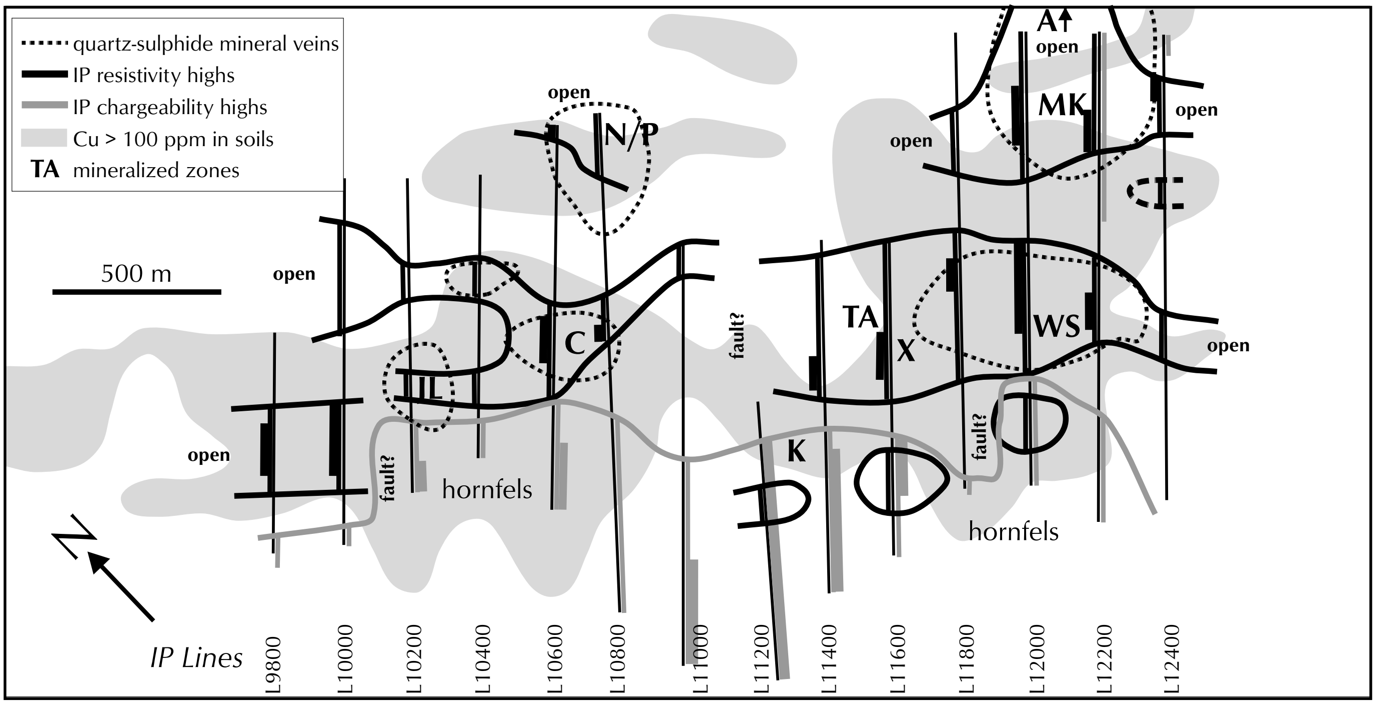

Figure 6. *Schematic reinterpretation of IP data for the Mars system. Relative strength of chargeability and resistivity highs indicated by thickness of lines. Chargeability anomalies reflect hornfels in the sedimentary host rocks to the pluton. Most resistivity anomalies are located within the pluton, and correlate spatially with exposed areas of abundant quartz-sulphide mineral veins. See text for further discussion. Geological contacts removed for clarity. Mineralized zones and Cu soil geochemistry as in Figure 2. Location of this figure is shown as outline on Figure 1. Data originally described by Wark (1998).*

provisionally considered reflective of relatively more prospective environments at the Mars property.

The observations and interpretations described in this paper are very preliminary, and additional work is required before the proposed exploration model for the Mars property can be sufficiently refined to undertake a comprehensive testing of its copper-gold-molybdenum potential. Mapping, prospecting, geochemical sampling, petrography and an initial stage of reconnaissance drilling are planned for the summer of 2004 in order to advance development of this interpretive framework.

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