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GEOLOGY OF THE BINGHAM MINING DISTRICT, SALT LAKE COUNTY, UTAH

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Abstract: The Bingham deposit is centred on a small 40 Ma stock of older, generally equigranular, monzonite that is cut by quartz monzonite porphyry, latite, and quartz latite porphyry dykes. The surrounding country rocks are quartzite and minor but important limestone. A body of fractured rock formed over the top of the monzonite as it cooled leaving a weakly fractured core below a dome of strong fracturing. Early fluids entered this fractured mass at about the time of the intrusion of the first porphyry resulting in an undetermined amount of alteration and mineralisation. This fracturing is a major control on the location of the ore shell and the concentric zoning pattern of alteration and mineralisation. Five porphyry intrusives have been described and each is followed by a cycle of veining, alteration and mineralisation. The porphyries all trend north-easterly across the northern half of the deposit, forming the *porphyry trend*. At least three overlapping centres of fracturing, alteration and mineralisation seem to be present within the stock, one centred in the fracture dome and two or more in the porphyry trend.

Alteration consists of Bingham Main stage biotite and K feldspar and Late stage sericite/clay. The Bingham Main stage mineralisation includes bornite, chalcocite, chalcopyrite and pyrite. Pyrite is dominantly in an outer halo with both potassic and phyllic alteration. Chalcopyrite lies inside the pyritic zone with potassic alteration. Bornite/chalcocite forms an annulus within the chalcopyrite zone with extreme concentrations in two centres within the porphyry trend. Gold is strongly correlated with bornite in the porphyry trend. There is a core of weakly fractured, weakly veined and mineralised rock in the centre of the deposit at the present level of exposure. Much of the molybdenite formed in quartz veins without alteration selvages at the end of the Bingham Main stage. A Late stage of quartz-sulphide-sericite is the last episode of mineralisation and includes lead-zinc-silver veins and replacements in and beyond the pyritic zone and copper sulphides in the outer ore shell. The Late stage is characterised by chalcopyrite and pyrite plus or minus bornite and chalcocite/covellite with sericitic alteration of the adjacent wallrock. Mineralisation accompanying the Late stage is economically significant. The Bingham Main stage formed during a period of about a million years.

Ore controls are the hot mass of the stock, temperature variations outward, host rock chemistry or reactivity and fracture controlled fluid access. The outstanding example of host rock effects is the limestone beds, which altered to garnet skarns and captured higher-grade copper mineralisation.

Introduction

The Bingham mining district is located on the east flank of the Oquirrh Mountains, just southwest of Salt Lake City in the state of Utah (Fig. 1). The Bingham district has been mined over a vertical interval of roughly 1500 m (4 800 feet), from the 2410 m (7 900-foot) elevation to the bottom of the underground workings. The first mining claim, the Jordan, was staked on the mineral rights September 17, 1863, (Boutwell, 1905). Lead, zinc and gold were the first products in the district from high-grade veins and replacements. It was not until a young mining engineer named Daniel Jackling convinced Spencer Penrose and Charles McNeill, wealthy investors, to develop the low-grade porphyry mineralisation that large-scale copper mining could begin. Steam shovel stripping operations began in June 1906 (Smith, 1975) and the Utah Copper Company began shipping open pit ore in June 1907. Utah Copper soon became the largest developed ore body in the world. The open pit copper mine has, with minor exception, been in continuous operation since then.

Regional Geologic Framework

The Bingham district is near the western end of the Uinta Axis, a structural trend that appeared in the Precambrian and remained an active structural element until the Tertiary (Fig. 1). The Uinta Axis marks the boundary between the Archaean Wyoming Province to the north and Proterozoic basement rocks to the south (Babcock *et al.,* 1997). The Wasatch fault east of Bingham and across the Salt Lake Valley marks the eastern limit of the Basin and Range fault block mountain province. Locally thick quartzite and thinner limestones represent the Permian and Carboniferous

(Pennsylvanian) in the immediate mine area, while most of the remainder of the Palaeozoic is also present in the surrounding region. Except for the more distant parts of the district, Mesozoic rocks are absent. The large thrust faults and extensive folding of the Cordilleran Orogeny that deformed all of these rocks are important ore controlling features within the mine area.

During the late Eocene and early Oligocene, the region underwent northeast-southwest compression as the Farallon plate was subducted along the western edge of the continental mass (Best *et al.,* 1989). At about 40 Ma the igneous intrusions responsible for the mineralisation in the Park City, Cottonwood, Bingham and Stockton mining districts were emplaced along the western extension of the Uinta Axis. A thick section of comagmatic volcanic rocks occurs east and southeast of the mine along the east flank of the Oquirrh Mountains as latite flows, breccias, and related volcaniclastics. These were the outflow of an eroded volcanic cone well over 1.5 km in height above the present surface (Moore, 1973).

At the about the time of these intrusions, Tertiary extension and normal faulting began, culminating in the Basin and Range topography that dominates much of the western United States. This extensional stress is reflected in the trend of many mineralised structures in the Bingham district (Presnell, 1997). Phillips and Kruhulek (2003) recognise an orthogonal, east-northeast and northwest structural grain around Bingham. This pattern is most evident in the northwest trending Ohio Copper porphyritic quartz monzonite and east-northeast trending quartz monzonite porphyry and later dykes as well the general boundaries of the Bingham stock.

Geology of the Bingham District

The Jurassic Elko and the Cretaceous Sevier Orogenies resulted in a complex series of northerly trending folds and associated thrust faults in the vicinity of the deposit (Presnell, 1992). These folded and thrust faulted Carboniferous (Pennsylvanian) and Permian quartzites and limestones are the host rocks of the Tertiary intrusions associated with the deposit (Fig. 2). The limestones, though a minor part of the stratigraphic column, are important loci of skarn alteration and sulphide mineralisation. Fig. 3 illustrates the folding and associated faulting along the north side of the deposit, the North Ore Shoot area. In this section the limestones are only present in the lower plate of the Midas thrust and these were not known to exist until discovered by drilling. At other locations in the deposit (Carr Fork, Fig. 2), the limestone beds are in both upper and lower plates. The upper bed is the Commercial Limestone and the lower bed is the Jordan. Ore in the limestone beds will be discussed later. Other thin limestone members, the Alphabet series, are present south of the open pit and are the hosts to lead/zinc replacements.

The hydrothermal system is centred on a small composite stock composed of four major rock units, monzonite, quartz monzonite porphyry, latite porphyry and quartz latite porphyry (Fig. 2). Age dates (Table 1) will be discussed below. The monzonite intrusion is crudely circular with extensions or protrusions along the northwestern boundary to both the northeast and southwest. The north-easterly trend of this side of the stock is reflected in all subsequent intrusions and is referred to as the *porphyry trend***.** The first intrusion was equigranular to porphyritic monzonite

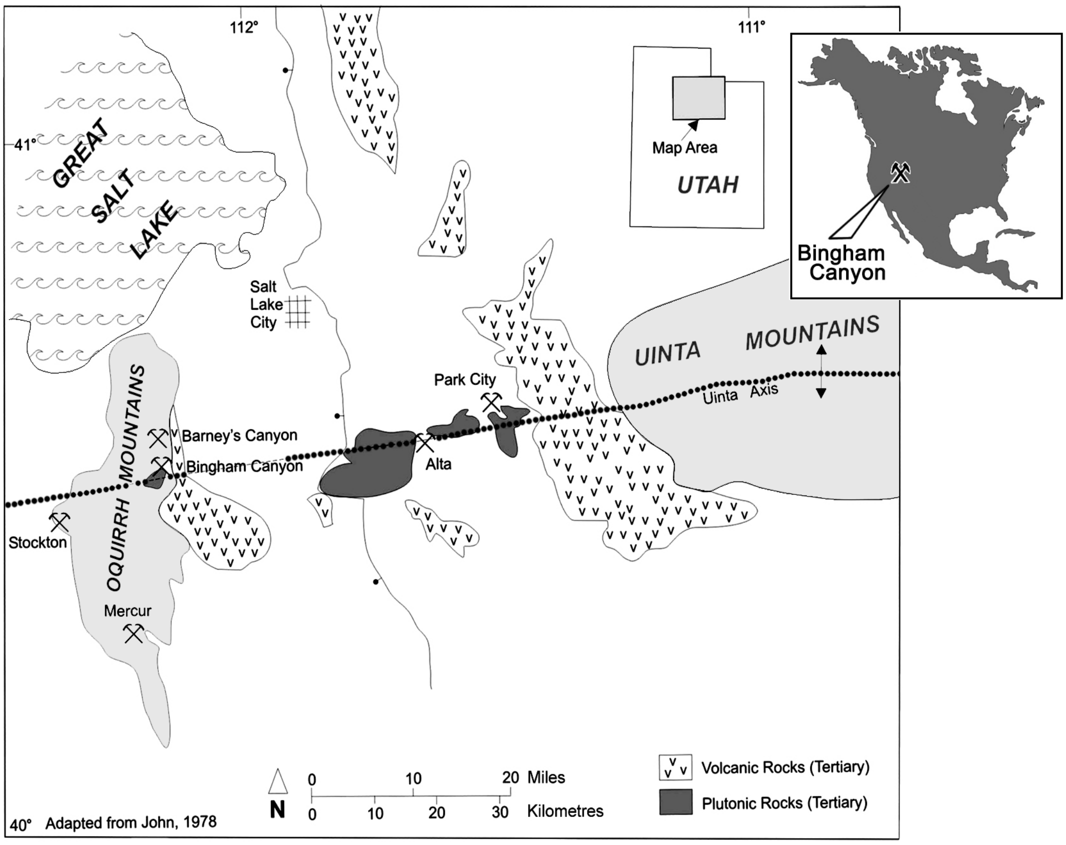

Figure 1: ***Location map and regional geologic features***

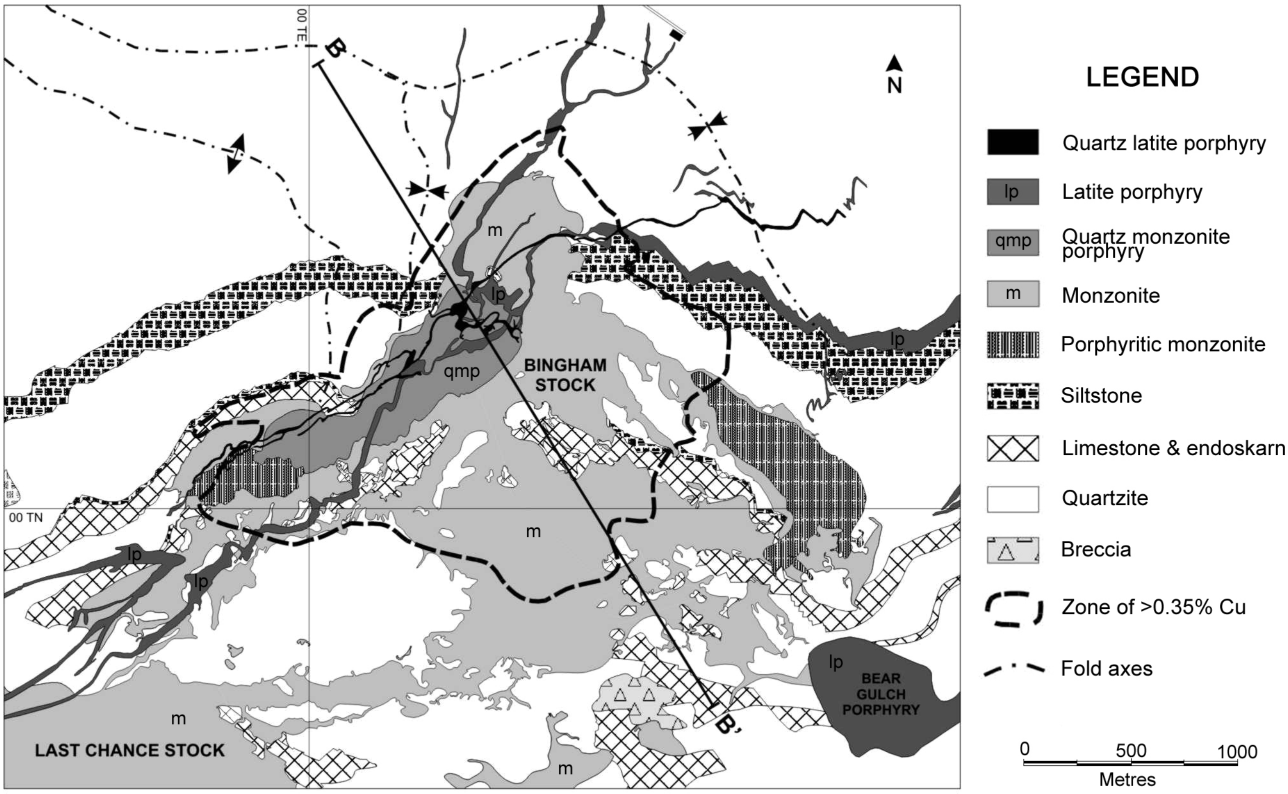

Figure 2: ***Geology of the Bingham Mine area***

or quartz monzonite (referred to here as monzonite) and may have been in part a diorite. This rock forms many dykes and sills, the contacts are irregular and extensive assimilation of the wall rocks is evident. Burnham (1979) suggests that this intrusion is the differentiated product of a melt originating in the subduction zone. Multiple stages of melting and differentiation produced the final melt with very high water and metal content at a depth of about 7 km (4.3 miles). Burnham's magma at 7 km fits with a magnetic anomaly extending from Bingham eastward to the Wasatch Mountains and is also the likely parent source for the Alta/ Park City intrusions and mineral districts.

The monzonite vented, heated the wall rocks and then cooled, crystallising to a depth of about 1.5 km (one mile) where the pressure of water exsolving from the underlying melt caused fracturing of the brittle roof and sides of the stock. The base of the resulting fracture dome retreated as cooling progressed to a depth of at least 2.5 km (1.6 miles). The result was a body of crackle and stockwork fractures above and around a dome of weakly fractured monzonite, which is a major control of the copper ore shell described below. Moore, *et al.,* (1968) suggest that sharp contacts between the monzonite and the second intrusion, quartz monzonite porphyry, are rare and therefore the two intrusions represent a continuous period of intrusive activity. Maughan, *et al.,* (2003) give reasons for a complex origin of the magmas intruded in the Bingham stock, in particular, they suggest a mafic component which added metals and fluid to the parent mass. Cline's work (1995) shows that the Bingham stock is much too small to have generated the fluids and metals in the deposit, and that the fluids therefore originated at depth as suggested by Burnham.

The quartz monzonite porphyry intrudes the monzonite along the northwestern margin of the stock having a thick dyke like shape with a north-easterly trend. Latite porphyry cuts both of the older intrusions and is in turn cut by a series of dykes that are mapped as quartz latite porphyry. The latite and quartz latite porphyry dykes are also limited to the northern half of the deposit. The porphyry trend

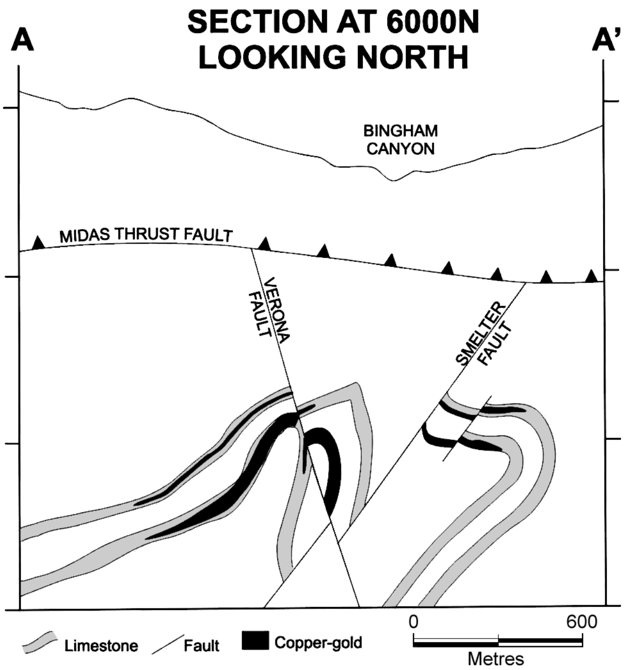

Figure 3: ***Section through the North Ore Shoot showing structure and mineralisation*** (located on Fig. 4) modified from Babcock *et al.,* (1998).

apparently was the result of the regional Tertiary extensional stress associated with regional block faulting (Presnell, 1997). At the eastern end of the quartz monzonite porphyry, irregular masses of the latite porphyry may have been emplaced in rocks that were still hot enough and deep enough to yield plastically.

Faulting in the district is dominated by the Midas thrust (Fig. 3) and parallel breaks in the pre-Tertiary rocks. Numerous younger, high angle structures with a general north-easterly trend cut the intrusive as well as the sedimentary rocks and are often referred to as fissures. The fissures usually have very little displacement but may have widths of a metre or more and are important localisers of veins and replacements where they cut the limestone beds.

Hydrothermal Alteration of Igneous & Sedimentary Rocks

The character of alteration at Bingham is highly dependent on the amount of fracturing and veining, the host lithology, and the location in the zoning pattern. The spacing between fractures and veins influences the pervasiveness of rock alteration as well as the quantity of sulphide present. In the porphyries, north-easterly trending sheeted veins may constitute 50% or more of the rock over widths of a metre or more and are closely related to high-grade copper/gold mineralisation. Systematic variations in fracture density control both the pattern of metal zoning and the amount of mineralisation. Carbonate rocks typically are more pyrite and chalcopyrite rich and bornite poor than other rocks. Monzonite tends to have more chalcopyrite, sometimes more pyrite and less bornite than rocks with less iron and calcium contents (intensely altered porphyry or quartzite). The variations in sulphide mineralogy due to rock chemistry occur immediately on crossing contacts and may make zoning relationships difficult to follow. The details of zoning are presented below.

Alteration of Igneous Rocks

The earliest recognised alteration is hydrothermal actinolite in the monzonite (Lanier *et al.,* 1978) followed or accompanied by biotite along fine, discontinuous fractures. The actinolite forms rims on or completely replaces augite. Lanier *et al.,* believed the actinolite to be an intermediate alteration stage between igneous augite and hydrothermal biotite (phlogopite). John (1978) stated that hydrothermal actinolite was the outermost selvage of early biotite veins. Biotite is the descriptor for hydrothermal biotite/phlogopite at Bingham, even when all the iron has been removed. Biotite is the first alteration to be associated with sulphide introduction and is most strongly developed in the monzonite (Fig. 4); no such strong early alteration is recognised in the quartz monzonite porphyry but may have been masked by later alterations. Hydrothermal biotite replaces primary biotite, magnetite and augite/actinolite. Magnetite usually disappears, or nearly so, with the first biotite alteration of the monzonite.

Orthoclase (K feldspar) is a minor or rare component in quartz veins, more often occurring as alteration rims around plagioclase phenocrysts that are adjacent to or cut by quartz veins (Lanier *et al.,* 1978). It is more strongly developed in the quartz porphyries than in the monzonite. In the quartz monzonite porphyry, quartz and K feldspar locally destroy the original rock texture and silicate iron may be absent, leaving only a suggestion of igneous origin. The K feldspar tends to replace the sodic rims of plagioclase while the cores are replaced or dusted with sericite/clay.

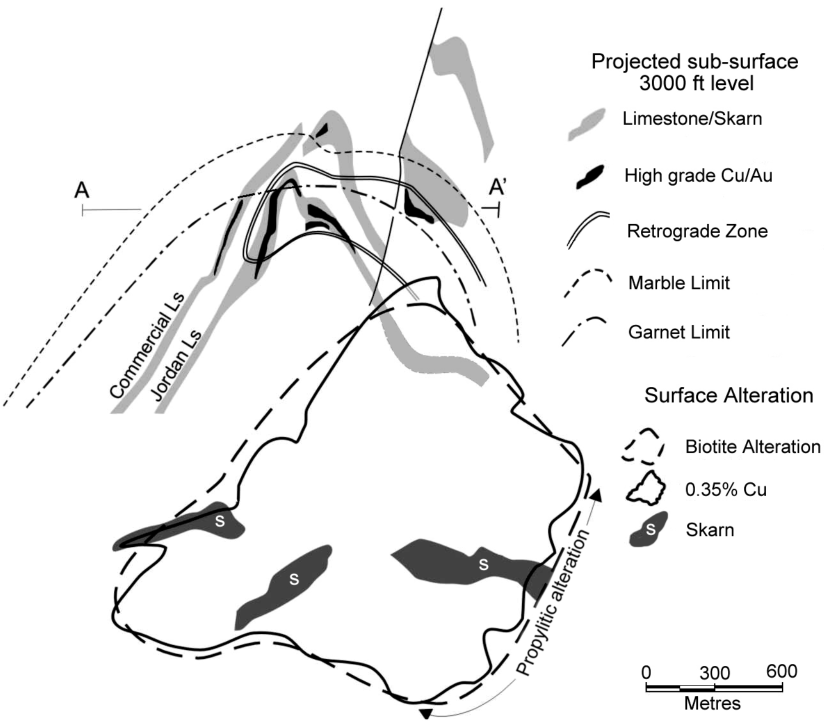

Figure 4: ***Biotite and skarn alteration on the pit surface*** with folded Jordan and Commercial skarn beds projected from 3000 level, showing Section A-A' location

Sericite and/or clays dust or completely replace plagioclase phenocrysts in all the intrusives and form selvages on quartz/pyrite/chalcopyrite veins. Orthoclase is rarely attacked by sericite except in the selvages of Late quartz/pyrite (chalcopyrite) veins. Sericite and clays are strongly developed along the porphyry trend and are much less evident in the monzonite south of the trend (Fig. 4). Pervasive development of sericite/clay is prominent where the porphyry trend crosses the outer ore shell and pyrite halo. Parry *et al.,* (1997) show the clay alteration assemblage to have formed at a final temperature near 200°C, although the sericite (white mica) could be an earlier, higher temperature product (Pers. Com. W. Parry).

Propylitic alteration characterised by actinolite-chlorite-(epidote) forms peripheral to, and interfingers with, the potassic zone in monzonite (Lanier *et al.,* 1978) and locally in the latite and quartz latite porphyry dykes (Bray, 1967).

Alteration of Sediments

The following description of alteration in the sediments is mainly from the work of Atkinson and Einaudi (1978) done on the northwestern (Carr Fork area) side of the deposit. The Early stage contact metasomatism affected rocks adjacent to the Bingham stock and resulted in the development of wollastonite with variable amounts of idocrase and garnet in the major limestone beds and diopside in quartzite and calcareous quartz sandstone. This mineralogy in quartzite/sandstone changes outward, with diopside being replaced by tremolite and talc and the addition of calcite. In quartzite, Early stage alteration minerals are overprinted by Bingham Main stage quartz and sulphide veinlets with biotite selvages near the stock and actinolite at greater distance. In the limestones, the Bingham Main stage replaces the Early wollastonite alteration with andradite garnet, diopside, quartz, magnetite, hematite and copper sulphides. In a late hydrous or retrograde phase of the Bingham Main Stage, garnet is altered to actinolite with major sulphide mineralisation. A Late stage alteration of skarn (later than all biotite-K-feldspar alteration) converted previously formed calc-silicates to chlorite, clays, sericite and talc. In the east side quartzite, Inan and Einaudi (2002) described Bingham Main Stage as K feldspar plus biotite while Late stage alteration is an assemblage of sericite-kaolinite-quartz overprinting and perhaps extending outward from the potassic alteration. Fig. 4 shows the relationship of high-grade copper/gold mineralisation to the garnet and retrograde alteration and to the stock contact in the North Ore Shoot area. Note that wollastonite is not common in this area and that retrograde alteration is more prevalent than in the Carr Fork area described by Einaudi and Atkinson.

The North Ore Shoot, Fortuna and Carr Fork (Fig. 2) are not separate ore bodies; they are segments of one extensive mineralised skarn developed in the Commercial and Jordan Limestones (Harrison and Reid, 1997) along the northern and eastern stock contact. Carr Fork is predominantly in steeply to moderately dipping upper plate beds. The larger and higher grade North Ore Shoot/Fortuna mineralisation is in the tightly folded anticlines of Jordan and Commercial Limestones in the lower plate (Fig. 3). The size and grades of the skarn are such that they constitute a major resource potential.

Sulphide Zones

The sulphide zoning (Fig. 5) is concentric, parallel to the contacts of the composite Bingham stock with a low grade, central and deep core which grades upward and laterally to the molybdenite zone, copper shell, pyrite halo a lead/zinc/silver zone and outermost gold in veins. All of the zones are overlapping and gradational. Disseminated gold at Barney's Canyon (Fig. 1) may also be related to the Bingham system. In detail, the copper shell is perturbed by what are interpreted to be secondary (multiple) centres of fluid flow and mineralisation along the porphyry trend (Fig. 5A).

Low-Grade Core

The low-grade core (or simply, *core*) in the vicinity of the ore reserve is potassically altered and typically contains less than 0.5% total sulphides as chalcopyrite, molybdenite and subordinate bornite. The core is centred at the monzonite/quartz monzonite porphyry contact and with depth, it expands and both the sulphide and metal contents decrease dramatically. The veins are widely spaced and the sulphide content tends to be low, accounting for the low metal grades. Bornite is variably present, more so where the porphyry trend intersects the core. Chalcocite and minor covellite accompany bornite as primary sulphides, and with the exception of Late stage sericite-pyrite veins, pyrite is virtually absent in the upper core. The dominant alteration is secondary biotite and is usually weak because of the low density of veining. Above roughly the 1650 m (5 400-foot) elevation of the mine, the core merged into the overlying copper shell. Near the outer limit of the core, vein frequency, chalcopyrite, and bornite content increase and there is a gradational change to the copper shell. At considerable depth, where the copper content drops to near background, pyrite again appears and becomes the only sulphide present in both monzonite and quartz monzonite porphyry.

Molybdenite Zone

Molybdenite and copper sulphides are essentially coextensive; the difference being that the peak molybdenite content lies just inside the core adjacent to the copper shell. The molybdenite content diminishes both into the core and outward to the pyrite halo. Molybdenite is present in a variety of vein types of various ages although the veins where molybdenite is the dominate sulphide are later than potassic alteration.

Copper Shell

The *copper shell* is a term for the three dimensional region of high copper values, occurring as a shell around the low-grade core (Fig. 5A), surrounded in turn by the pyrite halo. The 0.35% Cu copper contour roughly bounds the upper part of the copper shell. The copper shell owes its form

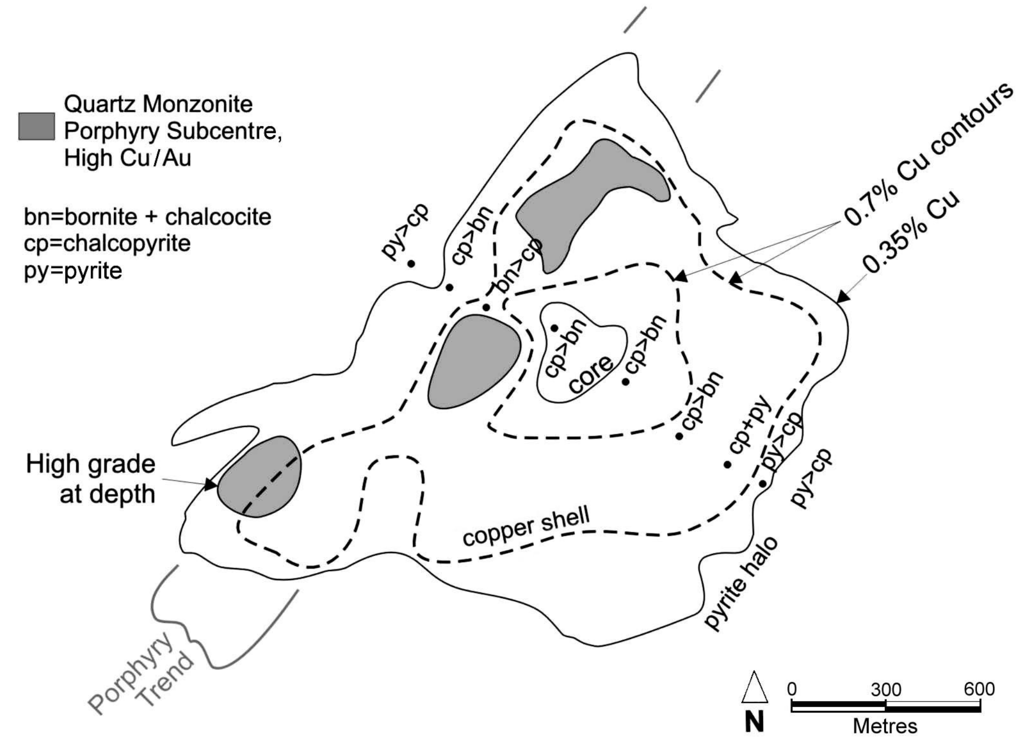

Figure 5A: ***Copper and sulphide zoning and high grade sub-centres of mineralisation.***

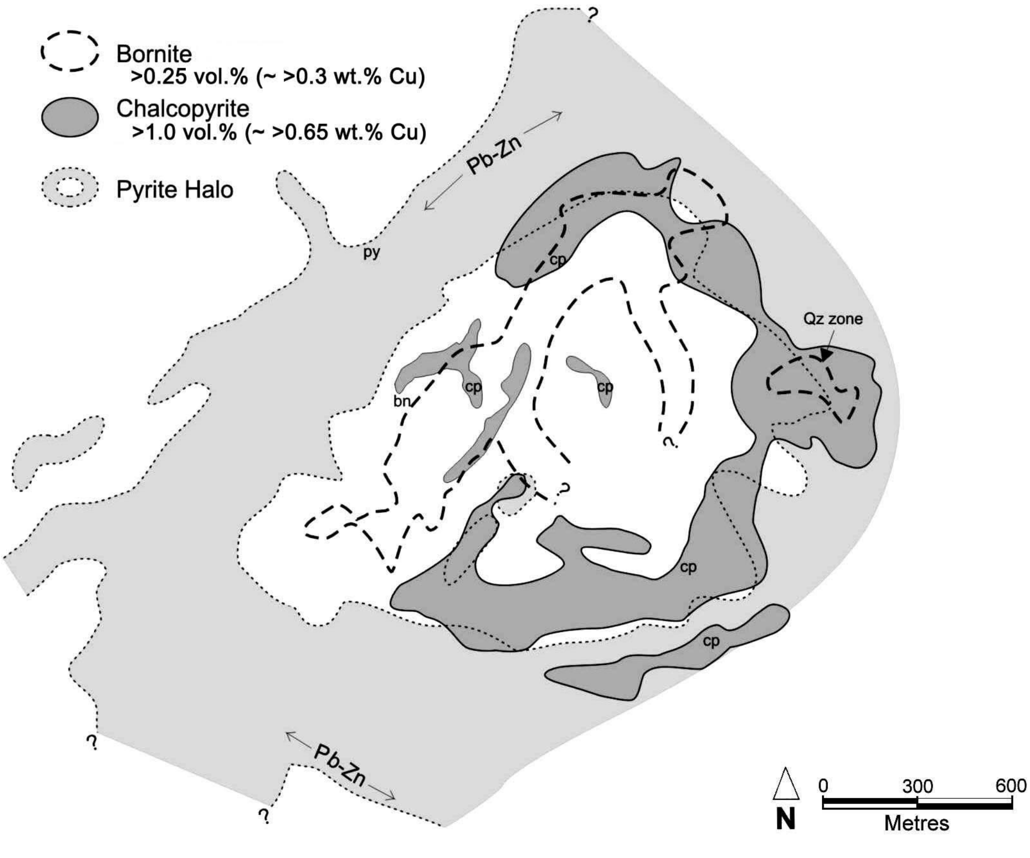

Figure 5B: ***Zoning of bornite, chalcopyrite, pyrite and Pb/Zn.*** All zones are gradational.

and variations to a complex set of geologic events. Foremost is the fracture dome already mentioned. No less important is the porphyry trend, which caused the monzonite stock and later porphyries to extend along the trend. The thermal events marked by the porphyry intrusions repeatedly rejuvenated the fracturing and fluid flows and formed at least two and perhaps three sub centres of high-grade mineralisation (Fig. 5A). The outer boundary of the copper shell crudely parallels the stock contact (Fig. 2), overstepping the contact into the quartzite for a hundred metres or more on the east and north. Prior to mining, the copper shell extended to the surface near the 2450 m (8 000 foot) elevation and is known to extend to the 600 m (2 000-foot) elevation at depth (Fig. 6). Fractures and/or veins are more closely spaced than in the core causing the biotite selvages of veins to overlap in the monzonite with the result that biotite alteration becomes pervasive. Much of the sulphide is truly disseminated, that is, it is neither in a vein or fracture nor can it be related to the envelope of a specific vein. This disseminated character holds true in thin section as well as in hand specimen. Disseminated sulphides commonly account for more of the mineralisation than do vein sulphides, especially in the high-grade areas. Potassic alteration is typical throughout the copper shell, except in skarn.

The habit of sulphides in the copper shell can be illustrated by a traverse across the centre of the deposit perpendicular to the porphyry trend (Fig. 5A):

- Starting at the north contact between quartzite and quartz monzonite porphyry, the copper grade is 0.3% and pyrite is greater than or equal to chalcopyrite.
- At the centre of the porphyry trend 150 m to the south, the grade may reach 2% Cu plus 1.8 g/t Au with 2% total sulphides (volume %) and bornite exceeding chalcopyrite with pyrite being absent. Mine studies show bornite to be coextensive with primary chalcocite therefore we use bornite to mean both are present.
- The south contact of the quartz monzonite porphyry would lie near the interface of the copper shell with the core zone where bornite abundance is less than chalcopyrite, total sulphides are near 0.5 volume percent and copper is around 0.3%.
- The core extends 300 m to the southern copper shell interface with local copper contents as low as 0.1% and less than 0.5% volume sulphides.
- As the copper shell is again crossed, copper grade and sulphide content increase and a small amount of bornite may accompany chalcopyrite to roughly the centre of the southern copper shell. At that point, pyrite appears and increases as chalcopyrite decreases into the pyrite halo.

Note the asymmetry of this concentric zoning relative to the location of the porphyries and the high-grade gold and copper. In the discussion section we will attempt to explain some of the anomalies in the zoning

Expanding from this traverse, bornite occurs (Fig. 5B) throughout the core and extends into the medial copper shell, across the eastern contact of monzonite/quartzite, south along that contact and weakly around the south side of the monzonite. Fig. 5B outlines the higher concentrations of bornite, although smaller amounts of bornite occur throughout the core and along the eastern quartzite/monzonite contact. Three centres of high grade are aligned in the porphyry trend. In these, (Fig. 5A), bornite may be more abundant than chalcopyrite, pyrite is typically absent and iron may be depleted to the point of being virtually absent except for iron in sulphides. In quartzite and in the southern monzonite, the bornite may be associated with pyrite. The general absence of pyrite in

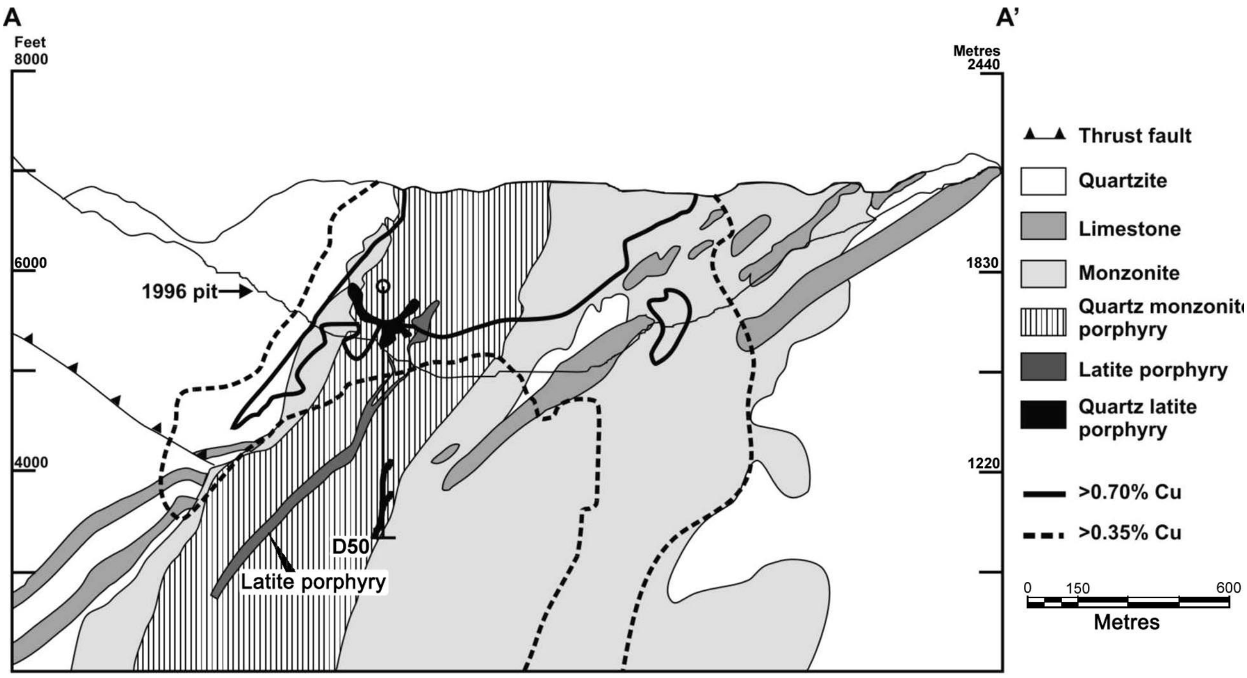

Figure 6: ***Copper grade zones on cross section 1000W.*** Location of the drill hole D50 is shown, from Ballantyne *et al.,* (1997).

the porphyry trend applies only to the present level of exposure. The early mine levels and the core zone do contain pyrite.

Inan and Einaudi (2002) reported on two bornite associations in the quartzite east of the porphyry trend, one without pyrite and associated with potassic alteration and a later association of sericite-pyrite-bornite. The potassic association in quartzite is similar to that found in the high-grade quartz monzonite porphyry except for lower gold content in the quartzite. At present, it appears that the bornite in Fig. 5B is a composite of two and perhaps three different types of bornite occurrences; the high-grade areas without pyrite, the wide envelope veins (see Origin of Fractures and Veins, below) and the Late stage.

Gold is such an important part of the Bingham ore that it must be specifically mentioned. Work by Kennecott has shown its close correlation with copper and bornite (Ballantyne *et al.,* 1997). In the porphyry trend and low-grade core, gold to copper ratios are high. Gold content is high in the porphyry trend and much lower in the core. Both the ratio and gold content are lower in the quartzite to the east and the monzonite to the south. Reasons for this gold distribution will be discussed below. Bodies of siliceous gold ore were mined above the western part of the orebody, apparently in the leached capping, and may be related to mineralisation presently mined in the Main Hill fault zone 150 m south of the western end of the quartz monzonite porphyry. Several of the northeast striking fissures in the Main Hill area have wide halos of gold with strong clay alteration and a widespread arsenic anomaly that is part of the gold mineralising event but does not always mark the presence of gold. The Main Hill gold zone has some similarities to Carlin and Barney's Canyon, being composed of sub-visible gold particles in the outer rim of pyrite grains. The Main Hill gold clearly overprints earlier copper mineralisation but its age relative to Late stage copper or to clay or sericite alteration has not been established. The best drill intercept of Main Hill Au-As is 15 m of 3 g/t gold and prior to mining the Main Hill gold zone may have contained on the order of 1 million tonnes.

Pyrite Halo

The pyrite halo (>1% pyrite, py>cpy, Fig. 5B) overlaps with the outermost copper shell and extends outward for a thousand metres or more. Chalcopyrite content in the copper shell decreases as pyrite increases to about 1 vol. % pyrite near the copper shell limit. Pyrite increases rapidly from one to greater than 2 vol. % over a distance of a hundred metres or more. The pyrite occurs as veinlets or fine-grained disseminations and may be accompanied by minor chalcopyrite. Limestones or skarns within the 2 vol. % region of the pyrite halo typically contain greater than 4% pyrite. The pyrite tends to be more disseminated near the copper shell and more fracture-vein controlled outward (Babcock *et al.,* 1995).

Lead-Zinc Zone

Past metal production from the lead-zinc zone has totalled around 33 million tonnes of lead-zinc ores with recovered grades of 7% Pb, 3% Zn, 115 g/t Ag, and 1.2 g/t Au (Kruhulek, 1997). The lead-zinc mines at the Lark (eastern), U.S. Mine (southern), and Carr Fork (western) areas were active from the initial discovery of the district in 1863 to 1971.

Veins (fissures) and replacement deposits with argentiferous galena, sphalerite, pyrite, tennantite-tetrahedrite, and minor chalcopyrite with or without calcite, quartz, clay, talc, sericite and opaline silica overlap the pyrite halo and extend to the outermost limits of recognisable sulphide introduction, a kilometre or more from the centre of the Bingham deposit.

In the Lark mine production came mainly from the Jordan, Lark, and Commercial limestone replacements or mantos particularly the Lark bed or vein and its associated bedding fault. The Lark bed lies closely below the Commercial Limestone and was commonly ore grade for its entire thickness, up to 4.5 m or more. The ore spread out along the limestone beds and followed numerous fissure intersections with ore thicknesses up to 6 m. Some ore bodies extended for well over 300 m along strike and down dip. The lead-zinc production in the U.S. Mine came dominantly from a series of sub-vertical, NNE fissures in quartzite and monzonite and from steeply dipping mantos where limestone beds were intersected by the fissures. A complex of workings extended over a vertical distance approaching 1500 m (Rubright and Hart, 1968). Particular fissures contained significant amounts of gold (Phillips and Kruhulek, 2004). In the Highland Boy area, north and west of the open pit, lead-zinc occurs along northeast-trending fissures especially at the intersection with the steeply dipping, westerly-striking Commercial and Jordan limestones. Copper was a much larger part of the production in this area.

The pyrite content in these mines increases both at depth and as the pyrite halo is approached until the lodes become essentially barren massive pyrite. Sphalerite is zoned from jet black (Fe-rich marmatite) at depth to red-brown sphalerite at higher levels apparently due to marmatite being the stable higher temperature phase. With increasing depth, the lead-zinc lodes of the U.S. mine pick-up coarser-grained pyrite and finally some pyrrhotite. The Mn content increases outward and rhodochrosite ± barite occurs locally in the outer fringe of the base metal zone. Enargite and cinnabar with orpiment and realgar were seen high in both the Lark and U.S. mines (Richard D Rubright, personal communication, 1995).

There is little doubt that most lead-zinc-silver mineralisation post-dates copper mineralisation. When found in the copper orebody, this type of mineralisation crosscuts potassic alteration and Atkinson and Einaudi (1978) equated it with their Late stage. Fluid inclusion studies have shown that the mineralising fluids were very dilute (Field and Moore, 1971; Roedder, 1971).

Fluid Inclusions

Fluid inclusions are extremely numerous and indicate boiling as well as a wide range of salinities. Temperatures are generally high in the core and decrease outward to the propylitic halo. Moore and Nash (1974) concluded that there were at least two episodes of high temperature veining, one of which was earlier than the dyke rocks. They also recognised two thermal peaks, one around 600° C and another about 400° C. Bowman *et al.,* (1987), estimated temperatures of 450° C to 600° C from 14 samples that were widely distributed across the deposit. In their samples, the limit of 600° C encompasses an area of about 300 by 450 m centred roughly on the core and overlapping the quartz monzonite porphyry and monzonite about equally. The 550° C isotherm extends 200 m into the copper shell and the 450° C temperatures extend to the outer copper shell in most locations but cut through the western quarter of the quartz monzonite porphyry and the copper shell. Inan and Einaudi (2002) estimated the temperature for the Bingham Main stage potassic alteration in quartzite on the east side of the copper shell to be 350° C with a 250° C estimate for Late stage alteration.

Redmond *et al.,* (2002) described a series of quartz veins following each of the porphyry intrusions, early veins with fluid inclusion temperatures from 400° to >575°C and later veins that formed below 400° C. They also found that inclusions from deep barren veins in the core have low salinity fluids carrying 8000 ppm copper, plus chalcopyrite crystals and estimated trapping temperatures of 470-590° C. They concluded that the barren, low temperature veins result from decreasing solubility of silica while metal solubility is increasing due to an adiabatic temperature drop of 50°C over a 1 km change in depth.

Fractures and Veins

The earliest fractures are the crackle and stockwork fractures related to the cooling of the monzonite as described by Burnham, followed by later sheeted and stockwork fractures created by the cooling of the porphyry intrusions. Finely sheeted quartz veins are prominently developed in the quartz monzonite porphyry but are not recognised in the monzonite.

Phillips, et al., 1997 noted that consistent vein offsets are rare at Bingham and reported a general progression from early short discontinuous veinlets marked by biotite alteration and uncommon chalcopyrite to more continuous, straight quartz veins with ubiquitous chalcopyrite, biotite selvages and increasing amounts of molybdenite. K feldspar was noted rarely in veins and more commonly as alteration in plagioclase adjacent to veins. Calcite was said to be more common in younger veins. Later quartz-molybdenite veins were associated with little or no biotite alteration or chalcopyrite. The latest veins noted were quartz-pyrite veins with sericite selvages. Chalcopyrite in the latter veins was present only in the high copper areas. These relationships came from core logging, mainly in the monzonite. They separated a single quartz-K feldspar vein type mainly occurring in the quartz monzonite porphyry. The quartz-molybdenite veins would be equivalent to the Transitional veins at El Salvador (Gustafson and Hunt, 1975) and vein types 4 and 5 at Butte, Montana (Brimhall, 1977).

The latite and quartz latite porphyry dykes have long been known to cut off veins, to contain fewer veins and to have less mineralisation than the earlier rocks. Moore and Nash (1974) suggested that the orebody was formed by multiple, recurring events including at least two episodes of high temperature veining, one of which was earlier than the dyke rocks. Redmond, *et al.,* (2002), vastly changed the interpretation of cross cutting relationships at Bingham by describing six new vein types or sub types in the porphyries (1 and 3 below). These are repeated cyclically, one cycle after each of five porphyry intrusions. This cyclic repetition explained what had previously seemed to be random cross cutting vein relations that can only be recognised at porphyry contacts. Their vein sequence was:

1. BG veins with selvages of biotite and green sericite with bornite (bn), chalcocite (cc) and chalcopyrite (cp). Quartz centrelines are thin to absent.
2. Hairline biotite veinlets with trace bn-cc-cp.
3. Five types of quartz stockwork veins, all with bn-cc-cp and K feldspar + biotite in their selvages. The latest of the five contained more sulphide mineralisation than the earlier veins. Fluid inclusions indicate temperatures declined from >500° C to < 400° C with increasing sulphide formation at lower temperatures.
4. Quartz-molybdenite-(cp) veins later than all the porphyries.
5. Pyrite ± quartz with sericite selvages.

The heat provided by the quartz monzonite porphyry and its exsolved fluids may have been sufficient to heat the entire mass of the mineralised body during the first vein cycle, but the later dykes are far too small to have contained the necessary ingredients. Therefore, fluids must have been the source of heat as well as metals. The production of fluid and porphyry intrusions from the deep magma source are closely tied and it is likely that the low density, low viscosity fluid arrived ahead of magma at any given depth.

Redmond *et al.,* (2003) plot fluid inclusion data from the five stockwork quartz veins (listed above). This sample group is an apparently random sampling of the 25 different stockwork quartz veins (5 vein types in 5 repetitions or cycles). These samples are from a lithostatic depth at about 2.3 km. The samples have evidence of boiling fluid and plot on a smooth P/T curve indicating that the 5 cycles have similar characteristics. Temperatures range from about 350° at hydrostatic pressure, to 550° C at lithostatic pressure. We interpret this to mean that each vein cycle begins near 350° C, rises to about 550° C and drops again to 350°, passing each temperature point twice in each cycle. Rising fluid cools as the rock temperature rises (heating phase) until both are at or near the temperature maximum before cooling (cooling phase). Veins may form before as well as after the peak temperature. If the early fluid rises ahead of the magma intrusions, the intrusive will cut any heating phase veins but there is no field evidence developed for this.

To explain the vein cycles described by Redmond *et al.,* we suggest a simple, repetitive process. A mechanism such as the heating and cooling phases in each cycle of hydrothermal activity coupled with boiling to create vertically zoned and overlapping fractures and veins. At the 2.3 km depth sample point, the stress of the upward movement of fluid may have caused hydraulic fracturing in the heating phase rock. Subsequent failure of the roof rock allowed boiling at and below the sample point to cause intense fracturing within the boiling zone (BZ) and stockwork fractures above. The samples are in the high-grade zone of the porphyry trend ore shell and apparently are near the upper limit of boiling (boiling is complete at this level) at a depth below 2 km. The rapid fall of pressure and temperature would decrease silica solubility to form the veins as well as raise the concentration of salts and metals in the remaining fluid by a factor of 5 to 10.

In this scenario the fracture types are vertically zoned reflecting variations in the pressure, temperature and strain rate. Retreat of the BZ results in crosscutting or overprinting of early fractures (and veins) by later veins resulting in the 5 recognisable vein types at a single location. The quartz poor BG veins may have been formed in the early heating phase before any large temperature or pressure decline lowered the solubility of silica.

The morphology of veins at Bingham is not fully worked out over the entire deposit. The vein types recognised by Redmond *et al.,* in the porphyries have not all been recognised or perhaps do not exist in the monzonite and some vein types in the monzonite apparently are absent in the porphyries. For example, drill logs and petrographic work (drill hole D392) relate the bornite in the southeastern monzonite to thin quartz veins that have wide, copper rich selvages (called wide envelope veins in Bingham drill logs) with bornite, chalcopyrite, and minor pyrite. These veins are straight and continuous and crosscut early biotite alteration with chalcopyrite, some weak K feldspar alteration is present along with bleaching (sericite?) of earlier biotite. On occasion it appears they may have biotite as an outer selvage and an inner bleached selvage. Wide envelope veins are somewhat similar to the BG (brown-green) veins described by Redmond *et al.,* (2002); however, the BG veins are among the earliest veins found in the porphyry and do not contain pyrite. The wide envelope veins do not seem to fit the Late stage as described by Inan and Einaudi.

Discussion and Conclusions

Controls of Mineralisation and Metal Grades

The descriptions above should demonstrate that there are systematic differences in mineralisation and alteration of the three major rock types intersected by the porphyry trend as well as differences between rocks within the trend and those lying generally south of the trend. These differences must be due to some combination of ore controlling features. The highest grades of gold and copper are in the quartz monzonite porphyry accompanied by intense fracturing, near total leaching of calcium and iron (except iron in sulphides), and flooding by K feldspar and silica. Bornite-chalcocite constitutes from zero to nearly 90% of the sulphide, pyrite is generally absent and chalcopyrite is ubiquitous. In contrast, the monzonite in the porphyry trend contains more chalcopyrite, somewhat less bornite-chalcocite, less K feldspar and more biotite; peak metal grades are lower (averages are about equal) and more iron and calcium remain in the rock. Quartzite in the trend is potassically altered and bornite-chalcocite locally are the major sulphides, but copper grades are lower than in the intrusives and Au/Cu ratios are much lower. These variations in metal grades and ratios can largely be explained by temperature changes across the deposit at the time of formation, host rock chemistry, and the fluid access via fracturing.

Simon *et al.,* (2000) relate temperatures in the range from 400° to 600° C and copper/iron ratio in sulphides to the amount of gold that can be loaded into chalcopyrite and bornite. The possible gold loading in bornite is as much as ten times that of chalcopyrite and temperature changes of 100° C may change the gold loading of bornite or chalcopyrite by a factor of 10. Fig. 6 from Ballantyne *et al.,* (1997) illustrates the control temperature exerts on the amount of gold that can be loaded into copper sulphides. In the figure, Au:Cu is 1.22 g/t:1.1% in the copper shell of D50 and 0.765 g/t:0.2% some 250 m deeper in the low-grade core. The copper:gold ratio is more than doubled in the higher temperature core zone. Similarly, declining temperature outward from the core zone, as indicated by fluid inclusion work, appears to be a major reason for the lower gold to copper ratio in the quartzite on the porphyry trend relative to both porphyry and monzonite. Another aspect of the work by Simon *et al.* is that given the copper and gold assay data and the sulphide ratios, it is possible to estimate the temperatures needed to form the gold mineralisation across the Bingham deposit (Phillips and Kruhulek, 2003). Estimates based on their work show temperatures near 500° C are required to produce the needed gold loadings across the low-grade core and most of the copper shell. Apparently, given high temperature, the only condition required to produce the high ratio of gold to copper in the porphyry trend is the abundance of bornite/chalcocite (high copper to iron).

Bingham drill logs indicate that chemically non-reactive rocks favour higher ratios of bornite-chalcocite to chalcopyrite than do reactive rocks; the monzonite and calcareous beds are both less favourable than quartzite. Where iron and calcium have been severely depleted by intense alteration along the porphyry trend, the intrusives are less reactive and these are the locations of high ratios of bornite/chalcocite to chalcopyrite. The abundance of bornite-chalcocite relative to chalcopyrite decreases away from the porphyry trend in all rock types providing a reason for lower gold content outside the trend even where temperatures were high. Host rock chemistry may at least partly explain the variation in the ratio of bornite-chalcocite to chalcopyrite and thereby the gold/copper ratio, however, fracture frequency must be added to temperature and host rock effects in order to fully account for the high copper and gold grades of the porphyry trend.

The monzonite fracture dome predates most (or all?) of the fracturing associated with the porphyry intrusions and provided the initial paths for sulphide introduction. The cooling of the later porphyry intrusions reopened old fractures and created new ones throughout the fracture dome, but the cycles of sheeted and stockwork fractures were stronger in the porphyry trend, providing greater access for the ore forming fluids than elsewhere. This increase in fluid flow facilitated more intense mineralisation and alteration along the porphyry trend. Variation in fracture patterns and therefore vein density, controls the amount of mineralisation, temperature variation from the low-grade core outward controls gold loadings in the sulphides and perhaps the type and quantity of sulphide, and finally, host rock chemistry influences the ratio of bornite-chalcocite/chalcopyrite and thereby the ratio of Au/Cu.

Age Dates and Genesis of the Orebody

Table 1 summarises the radiometric age dates and the sequence of geologic events that fit those dates. Before any event recorded in the orebody, the monzonite formed a large volcanic edifice and heated the surrounding wall rocks. The first age date, 38.55 Ma (U/Pb, Parry, *et al.,* 2001), is for the unaltered Last Chance Stock located adjacent to the Bingham Stock on the southwest. The two stocks are accepted as time equivalents. The fracture dome formed between this date and the 38.45 ± 0.19 Ma age determined for the fracture controlled hydrothermal actinolite. John (1978) stated that actinolite was a precursor to the biotite alteration in the monzonite and the first biotite is assumed to be close to this age also. The sequential formation of the fracture dome followed by hydrothermal actinolite and earliest biotite alteration occurred immediately after the crystallisation of the monzonite. The first chalcopyrite mineralisation in the monzonite may also have been in place before the quartz monzonite porphyry intruded the north flank of the monzonite. The fracture dome and the concentric alteration zoning in the monzonite are independent of the quartz monzonite porphyry, this plus the immediate onset of hydrothermal actinolite alteration suggest the intrusion of the porphyry after the initiation of potassic alteration and mineralisation. The common absence of sharp contacts between the monzonite and the quartz monzonite porphyry indicates that a large mass of rock remained at high temperature.

The quartz monzonite porphyry intruded the monzonite, cooled and was intensely fractured, including minutely sheeted zones parallel to the east-northeast porphyry trend. Six episodes of fracture and vein formation followed this intrusion (Redmond *et al.,* 2002), each with associated

Age Dates	Dated Events	Undated Geologic Events
		intrusion of mz, venting, heating wallrocks, cooling of stock
38.55 ± 0.16	**X LAST CHANCE STOCK MONZONITE**	
	?	fracture dome in Bingham monzonite
38.4 ± 0.16	**X hydrothermal actinolite**	
	?	biotite plus chalcopyrite form early ore shell in fracture dome
	?	QUARTZ MONZONITE PORPHYRY INTRUSION
		cooling produces fractures
	?	sequence of 7 potassic vein types
	?	LATITE PORPHYRY INTRUSION
	?	cooling produces fractures
	?	sequence of 6 potassic vein types
	?	BIOTITE PORPHYRY DYKE
	?	cooling produces fractures
	?	sequence of 6 potassic vein types *
37.81 ± 0.20	**X vein sericite cutting biotite alteration in monzonite**	
		QUARTZ LATITE PORPHYRY BRECCIA
	?	cooling produces fractures
	?	sequence of 6 potassic vein types,
	60% of Cu mineralisation completed in the porphyry trend	
37.72 ± 0.09	**X QUARTZ LATITE PORPHYRY DYKE**	
	?	cooling produces fractures
37.57 ± 0.11	**X biotite age in monzonite**	**earlier part of 6 vein sequence**
37.07 ± 0.21	**X biotite age in quartz monzonite porphyry**	**last potassic alteration**
37.0 ± 0.27	**X molybdenite age** **most of copper mineralisation completed**	
	??	LATE STAGE
	??	pyrite
	??	cataclastic fracture
		bornite digenite chalcopyrite

* Vein cycles described by Redmond *et al.,* (2002)

Table 1: ***Age dates and actual or likely progression of geologic events, Bingham, Utah***

potassic alteration and bn-cc-cpy mineralisation. Temperature measurements indicate that the earlier veins formed at 400 to >575° C while the latest veins formed below 400° C. The latest vein type was found to contain more sulphide than the earlier veins and fluid inclusions in the later veins contained an order of magnitude less copper than did the early veins. They concluded that sulphide deposition was a function of cooling. This sequence of sheeted fractures, veining and mineralisation was cyclically repeated after each of the five porphyry intrusions creating a complex of cross-cutting vein relationships all part of the Bingham Main stage. Prior to intrusion of the latite porphyry, only 10% of the copper in the porphyry trend was in place.

The irregular, often discontinuous masses of latite porphyry along the eastern margin of the quartz monzonite porphyry suggest that the older rocks were at high enough temperature to locally yield plastically to the intruding latite magma. The frequent absence of chilled margins also indicates high temperatures in the wall rocks. The cycle of veining that follows the latite porphyry dyke emplacement accounts for 5 times the copper that was introduced by the quartz monzonite porphyry vein cycle. Redmond *et al.,* defined biotite porphyry and a quartz latite porphyry breccia that are both younger than latite porphyry but older than quartz latite porphyry and both are followed by a cycle of veining. Both these units are included with the quartz latite porphyry in the mine database and the volume of each is very small. No information is available to define the amount of total copper introduced in these two vein cycles.

The sericitic vein at 37.81 ± 0.02 Ma cuts Bingham Main stage potassic alteration in the monzonite and is essentially the same age as the quartz latite porphyry date of 37.72 ± 0.09 Ma. This vein event with galena and tetrahedrite seemingly denotes an interim of Late stage veining between cycles of potassic alteration and probably represents significant cooling of the stock mass before intrusion of the quartz latite sequence of dykes. The exact relationship of the sericite vein to the biotite porphyry and the quartz latite porphyry breccia is not known. The time span from the hydrothermal actinolite to the sericite vein and intrusion of the quartz latite porphyry is 600 000 years.

A further 700 000 years elapsed between the quartz latite porphyry intrusion and the end of the Bingham Main stage. This time is constrained by the date for the quartz latite porphyry and a Re/Os date of 37.0 ± 0.27 Ma for molybdenite in late molybdenite rich veins (Chesley and Ruiz, 1997). A biotite date in the quartz monzonite porphyry of 37.07 ± 0.21 Ma is the same as the age of the molybdenite veins and should be the latest biotite alteration. This last cycle of potassic mineralisation accounts for possibly 40% of the total copper. Phillips *et al.,* (1997) and Redmond *et al.,* (2002) both recognised that molybdenite rich veins mark the termination of potassic alteration. Much of the molybdenite veining must have been formed rapidly at the end of the Bingham main stage.

There is no age date for the Late stage of Inan and Einaudi (2002). It is a sequence of sericite alteration with pyrite in veins and disseminated in the wall rock followed by brecciation of the veins and finally the introduction of bornite-chalcocite and chalcopyrite filling fractures in the quartz and pyrite. This Late stage cuts the quartz latite porphyry making it the last alteration phase rather than an earlier Late stage cycle as for the dated sericite vein in monzonite. The Late stage is a widespread overprint of earlier mineralisation in the quartzite and represents a significant amount of the copper produced in this area. The authors believe that more work must be done to determine the relation to the quartz-sericite-pyrite and sericite-galena-tetrahedrite veins.

While much emphasis is often placed on porphyritic rocks as the drivers of porphyry systems, at Bingham, the porphyritic rocks are little more than host material for mineralising solutions. The porphyries are associated with the fluids but are directly responsible for little of the fracture or mineralisation. The possible arrival of fluids in advance of the intrusions may explain the late barren porphyry seen in many porphyry districts, porphyries that followed their associated fluids.

Changes in the Ore Body with Depth

The original mine was 800 m above the current pit bottom and the reference material to the original geology consists of reports by Beeson (1917) and Butler (1920), scraps of information in the mine files and a collection of 24 samples**.** Beeson refers to the monzonite as the Dark Porphyry and says it is extensively sericitised and silicified. Pyrite and chalcopyrite are the sulphide minerals that occupy most of his discussion of primary mineralisation. There is only minor mention of bornite with the comment that pyrite is uncommon where bornite is present. Bornite and chalcocite are mostly discussed as part of the thin enrichment zone. The Payroll porphyry (Light Porphyry) was said to outcrop boldly at the top of the mountain where it was white, silicified, sericitised and 200 feet (60 m) wide. Beeson concluded that this white rock was only an alteration of the Dark Porphyry. Beeson and Stringham (1953) both found apparently common examples of chalcopyrite rimming and replacing bornite/chalcocite.

Butler (1920) said that the orthoclase was highly sericitised and that the Light Porphyry was white because of the sericite content and biotite that was bleached of all colour. He found abundant fine-grained silica and orthoclase flooding in the Light Porphyry and a north-easterly striking fault with northerly dip was found to separate the Light and Dark porphyries. The Light porphyry was said to locally have much better metal grade than the Dark porphyry. Most of the sulphides were disseminated and veins were relatively scarce. More recently, John (1978) noted that bornite in the concentrates increased significantly during the first 40 years of mining.

In comparing the near surface ore deposit with that presently exposed, we find that the Light Porphyry was a combination of the quartz monzonite porphyry, latite porphyry and quartz latite porphyry. The alteration of the porphyry was similar to that in the present mine except there was more sericite and the width was locally narrowed to 60 m at the outcrop giving it a definite dyke form. The information from churn drill holes shows the quartz monzonite porphyry to have outcropped as two segments: the eastern segment about 250 by 300 m in area and a western segment as a dyke not much more than 60 m wide and 250 m feet long. Bornite related to potassic alteration was weaker at the surface and was associated with pyrite as indicated by the few remaining samples. The little notice given to primary bornite by Beeson and Butler was due to a lower abundance of bornite relative to chalcopyrite. The total sulphide content of the ore was quite high, as much as 3 or 4 volume percent, perhaps double that presently mined. The association of extreme depletion of iron and calcium with the high copper/high bornite area(s) was also present as indicated by the bleaching of the rock and removal of all colour in biotite.

The observation by Butler (1920) that orthoclase was highly sericitised is in sharp contrast to the present exposures where orthoclase is usually untouched by sericite. The rims of chalcopyrite on bornite and chalcocite plus ubiquitous pyrite suggest that there was a large component of mineralisation possibly related to the Late stage described in quartzite by Inan and Einaudi (2002). Both Marco Einaudi and Patrick Redmond have noted that the deep, high-grade bornite/chalcocite mineralisation is devoid of pyrite and that chalcopyrite is not in contact with chalcocite (pers. comm.) again a contrast with the high level samples where chalcopyrite is intimately mixed with chalcocite.

Both Beeson and Butler refer to the monzonite as Dark Porphyry, suggesting a more porphyritic texture in the shallow ore body and also to silicification and sericitisation of the monzonite, which were apparently more strongly developed than in the deeper ore. Perhaps the porphyritic phases of the monzonite only locally noted in the present mine were more prevalent higher in the system.

In the shallow workings, the relationship of the porphyry trend to the overall zoning was unchanged, the trend held tightly to the north wall of the orebody. Geologic sections of Bingham confirm that the western part of the deposit narrowed upward to the original topography and the alteration and mineralisation in the western pit wall grade down to the high-grade mineralisation at the western extremity of the quartz monzonite porphyry. This is a type of mineralisation that could not have been anticipated from evidence at the surface; it is a blind body of mineralisation.

Vein silica decreased upward, bornite decreased, pyrite became more common as did sericite and perhaps clay, sulphide content of the ore increased, the deposit narrowed and the western high grade centre pinched out or nearly so.

Bingham, Why a Giant Porphyry Copper Deposit?

Human factors determine what we see as size; tonnage or volume is only one parameter. Grade is the primary limit of deposit size and is perhaps the outstanding feature in any ore deposit. Other determinants of size are the physical mineability of the material. There are five concentric alteration/mineralisation zones in the Bingham deposit, a typical porphyry system as described by Lowell and Guilbert (1970). In searching for reasons for the immense size of Bingham it is more important to look at the atypical features of the deposit:

i). the upward change of the core zone from weakly veined and mineralised to strongly fractured and mineralised,
ii). the porphyry trend of sheeted veins with high gold and copper grades associated with bornite and chalcocite,
iii). the indications that the ore body was narrowing near the pre-mine topography,
iv). the very early appearance of propylitic and potassic (?) alteration in monzonite followed by cyclic episodes of intrusion of porphyritic rocks, each followed by veining and metal introduction,
v). massive flows of magmatic fluids well beyond the stock as indicated by extensive Bingham Main stage alteration and mineralisation of the quartzite as well as,
vi). unusually large and high-grade bodies of skarn mineralisation; and
vii). significant introduction of copper during the post potassic Late stage of mineralisation.

Ballantyne *et al.,* (1996), observed that: the intrusions at Bingham are superimposed rather than spread out and consequently the phases of mineralisation are all within one pipeline, the Bingham stock; that the coincidence of geologic structure and erosion were such as to allow discovery with but limited destruction or disruption of the mineral deposit and that the limestone beds are present at locations favourable to the formation of copper rich skarns which were part of past production and contribute especially to the future resource.

Phillips and Kruhulek (2003) noted the early formation of the fracture dome/copper shell cut by a later dyke/fracture zone, the porphyry trend. We note here that there were multiple centres of mineralisation. Redmond, *et al.,* gives evidence for multiple episodes of veining and mineralisation after each of the porphyry intrusions. Innan and Einaudi (2002) document a Late stage of copper introduction that locally made a significant improvement to grade and/or an enlargement of reserves. Burnham (1979) and recently Maughan *et al.,* (2003), suggest high metal and water content of the parent magmas.

Most of these characteristics of the geologic environment may contribute to size and grade at Bingham. In addition, the ore controls discussed above, collectively added to the resource. The character of the mineralisation provided good metallurgical recovery and concentrate grades, and the structure plus rock quality have allowed reasonable pit slopes. Gold, molybdenite and silver have added to the economics of mining copper at Bingham, allowing flexible cutoff grades and sometimes providing a cushion against poor copper prices.

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remains one of the largest mines and ore bodies in the world and despite the attention of many well known geologists, we believe there is much yet to learn about its origins and the specific controls of grade and size.

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