Environmental geochemistry of the Bingham Canyon porphyry copper deposit, Utah

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Abstract At the Bingham Canyon porphyry copper deposit, sulfide mineralization progresses outward from a low-grade core through the following general zones: (1) molybdenite, (2) chalcopyrite–bornite, (3) chalcopyrite–pyrite, (4) pyrite, and (5) sphalerite–galena. The low-grade core and the molybdenite zone are composed of net neutralizing rock and will generally not acidify when exposed to surface weathering conditions. The copper-bearing zones of the orebody and the surrounding pyrite halo are net acid-generating and so will tend to acidify when exposed. Rocks in the lead–zinc halo are typically net neutralizing. In plan view, the distribution of net neutralization potential (NNP) is doughnut-shaped, with a positive (net neutralizing) 1,000-m-diameter core surrounded by a negative (net acid-generating) 3,000-m-diameter ring. Rock exposed in the lower 100 m of the current pit has a positive NNP and is overlain by 500 m of rock with a negative NNP.

Keywords Acid rock drainage · Bingham Canyon · Geochemistry · Porphyry copper · Utah

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Introduction

Porphyry copper deposits account for more than 40% of world copper production and more than a third of world copper reserves (Vanecek 1994). The mining of porphyry copper ore bodies typically exposes sulfide minerals to the surface weathering conditions, accelerating natural chemical weathering processes and potentially releasing acid, metals and sulfate to the environment. If sulfide-bearing rock acidifies, metal mobility and bioavailability are greatly increased. The proper management of acid-generating mine wastes is one of the largest environmental concerns associated with metals mining operations worldwide (Warhurst and Noronha 2000). It is estimated that in the United States alone more than 17,000 km of streams and rivers have been impacted by acid rock drainage (ARD) from abandoned mines (Skousen 1995). The Bingham Canyon porphyry copper orebody ranks as one of the world's largest metal deposits. The concept of large-scale open-pit mining was first implemented at Bingham Canyon in 1906, and net production from the orebody totals more than 15 million tonnes of copper. The Bingham Canyon open pit is currently more than 3 km in diameter and more than 900 m deep. The Bingham Canyon deposit has also been one of the most intensely studied ore bodies in the world. The geometry of the deposit is well exposed in three dimensions, and it exhibits the classic mineralization and alteration zoning expected for a porphyry copper deposit (Babcock and others 1995). Since the first scientific studies were produced almost a century ago (Boutwell 1905; Boutwell and others 1905), more than 50 papers have been written about Bingham Canyon geology. Most of these papers have focused on various aspects of alteration and sulfide mineralization, but none have examined the environmental geochemistry of the deposit. This study examines the environmental geochemistry of the Bingham Canyon porphyry copper deposit in terms of its acid/base accounting characteristics. The data presented in this study can be used to evaluate the geochemical behavior of similar porphyry copper deposits when they are exposed to accelerated surface weathering conditions by mining operations.

Acid/base accounting theory

Under typical surface weathering conditions, sulfide minerals such as pyrite (FeS_2), chalcopyrite ($CuFeS_2$), bornite (Cu_5FeS_4), and molybdenite (MoS_2) will oxidize to release sulfate, metals, and acidity. A generalized oxidation reaction for pyrite, the most common sulfide mineral is:

$$FeS_2 + 15/4O_2 + 7/2H_2O = Fe(OH)_3 + 2SO_4^{2-} + 4H^+$$

$$(1)$$
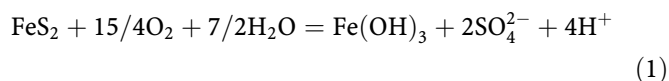
Sphalerite (ZnS) may sometimes act as an acid-generating mineral, but galena (PbS) and chalcocite (Cu_2S) will not produce acid under typical surface weathering conditions. Sulfate minerals, such as gypsum ($CaSO_4 2H_2O$) and barite

($BaSO_4$), will not produce acid under any conditions (Plumlee 1999; Jennings and others 2000; Kwong 2000). Acidity that is generated by sulfide oxidation in a rock may be stored in the rock as soluble salts, may contribute to ARD, or may be neutralized in-situ by acid-neutralizing minerals. Most carbonate minerals will react with acidic solutions to maintain a near neutral pH. A generalized neutralization reaction involving calcite ($CaCO_3$) is:

$$CaCO_3 + 2H^+ = Ca^{2+} + H_2CO_3 \qquad (2)$$

In theory, silicate minerals will also neutralize acidity and maintain a near neutral pH. However, in practice, most silicates provide much less neutralizing capacity than carbonates because of their slow reaction kinetics (Plumlee 1999). In most cases, silicate weathering will only provide a significant source of neutralization potential under strongly acidic conditions and in the very long term (Lawrence and Wang 1997; Stromberg and Banwart 1999; Jambor and others 2000).

Most rocks contain a combination of acid-generating sulfide minerals and of acid-neutralizing minerals. The modified Sobek acid/base accounting method uses static tests of sulfur content and acid-consumption to characterize the bulk acid-generating and acid-neutralizing characteristics of a sample (Sobek and others 1978; Lawrence 1990). The acid potential (AP) is calculated by multiplying the weight percent of sulfur associated with acid-generating minerals in the sample by 31.25. This conversion factor, based on the mass balance relationships expressed in Eqs. (1) and (2), expresses the AP in terms of kilograms of calcium carbonate required to neutralize the acid that would be generated by complete oxidation of all of the potentially acid-generating sulfides in 1,000 kg of rock. The neutralization potential (NP) is also expressed in terms of kg of calcium carbonate equivalent per 1,000 kg of rock, although other minerals in addition to calcite may contribute to the NP. The carbonate NP is calculated from a direct measure of the amount of carbonate in the rock. The net neutralization potential (NNP) of the sample is derived by subtracting the AP from the NP. The neutralization potential ratio (NPR) is derived by dividing the NP by the AP. A negative NNP or an NPR of less than one indicates that there is an excess of AP over NP in the rock, and that it will likely generate ARD. In theory, a rock with an excess of NP will not generate ARD. However, because of the uncertainties created by differential reaction kinetics, leaching rates and mineral distribution in the rock, a commonly used screening criteria assumes that rocks with NNP values above 0 and NPR values above 1 are possibly acid-generating unless the sulfide content is less than 0.3% (AP<10 kg/1,000 kg), or the NPR is greater than 2 (Price and others 1997).

Geology of the Bingham Canyon orebody

The Bingham Canyon porphyry copper deposit is centered on the Eocene Bingham Stock (James and others 1961;
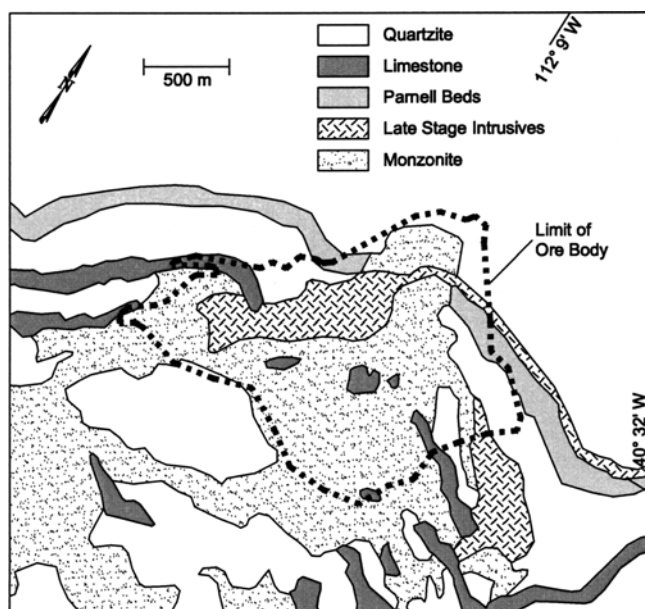
Fig. 1
Simplified geologic map of the Bingham Canyon porphyry copper deposit

Lanier and others 1978a). Economic mineralization is hosted in the stock and extends a short distance into the surrounding sedimentary rocks (Fig. 1). From youngest to oldest the stock is composed of monzonite, porphyritic quartz monzonite, quartz monzonite porphyry, latite porphyry, and quartz latite porphyry. The intrusive complex is primarily composed of monzonite with a much smaller volume provided by the other late stage porphyritic intrusive phases. The stock was intruded by magmatic stoping and replacement into the Pennsylvanian Oquirrh Group, a sedimentary sequence composed of quartzite with lesser amounts of interbedded limestone, calcareous sandstone, and siltstone. Two limestone beds that range between 36 and 70 m thick can be traced across the open pit. The Parnell beds, a 120-m-thick sequence of interbedded limestone, calcareous sandstone, and quartzite, are also continuous across the open pit.

Sulfide mineral zones are concentrically arranged around the center of the orebody. Mineral zoning patterns have been described by numerous previous workers including James and others (1961), Rose (1970), John (1978), and Phillips and others (1997). The innermost zone of the deposit, exposed in the bottom of the pit, consists of a low-grade core with generally less than 0.5% total sulfides. It contains low concentrations of molybdenite, pyrite, chalcopyrite, and bornite. Surrounding the low-grade core is a zone of molybdenite mineralization followed by the ring-shaped copper zone of the orebody. The inner portion of the copper zone is dominated by bornite and chalcopyrite mineralization with lesser molybdenite and pyrite. The outer edge of the copper zone is dominated by pyrite and chalcopyrite. The entire orebody is approximately 1,800 m in diameter and currently averages about 0.6% copper. A pyrite halo surrounds the copper zone of the orebody. This

zone may contain over 5% pyrite on the immediate margins of the orebody, but pyrite concentrations decrease outward to 1–2% at 600–900 m from the orebody contact. Locally, skarn deposits in the limestone beds may contain as much as 90% sulfides. Sulfide mineralization changes from both disseminated and fracture-controlled within and on the margins of the orebody to almost exclusively fracture-controlled on the outer margins of the pyrite halo. A broad lead–zinc zone with load galena and sphalerite deposits surrounds the pyrite halo between about 1,500 and 2,700 m from the center of the orebody.

The low-grade core and the zones of molybdenite and copper mineralization typically coincide with the zone of potassic hydrothermal alteration. The pyrite halo generally coincides with phyllic and propylitic alteration zones. Limestone and calcareous sandstone beds become progressively more altered nearer the orebody and the center of the Bingham Stock. From the uppermost exposures in the open pit to the bottom of the pit the following mineralogical zones are present in limestone beds (Reid 1978): (1) unaltered rock, (2) marble, (3) wollastonite, (4) cristobalite, (5) garnet–clay, (6) garnet–quartz, and (7) amphibole–epidote. Garnet composition is believed to be an intermediate member of the grossularite–andradite series. These zones generally reflect a gradual decrease in the percentage of calcium carbonate in the limestone and calcareous sandstone beds, and an increase in calcium-silicate minerals. Reid (1978) noted that the soluble fraction of the limestone decreases from 44% in the marble zone to only 5% in the amphibole–epidote zone.

The oxidized cap of the orebody has been completely removed by mining, and the remaining orebody is unoxidized. However, a deep weathering profile exists in bedrock exposed immediately beneath the pre-mining topographic surface on the outer margins of the open pit. This zone contains few intact sulfides and extends several tens of meters beneath the old topographic surface.

Methods

A total of 88 bedrock samples were collected from recently exposed surfaces in the pit during a preliminary acid/base accounting study. Sample sites were selected to provide a uniform geographic distribution in the pit while insuring that all lithologies were adequately characterized. Samples were composited from 20 to 30 randomly selected locations across several hundred feet of exposure. The Kennecott Utah Copper Environmental Laboratory analyzed all samples by a modified Sobek acid/base accounting technique. Each sample was crushed and homogenized before being ground to minus 200 mesh. The following analyses were then performed: (1) total sulfur, (2) sulfur remaining in the sample after an HCl leach, (3) NP as defined by the amount of 0.10 or 0.50 N HCl consumed by 1 g of the sample, and (4) total metals. It is assumed that almost all sulfate minerals except barite are removed from the sample by an HCl leach. The samples contain very little barium, so almost all the sulfur remaining after the HCl leach is likely in sulfide form. The sulfide sulfur that contributes to AP was calculated by subtracting the sulfur associated with galena and sphalerite from the sulfide sulfur value. Samples were also analyzed for total carbon and carbon remaining after an HCl leach. The carbon removed from the sample by the HCl leach is assumed to be associated with calcite.

In addition to the 88 outcrop samples, there are about 80,000 boring samples collected near the current pit surface that have been analyzed for total sulfur and about 500 that have been analyzed for total carbon. All of the sulfur and carbon analyses were performed with a Leco furnace.

Results and discussion

The analytical results from the 88 outcrop samples indicate that, on average, about 9% of the total sulfur in the rock samples was in the form of non-acid-generating sulfate and sulfide minerals, and about 13% of the total carbon is in a form that was not leachable by HCl. Based upon these results, it was determined that the AP distribution within the open pit can be conservatively mapped using existing total sulfur data available from the borings. AP distribution was mapped by averaging all of the sulfur values in a series of 30×30 m squares on the pit surface and then contouring the averaged values. The following description of NP distribution is based predominantly on the 88 samples collected as part of the preliminary study. However, the total carbon data provided by the 500 boring samples was used to support the outcrop sampling results. The descriptions of NNP and NPR distribution are based upon the total sulfur and Sobek NP data.

Distribution of acid potential

Pyrite and to a lesser extent chalcopyrite, bornite, and molybdenite are the primary minerals contributing to AP in the Bingham Canyon deposit. In plan view, the distribution of AP in the pit is doughnut-shaped with a low AP core surrounded by a 3,000-m-diameter ring with elevated AP (Fig. 2). In vertical profile, the low AP core is exposed in the bottom of the pit and is overlain by 500 m of rock with elevated AP (Fig. 3). The low-grade core of the orebody contains very few sulfide minerals and has AP values as low as 3 kg/1,000 kg. Much of the AP in the low-grade core and the molybdenite zone of the orebody is provided by molybdenite. Although molybdenite can generate acidity under surface weathering conditions, in practice it is one of the most resistant sulfides to oxidation and so is likely to be a minor contributor to acid production (Plumlee 1999). The exposed center of the low grade core, with AP values of less than 10 kg/1,000 kg, is currently 150–300 m wide and 1,200 m long. The inner portion of the copper zone of the orebody contains abundant chalcopyrite and bornite, with very little pyrite, and generally has AP values of between 10 and 30 kg/1,000 kg. Pyrite content increases on the outer margins of the copper orebody, and AP values range from about 30 to more than 80 kg/1,000 kg. Within the orebody, chalcopyrite, bornite,
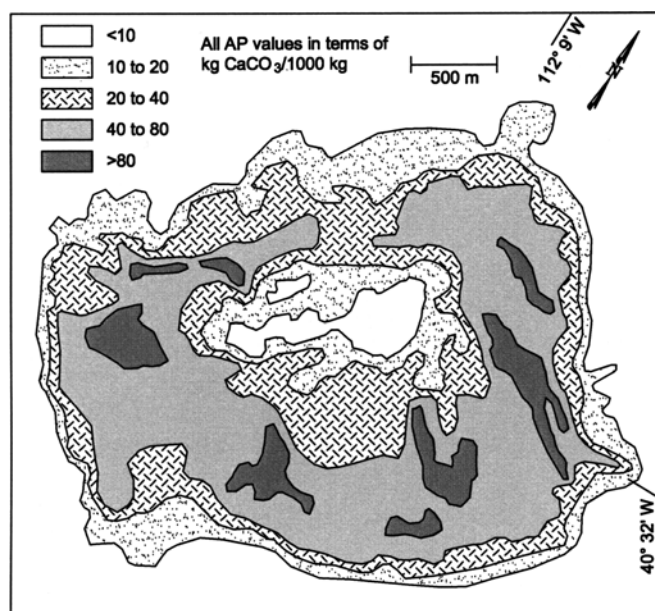
Fig. 2
Plan view distribution of AP in the Bingham Canyon porphyry copper deposit. AP was calculated from total sulfur data
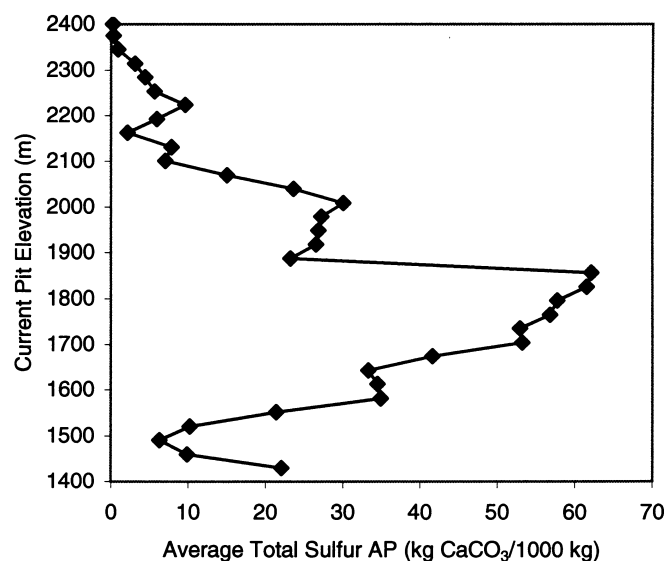

Fig. 3
Average AP versus elevation in the Bingham Canyon open pit. Total sulfur AP is averaged in approximate 30-m vertical increments. Ore grade mineralization extends from the pit bottom to approximately 1,700 m elevation

and molybdenite typically do not contribute more than 20 kg/1,000 kg towards the total AP.

Rocks with the highest AP occur in the pyrite halo immediately surrounding the orebody. In plan view, this zone is about 900 to 1,200 m from the center of the low-grade core. In vertical profile it is about 300 m above the low-grade core on the current pit walls. Locally, maximum AP values within the pyrite halo may reach about 250 kg/ 1,000 kg. In general, any AP in excess of about 5 kg/ 1,000 kg within the pyrite halo is provided by pyrite. AP values decrease dramatically on the outer margins of the pyrite halo. Most of the rock exposed in the lead–zinc zone on the uppermost benches of the pit has AP values of less than 10 kg/1,000 kg, and AP values of 0 kg/1,000 kg are common near the pre-mining topographic surface. This results from both a decrease in the original pyrite mineralization more than 1,500 m from the low-grade core of the orebody, and because much of the pyrite that was originally present has been oxidized by long-term weathering immediately beneath the pre-mining surface.

Distribution of neutralization potential

The distribution of NP on the current pit walls is closely related to the lithologic distribution with significant overprinting by contact metamorphic alteration. As shown in Table 1 and Fig. 4, rocks that contain abundant calcium carbonate, such as limestones and the Parnell beds, have the highest NP values followed by igneous rocks and lastly by quartzites.

About 90% of the NP in sedimentary rocks is provided by calcium carbonate. The remaining NP is probably provided by relatively fast weathering calcium-silicate minerals such as wollastonite, calcium-rich garnet, and diopside, which are related to skarn alternation in the calcareous portions of the sedimentary sequence (Reid 1978; Plumlee 1999). The average NP contributed by non-carbonate minerals is 19 kg/1,000 kg in limestone, 7 kg/ 1,000 kg in the Parnell beds, and 2 kg/1,000 kg in quartzites. For each sedimentary rock type, NP generally decreases towards the Bingham Stock as calcium carbonate is replaced by less reactive calcium-silicate minerals. Sulfide mineralization in the sedimentary sequence increases towards the stock resulting in an inverse relationship between NP and AP in the limestone and Parnell beds (Fig. 4). Samples from the limestone beds have NP values that range from 517 kg/1,000 kg in relatively unaltered limestone high on the pit walls to 19 kg/1,000 kg in intensely altered limestone skarn near the contact with the Bingham Stock. Similarly, NP values in the Parnell beds vary between 177 kg/1,000 kg and 14 kg/1,000 kg

Table 1
Neutralization potential data for Bingham Canyon lithologies. All NP values are reported in kg $CaCO_3$/1,000 kg

Lithology	Average Sobek NP[a]	Average carbonate NP[a]	Sobek NP range	Carbonate NP range
Limestone	178±85	159±68	19–517	14–363
Parnell beds	60±30	53±31	14–177	0–173
Quartzites	10±4	8±4	0–70	0–68
Igneous rocks	23±4	10±4	6–76	0–66

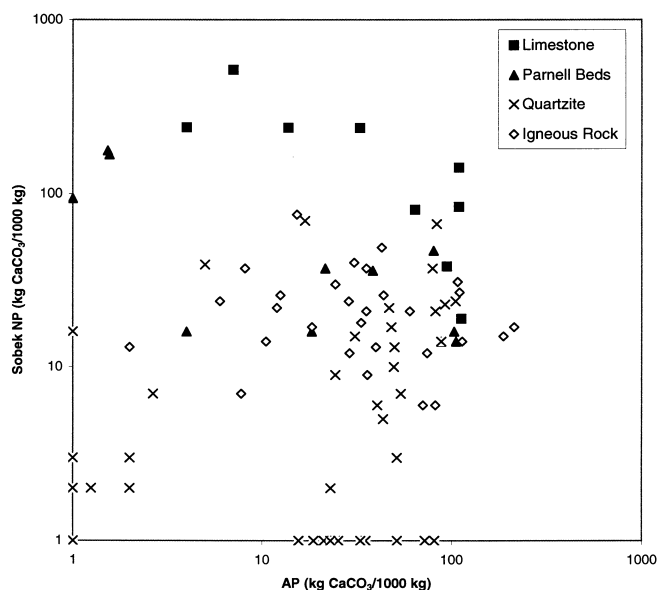[a]Includes the 90% confidence interval based on the t-statistic for each mean

Fig. 4
AP versus Sobek NP for various rock types associated with the Bingham Canyon porphyry copper deposit. Quartzites include some relatively minor calcareous sandstone and limestone interbeds

Fig. 5
Plan view distribution of NNP in the Bingham Canyon porphyry copper deposit. NNP is based upon total sulfur AP and Sobek NP

depending on the proximity of an igneous contact. The sedimentary sequence to the northeast of the orebody has much less NP than in any other area. There are no significant limestone beds, and NP values in the quartzite samples from the northeast only average 3 kg/1,000 kg versus an average of 15 kg/1,000 kg for quartzite samples from other areas.

For igneous rocks, calcium carbonate typically provides less than 50% of the total NP. Where present, the carbonate is generally contained within fractures and thin veins. The remaining NP is probably provided by silicate minerals such as plagioclase, biotite, phlogopite, chlorite, actinolite, and augite. On average, these six minerals comprise about 55% of the monzonite, while relatively unreactive orthoclase and quartz comprise an additional 40% (Lanier and others 1978b). The average NP contributed by non-carbonate minerals in the igneous rocks is 13 kg/1,000 kg. This value is broadly consistent with NP values measured for a large suite of aluminosilicate minerals by Jambor and others (2000). On average, the early monzonite and quartz monzonite phases of the intrusion contain more carbonate than the late stage latite porphyry and quartz latite porphyry phases. Within the monzonite and quartz monzonite phases, carbonate contents are generally highest adjacent to limestone beds. NP values are very low in the northeast portion of the stock, adjacent to the low NP portions of the surrounding sedimentary sequence. The correlation coefficient between carbonate content in the monzonite and quartz monzonite, and the distance to the closest limestone contact is –0.3. Carbonate may have been assimilated into the stock from the surrounding sedimentary rocks during emplacement or mineralization. As noted by Reid (1978), the altered limestones adjacent to the Bingham Stock are strongly depleted in CaO and CO_2.
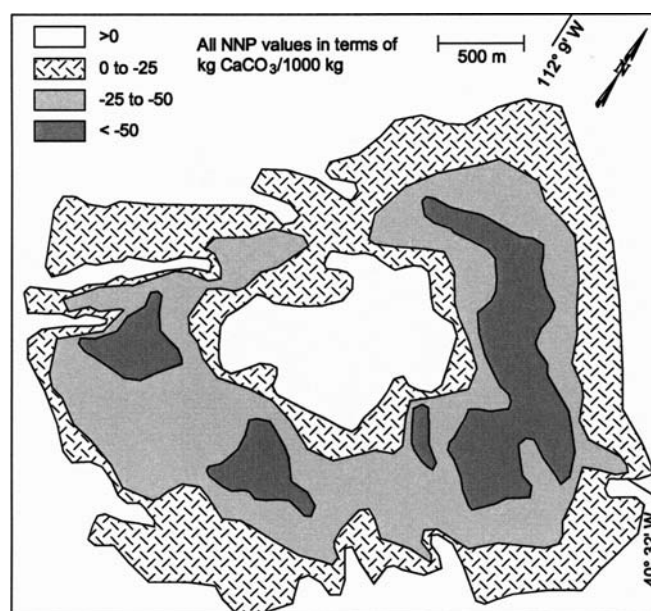
Distribution of net neutralization potential

The distribution of NNP in the Bingham Canyon deposit is doughnut shaped, with a positive 1,000-m-diameter core surrounded by a negative 3,000-m-diameter ring (Fig. 5). Rock exposed in the lower 100 m of the pit is generally net neutralizing, and is overlain by about 500 m of net acid-generating rock (Fig. 6).

NNP values in the low-grade core of the orebody are positive, and the zero NNP contour generally conforms to the outer limit of molybdenum mineralization in the orebody. The center of the low-grade core, where total sulfur is less than 0.3%, typically has NNP values above 10 kg/1,000 kg and NPR values above 2. The highest NNP value sampled in the low-grade core was 28 kg/1,000 kg (NPR =4.6). These values may underestimate the effective NNP of the low-grade core because much of the AP is provided by relatively inert molybdenite. The outer limit of the orebody is generally defined by the –25 or the –50 kg/1,000 kg NNP contour line. Within the pyrite halo, NNP values below –75 kg/1,000 kg and NPR values below 0.1 are locally common about 1,100 m from the center of the low-grade core. Net neutralizing rocks are exposed on the margins of the pyrite halo and in the lead–zinc zone around the top of the pit. As shown in Fig. 5, the 0 kg/1,000 kg contour completely encircles the orebody about 1,500 m from the low-grade core.

Conclusions and implications

The well-developed mineralization and alteration zoning that has been noted by many previous studies at Bingham Canyon is mimicked by the acid/base accounting
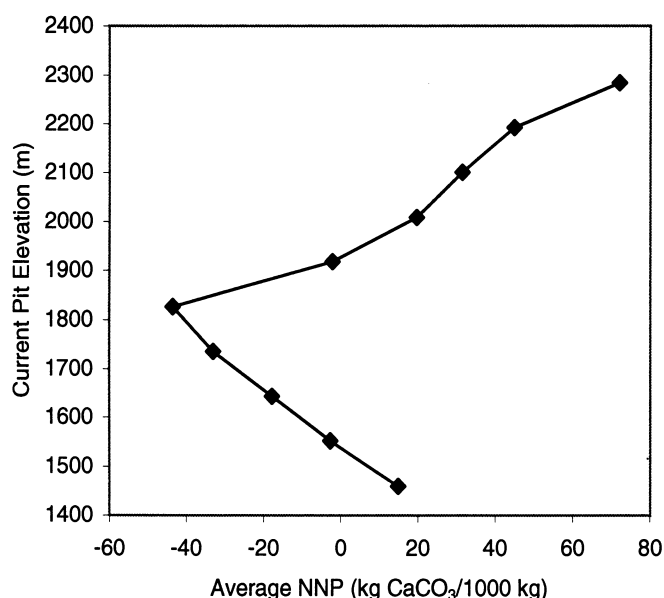
Fig. 6
Average NNP versus elevation in the Bingham Canyon open pit. NNP is based upon total sulfur AP and Sobek NP averaged in approximate 90-m vertical increments. Ore grade mineralization extends from the pit bottom to approximately 1,700-m elevation

characteristics of the deposit. The low-grade core and the molybdenite zone of the orebody, exposed in the bottom of the pit, are generally net neutralizing and rock here is unlikely to generate ARD when exposed to surface weathering conditions. Water currently being pumped from the bottom of the pit, in contact with these net neutralizing rocks, has a near neutral pH and an alkalinity in excess of 50 mg/l as $CaCO_3$. The main copper zone of the orebody and the surrounding pyrite halo are generally net acid-generating and the rock will tend to acidify when exposed. Waste rock mined from the pyrite halo generally acidifies within a decade of exposure to surface weathering conditions, and soils forming on some pyrite-bearing waste rock surfaces attain paste pH values as low as 2.1 (Borden 2001). Rock exposed near the pre-mining topographic surface and in the lead–zinc halo, approximately 1,500 m from the center of the orebody, contains few intact acid-generating sulfides and so poses little risk of acidification. Water that drains from underground workings in the lead–zinc halo surrounding the open pit generally has a neutral pH and an alkalinity in excess of 200 mg/l as $CaCO_3$. Waste rock generated from the upper-pit benches will typically maintain a near-neutral pH, even after several decades of weathering (Borden 2001). The alteration and metals zoning observed at Bingham Canyon has been noted at other porphyry copper deposits, so these general acid/base accounting relationships are probably repeated at many other ore bodies. The Bingham Canyon acid/base accounting data can also be used to semi-quantitatively compare this deposit's potential to generate ARD with other porphyry copper deposits. For example, samples collected from the Berkeley Pit in Butte, Montana have much higher AP values and much lower NP

values than are typical for the Bingham Canyon deposit (Newbrough and Gammons 2002). The average NNP values reported for the Berkeley pit by Newbrough and Gammons (2002) are at least four times more negative than the average NNP data derived from the Bingham pit. These data indicate that, although significant portions of the Bingham Pit may generate ARD, the current pit as a whole is unlikely to produce the extremely low pH and high sulfate water that has accumulated in the Berkeley Pit since its closure.

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