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LETTER

Kéiko H. Hattori · Jeffrey D. Keith

Contribution of mafic melt to porphyry copper mineralization: evidence from Mount Pinatubo, Philippines, and Bingham Canyon, Utah, USA

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Abstract Mount Pinatubo in the Philippines, known for its cataclysmic eruption in 1991, hosts several porphyry copper deposits and active geothermal systems. An underlying mafic melt supplied much of the sulphur for the dacitic magma and its injection into the dacitic magma chamber triggered the eruption. The eruption caused purging of the sulphur-rich fluid from the dacite to the atmosphere and extensive fracturing. Similar events took place at Bingham Canyon, Utah, site of the largest copper and gold deposit in North America at 38 Ma. The Bingham Canyon mineralization took place beneath an active stratovolcano and pyroclastic flows contemporaneous with the mineralization show evidence for magma mingling. Ascent of mafic melt supplied sulphur and chalcophile elements to the felsic magma, which consolidated to form the Bingham stock and its underlying magma chamber. Injections of the mafic melt caused periodic eruptions of felsic magma to form the stratovolcano and deposition of sulphide minerals in highly fractured rocks in and around the stock.

Introduction

Porphyry deposits produce more than one half of the world's copper (e.g. Kirkham and Sinclair 1995) and they are described in several comprehensive reviews (e.g. Sillitoe 1973; Hunt 1991; Kirkham and Sinclair 1995). Deposits occur in close association with calc-alkaline and alkaline felsic intrusions emplaced at shallow depths. Magmas supplied the heat for the ore-forming hydrothermal systems. The source of metals and sulphur is still debated, with the most widely held options being the felsic magmas themselves (Burnham 1979), or surrounding country rocks unrelated to magmatism (Sheppard and Taylor 1974; Ohmoto and Goldhaber 1997). Deposits contain large quantities of sulphur as copper-sulphide minerals and significant anhydrite, and much larger quantities as pyrite in alteration halos; the deposits are first and foremost huge sulphur anomalies (Hunt 1991). But, felsic melts have a low solubility for sulphur (Wallace and Carmichael 1992) and generally low contents of copper and other metals. Enclosing country rocks cover the gamut of metamorphic, sedimentary and igneous rocks and it is difficult to imagine such variable country rocks being the source of such a constant assemblage of sulphide minerals with relatively uniform sulphur isotope values of ~ 0‰ for large deposits.

Mount Pinatubo is famous for the cataclysmic eruption of June 1991, but less known are the active geothermal systems and porphyry copper systems, including that at the Dizon deposit on the flank of the volcano. Close monitoring of the 1991 eruption and studies of the eruption products revealed the important role of mafic melt in the eruption, particularly in supplying sulphur to the felsic magma and hydrothermal fluid (Pallister et al. 1992; Hattori 1993; Gerlach et al. 1996). Discharge of SO_2 from mafic melt was accompanied by the transfer of chalcophile elements, including copper and selenium (Hattori 1993, 1996). We suggest that a similar process took place at ~38 Ma at Bingham Canyon, forming the largest copper and gold deposit in North America.

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K.H. Hattori (✉)
Department of Earth Sciences, University of Ottawa,
Ottawa, K1N 6N5, Canada
E-mail: khattori@uottawa.ca

J.D. Keith
Department of Geology, Brigham Young University,
Provo, Utah, 84602, USA

Geological settings and the evidence for mafic melt

Pinatubo

Mount Pinatubo is located in the Bataan arc in western Luzon Island, Philippines (Fig. 1a). This arc contains several young porphyry copper–gold deposits of significant size, such as the Lepanto Far Southeast and Santo Tomas II mines (Fig. 1a). Mount Pinatubo itself hosts several porphyry copper–gold deposits (Fig. 1a; Sillitoe and Gappe 1984; Malihan 1987). The Dizon deposit, 14 km from the present summit, was mined until 1999, with reserves of 187 Mt at 0.36% Cu and 0.75 g/t Au (Kirkham and Sinclair 1995). The Pisumpan and Pinpin deposits each has reserves of 20 Mt at 0.4% Cu and ~1 g/t Au (Sillitoe and Gappe 1984; Malihan 1987). The Dizon deposit is hosted by andesitic to dacitic volcanic rocks and quartz diorite porphyry of Pliocene age, whereas the Pinpin and Pisumpan deposits occur in Quaternary dacitic eruption products, ~6 km from the summit (Malihan 1987; Fig. 1a). Geothermal drilling to 2,700 m depth prior to the 1991 eruption intersected intensely altered rocks containing anhydrite and sulphide minerals, including chalcopyrite, associated with active geothermal systems at temperatures up to 336 °C (Pagado and Aniceto-Villarosa 1989; Delfine et al. 1996).

The Mount Pinatubo volcano consists of dacitic pyroclastic flows and lahars. The June 1991 eruption discharged >5 km^3 of pyroclastic material over a 15-km radius. Although this ranked as one of the world's most voluminous 20th century eruptions, it was one of the smallest in Pinatubo's history (Pallister et al. 1996). The 1991 eruption followed extrusion of a small andesite dome and scoria, which formed by mixing of basaltic and dacitic melt several weeks before the eruption (Pallister et al. 1992, 1996; Hattori and Sato 1996). Pre-eruption ascent of mafic melt was further evidenced by increased SO_2 discharge and deep seismic activity in the mantle. Prolonged, long-frequency earthquakes originating from >35 km depth within the mantle were caused by the ascent of mafic magmas and associated fluid discharge (Harlow et al. 1996; White 1996). Similar composition and textures in the older eruption products, including evidence of mafic melt, suggest that the volcano formed by repeated events similar to the 1991 eruption (Pallister et al. 1996).

Bingham Canyon

The Bingham Canyon porphyry deposit has production plus reserves of >22 Mt Cu and $>1,250$ t Au, ranking it as both the largest copper and largest gold deposit in North America (Kirkham and Sinclair 1995; Ballantyne et al. 1997). Ore occurs primarily in 39.2–37.7 Ma quartz monzonitic intrusive rocks, which are contemporaneous with pyroclastic rocks and lavas on the flank of the Oquirrh Mountains, about 10 km from the Bingham mine (Deino and Keith 1997; Waite et al. 1997). The volcanic products show wide compositional variation, from primitive melanephelinite

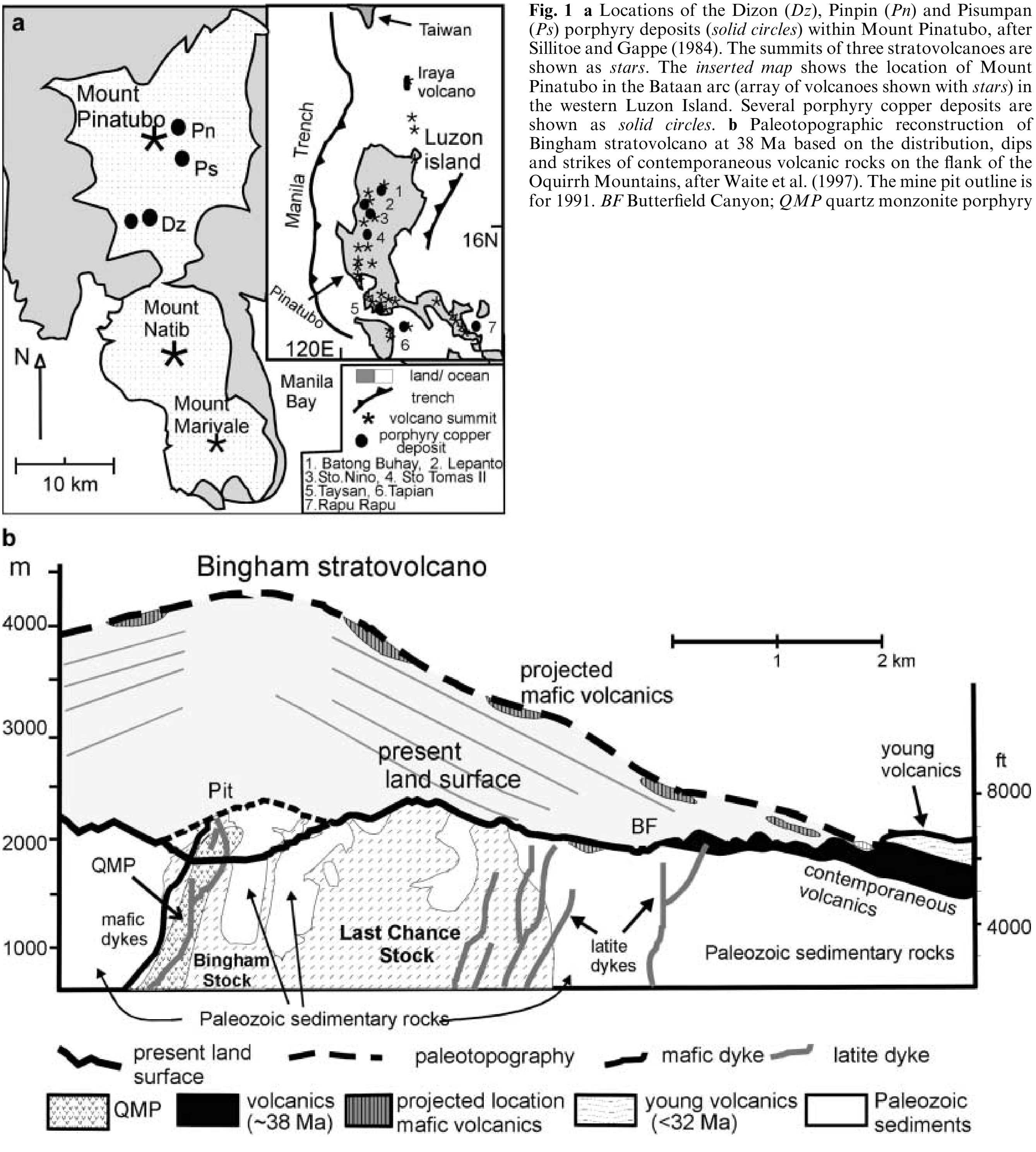

Fig. 1 **a** Locations of the Dizon (*Dz*), Pinpin (*Pn*) and Pisumpan (*Ps*) porphyry deposits (*solid circles*) within Mount Pinatubo, after Sillitoe and Gappe (1984). The summits of three stratovolcanoes are shown as *stars*. The *inserted map* shows the location of Mount Pinatubo in the Bataan arc (array of volcanoes shown with *stars*) in the western Luzon Island. Several porphyry copper deposits are shown as *solid circles*. **b** Paleotopographic reconstruction of Bingham stratovolcano at 38 Ma based on the distribution, dips and strikes of contemporaneous volcanic rocks on the flank of the Oquirrh Mountains, after Waite et al. (1997). The mine pit outline is for 1991. *BF* Butterfield Canyon; *QMP* quartz monzonite porphyry

(~45 wt% SiO_2) to dacite/trachyte (66 wt% SiO_2), which volumetrically is the most important in the volcanic sequence. These volcanic rocks are interpreted as part of a stratovolcano, with its summit approximately over the Bingham Canyon deposit (Fig. 1b; Waite et al. 1997).

Intrusive rocks at Bingham Canyon are predominantly felsic, but there are primitive high-magnesium minette dykes with identical ages to the mineralization and felsic igneous rocks (Fig. 1b; Deino and Keith 1997). Both mafic and felsic magmas coexisted during the mineralization because of common mingling textures in the volcanic rocks of the Oquirrh Mountains (Waite et al. 1997). Furthermore, juvenile mafic rocks occur as quenched fragments in intermediate and felsic volcanic rocks that are contemporaneous with the mineralization (Waite et al. 1997). This coexistence of felsic and mafic magmas is further supported by partially destabilized plagioclase and corroded olivine in felsic rocks (Keith et al. 1998), which are indicative of injection of hot, mafic melt into a cool felsic magma. Unusually high chromium, up to 180 ppm, in felsic rocks (60–66 wt% SiO_2) further suggests input from mafic melt (Waite et al. 1997).

Transfer of sulphur and metals from mafic melt to a shallow felsic magma chamber

Pinatubo

Felsic magmas have low sulphur solubility because the solubility decreases with lesser amounts of iron in silicate melt (Fig. 2). The sulphur content of the felsic melt at Pinatubo was low ($<$ 90 ppm; Gerlach et al. 1996; Fig. 2). Yet, the bulk dacite contains high sulphur, up to 2,000 ppm, as anhydrite (Pallister et al. 1992, 1996), which suggests that the dacitic magma acquired sulphur from an external source. The occurrence of anhydrite and destabilized sulphide minerals in the groundmass glass suggests oxidation of the magma. Therefore, the crystallization of anhydrite in dacitic magma required oxidation of the magma and addition of sulphur, most likely from underlying mafic magmas (Hattori 1993, 1996; Pallister et al. 1996; Kress 1997). The SO_2 released from underlying hot mafic melt was converted into H_2S in a hydrated, semi-solidified, felsic magma, forming a magmatic sulphide phase with elevated concentrations of hydrophile and chalcophile elements such as selenium, copper and arsenic (Hattori 1993, 1996). These magmatic sulphide phases with high copper commonly show irregular shape in the groundmass glass, suggesting their late formation within the already semi-solidified magma chamber. The conversion of SO_2 to H_2S in the felsic magma caused oxidation of the magma. Continued addition of SO_2 resulted in further oxidation of the felsic magma, causing partial resorption of sulphide minerals and crystallization of anhydrite (Hattori 1993, 1996).

The felsic magma was H_2O-saturated (~6 wt% H_2O) and contained an immiscible aqueous fluid, as evidenced by the ubiquitous presence of aqueous fluid inclusions in plagioclase phenocrysts and aqueous vapour phase in melt inclusions (Wallace and Gerlach 1994; Gerlach et al. 1996). This fluid contained high sulphur that originated from the mafic melt (Wallace and Gerlach 1994; Gerlach et al. 1996). Periodic ascent of mafic melt, some even from mantle depths (White 1996), brought SO_2 to shallow crustal depths, which disproportionated to SO_4^{2-} and H_2S where it encountered water, leading to the formation of sulphate and sulphide minerals (e.g. Giggenbach 1997). High sulphur contents are also observed in the geothermal fluids at Mount Pinatubo, as geothermal wells discharged sulphur, up to 3,100 ppm SO_4^{2-} (Pagado and Aniceto-Villarosa 1989; Delfin et al. 1996). These high-sulphur fluids were purged during the eruption, releasing 17 Mt of SO_2 into the stratosphere (Gerlach et al. 1996), which also caused extensive rock fracturing and even fragmentation of crystals in the magma chamber (Pallister et al. 1996).

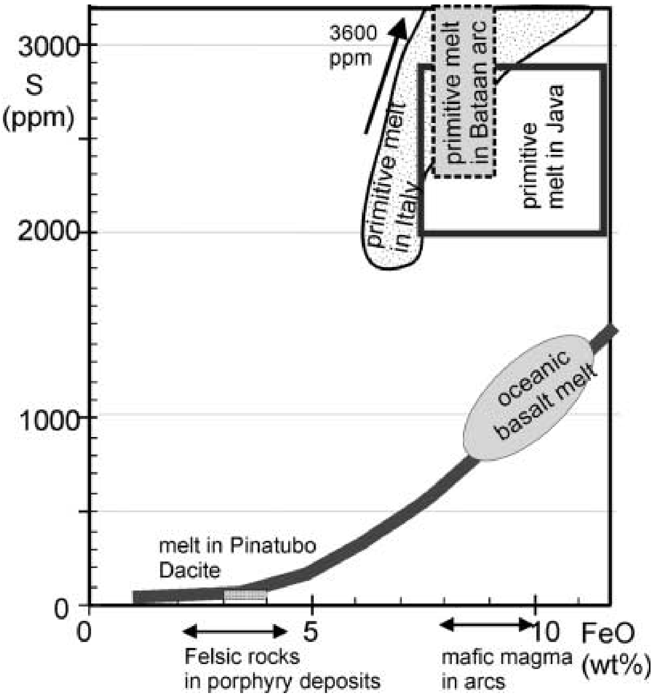

Fig. 2 Sulphur contents of mafic and felsic magmas. Data sources: melt inclusions and groundmass glass of dacitic eruption product at Mount Pinatubo (Wallace and Gerlach 1994; Gerlach et al. 1996); primitive basalt melt at Mount Iraya, north of Pinatubo in Bataan arc (location shown in Fig. 1a; Métrich et al. 1999), primitive melt at Galunggung volcano, western Java (DeHoog et al. 2001), mafic alkaline magmas in Italy (Métrich et al. 1993, 1999; Marianelli et al. 1995; Métrich and Clocchiatti 1996), and oceanic basalts (Wallace and Carmichael 1992). The *thick curve* shows the compiled solubility of sulphur in silicate melt (Wallace and Carmichael 1992; Nilsson and Peach 1993)

Bingham Canyon

Mafic melt contained a high concentration of sulphur, as demonstrated by high sulphide mineral content (~0.2 modal %) in a quenched latite dyke that exhibits clear petrographic evidence of magma mixing. Felsic volcanic rocks were also saturated with sulphur as evidenced by the occurrence of immiscible sulphide blebs, but they contain a low abundance of sulphide (~15 ppm S) because of low solubility of sulphur in felsic magmas and later resorption of magmatic sulphide phase. The sulphide mineral grains that are present in the felsic volcanic rocks are copper-rich with unusually high contents of zinc, arsenic, silver and lead (Keith et al. 1997). Some grains in the groundmass glass are angular and partially resorbed, similar to the textures and compositions of sulphide minerals in the dacitic eruption products from Mount Pinatubo (Hattori 1993, 1996).

The occurrence of sulphide minerals in the groundmass glass in the felsic volcanic rocks indicates late saturation of sulphur in the parental magmas, as well as showing that the felsic magmas did not supply excess sulphur to the ore-forming hydrothermal system. Another notable feature of the quenched glassy latite dykes is the ubiquitous presence of fluid inclusions in a variety of phenocrysts including hornblende (Keith et al. 1998; this study). The semi-solidified felsic magma was apparently saturated with fluids and sulphide minerals, similar to the eruption products at Mount Pinatubo (Gerlach et al. 1996; Hattori 1996).

Sources of metals and sulphur in porphyry copper deposits

Two most frequently proposed sources of copper in porphyry copper deposits and sulphur are felsic magmas, or country rocks that are unrelated to magmatism. The latter possibility was suggested based on meteoric water signatures of hydrogen and oxygen isotopes (e.g. Sheppard and Taylor 1974). The former possibility is based on the intimate association of ore with the felsic intrusions. Copper would be enriched in aqueous fluid when it separates from felsic silicate melt (Candela and Holland 1984; Williams et al. 1995). This magmatic origin was popular for a long time and was supported by δ^{34}S values close to 0‰ for sulphide minerals from many porphyry copper deposits (Field and Gustafson 1976; Eastoe 1983). This source is, however, challenged. Felsic intrusions in porphyry deposits are small, 0.5 to 2 km in diameter, requiring much larger, felsic magma reservoirs at depth. Such parent chambers, at least 50 km^3 in size, would be sufficient to supply copper and other metals to porphyry deposits (Dilles and Proffett 1995), but they could not supply the sulphur in the deposits.

The total sulphur contained in the Bingham Canyon deposit would require at least 4,800 km^3 of felsic melt assuming that felsic melt discharges 80 ppm S (Table 1). This is the minimum estimate considering 80 ppm is high for the solubility of sulphur in high SiO_2 melt (Fig. 2). The unreasonably huge volume rejects this possibility that felsic melt supplied significant amounts of sulphur. Furthermore, the occurrence of late-stage magmatic sulphide minerals in felsic magmas at Bingham, as described above, confirms an addition of sulphur to felsic magmas. Felsic magmas are not the sole source of sulphur for the ore. Banks (1982) also reached the same conclusion based on a detailed study of magmatic sulphide minerals in felsic igneous rocks related to the Ray porphyry copper deposit, Arizona, USA. In both cases, felsic magma gained sulphur from an external source (Banks 1982; Keith et al. 1998), just like dacitic magma at Mount Pinatubo (Hattori 1993, 1996). The evidence combined with the low solubility of sulphur in felsic magmas prompted the idea of derivation of sulphur and other constituents from country rocks unrelated to magmatism (Banks 1982; Ohmoto and Goldhaber 1997).

We suggest that much of the sulphur, together with a significant proportion of the metals, is derived from mafic melt underlying the felsic magma. Mafic melt contains high concentrations of copper and sulphur; thus, only a relatively small amount of mafic melt is necessary to account for the sulphur and metal budgets of huge porphyry deposits (Table 1). In addition, our proposal is supported by several lines of evidence, including (1) fracturing of ore and rocks, (2) the generally oxidized nature of these felsic intrusions, (3) the mantle-like sulphur isotope signatures of sulphide minerals (Fig. 3), and (4) the commonly high concentration of Pt and Pd in the porphyry copper-gold ore.

Stockwork mineralization

Abundant fractures characterize porphyry copper deposits (Kirkham 1971; Sillitoe 1973). The fracturing has been explained by release of aqueous fluids from solidifying felsic magma and second boiling of the aqueous fluid (e.g. Burnham 1979). If most of the sulphur, together with significant amounts of CO_2 and water, are derived from the mafic magma, the cause of stockwork fracturing may not be second boiling of fluids from felsic magma. Injection of mafic melt into felsic magmas should result in sudden release of volatiles from the mafic melt, causing an overpressure of fluids in the viscous felsic magma (Sparks et al. 1977). The timing of fracturing may be closely linked to the arrival of mafic magma at the base of the chamber and volatile release from such quenched magma. After the combined volatiles reach the magma cupolas, release of such trapped fluid will cause extensive fracturing of solidified rocks and even crystals in semi-solidified magma, as documented in the eruption products at Mount Pinatubo (Pallister et al. 1996).

Oxidized nature of host rocks

Felsic intrusions associated with porphyry copper deposits are mostly oxidized as opposed to many other felsic intrusions (e.g. Burnham 1979; Ishihara 1981). SO_2 is the predominate gas under dry and hot conditions, whereas H_2S at low temperatures under high H_2O pressures. Therefore, incorporation of SO_2 from hot mafic melt could oxidize cool, hydrated felsic magmas, $SO_2 + H_2O = H_2S + O_2$, as demonstrated at Pinatubo (Hattori 1993).

Mantle-like sulphur isotope signature

Considering the diversity of the country rocks, including graphitic shales and evaporite (Kirkham and Sinclair 1995), it is remarkable that sulphide minerals from many deposits show such similar isotopic values (Fig. 3). Importantly, large deposits show a narrow range of mantle-like values (Fig. 3). Sulphide minerals from lead–zinc veins in limestone adjacent to the Bingham Canyon deposit have values similar to the porphyry deposit, δ^{34}S = 0‰ (Field and Moore 1971). The host Mississippian limestone sequence contains abundant evaporitic sulphate with δ^{34}S > +15‰ (Fig. 3), the mantle-like δ^{34}S values for all sulphides suggest a supply of sulphur from a deep-seated source, the mantle.

Table 1 Magma volume required to supply the sulphur and copper in porphyry deposits. Data sources for copper are Sillitoe and Gappe (1984), Malihan (1987) and Kirkham and Sinclair (1995)

	Size in Mt[a]			Magma volume required for sulphur in the ore (km^3)		Magma volume required for Cu (km^3)	
	Ore	Total copper	Total S[b]	Felsic melt[c]	Mafic melt[d]	Felsic melt[e]	Mafic melt
Bingham	3,543[f]	30.1	960	4,801	152	300	86
Dizon	187	0.66	21	106	3.4	6.6	1.9
Pinpin and Pisumpan	40	0.16	5.1	26	0.8	1.6	0.5

[a] Mt = 10^6 metric tonnes

[b] Total sulphur calculated assuming a pyrite/chalcopyrite ratio of 20 in the deposit. The ratio is a minimum suggested by Kennecott Exploration. The ratio takes into consideration the abundant pyrite in halo to the deposits

[c] Melt containing 100 ppm sulphur and retaining 20 ppm sulphur after degassing

[d] Melt containing 2,550 ppm S, average content in primitive basalt melt in Bataan arc (Métrich et al. 1999), and retaining 20 ppm sulphur after degassing

[e] 50 ppm Cu is released from felsic melt and 10 ppm Cu is retained (Dilles and Proffett 1995)

[f] Total copper from the Bingham deposit, Ken Krahulec of Kennecott Exploration (written communication, 2001)

High Pt and Pd

Bingham, Dizon and many other porphyry copper deposits are known for high contents of gold, platinum and palladium. Palladium is commonly the fourth most economically important metal in porphyry copper deposits, after copper, gold and silver (Kirkham and Sinclair 1995). The concentrations of platinum group elements are low in evolved felsic rocks and elevated concentrations of these elements in many deposits suggest a contribution from primitive mafic melt derived from the mantle.

Porphyry copper mineralization in stratovolcanoes

Evidence from Mount Pinatubo and Bingham Canyon suggests copper–gold mineralization took place under active volcanoes (Fig. 4). This was earlier proposed by Sillitoe (1973), based on his insightful observations of many deposits. Magmas ascend repeatedly through the conduit of the volcano, forming multiple stocks, dykes and plugs of porphyries. This intrusive conduit is also the focus for fluid discharge from magma at depth. Furthermore, incursion of mafic melt is an integral part of the formation of many stratovolcanoes, which form by repeated explosive eruptions of intermediate to felsic magmas. Various processes can cause these explosive eruptions, but the most common is considered to be injection of hot mafic melt into overlying cool, felsic magma chambers (e.g. Sparks et al. 1977; Huppert et al. 1982; Pallister et al. 1992). Injection of primitive mafic magma is a replenishing process for a crustal magma reservoir (Sparks et al. 1977), and such an injection of mafic magma after a period of quiescence would destabilize viscous, semi-solidified, evolved magma (Sparks et al. 1977; Eichelberger 1980). The injected mafic melt would cool rapidly and cause sudden over saturation and exsolution of volatiles (Huppert et al. 1982).

Mafic melts have great capacity to transfer sulphur from the mantle to the shallow crust as a result of their high sulphur solubility (Fig. 2). The sulphur content of oceanic basaltic melt is >1,000 ppm, and alkaline mafic magma contains even higher contents, >3,000 ppm S (Fig. 2). Perhaps, it is not coincident that the mafic rock at Bingham Canyon is alkaline (Waite et al. 1997) and the basaltic mafic melt at Mount Pinatubo also had an affinity with alkaline basalt (Bernard et al. 1996). Many basaltic arc magmas are also sulphur-rich, although the enrichment of sulphur and the variation in sulphur contents in arc magmas are not well understood (DeHoog et al. 2001). Melt inclusions in primitive basalts at Mt. Iraya, north of Mount Pinatubo in the same arc (Fig. 1a), contain ~3,200 ppm sulphur (Fig. 2; Métrich et al. 1999).

If mafic melt supplied much of the sulphur and significant quantities of metals, what was the role of felsic magmas in the mineralization process? Shallow felsic magma chambers drive long-lasting (>10,000 years) hydrothermal activity to concentrate copper in the ore deposits. In addition, explosive eruptions of viscous felsic magmas generate fractures that provide passage for hydrothermal fluid during quiescent periods.

Stratovolcanoes as sites of porphyry copper mineralization are well-recognized in young (Pliocene–Quaternary) deposits, but not for some large Andean porphyry deposits that formed during mid-

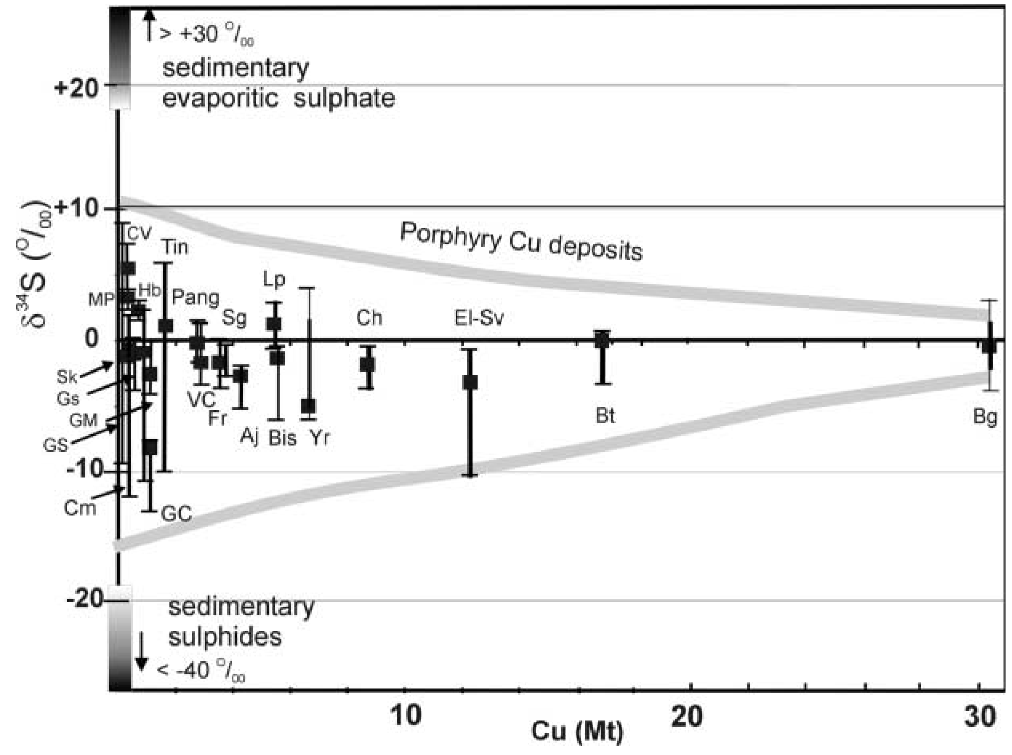

Fig. 3 δ^{34}S for sulphide minerals vs copper contained in porphyry copper deposits in Mt (million tonnes). The deposits are Bingham in Utah (*Bg*; 30.1 Mt Cu), Butte in Montana (*Bt*; 17.7 Mt Cu), El Salvador in Chile (*El-Sv*; 12.21 Mt Cu), Chino in New Mexico (*Ch*; 8.72 Mt Cu), Yerington in Nevada (*Yr*; 6.67 Mt Cu), Bisbee in Arizona (*Bis*; 5.58 Mt Cu), Lepanto Far Southeast in Philippines (*Lp*; 5.48 Mt Cu), Ajo, Arizona (*Aj*; 4.28 Mt Cu), Sungun in Iran (*Sg*; 3.80 Mt Cu), Frieda River in Papua New Guinea (*Fr*; 3.57 Mt Cu), Valley Copper in British Columbia (*VC*; 2.86 Mt Cu), Panguna in Papua New Guinea (*Pang*; 2.76 Mt Cu), Tintic area in Utah (*Tn*; 1.65 Mt Cu), Galore Creek in British Columbia (*GC*; 1.20 Mt Cu), Globe-Miami in Arizona (*GM*; 1.06 Mt Cu), Craigmont in British Columbia (*Cm*; 0.51 Mt Cu), Gaspé Copper in Québec (*Gs*; 0.57 Mt Cu), Cerro Verde-Santa Rosa in Peru (*CV*; 0.45 Mt Cu), Mineral Park in Arizona (*MP*; 0.36 Mt Cu), Skouries in Greece (*Sk*; 0.36 Mt Cu), Hillsboro in New Mexico (*Hb*; 0.21 Mt Cu), and Golden Sunlight in Montana (*GS*; 0.00015 Mt Cu). Data sources: Eastoe (1983), Field (1966), Field and Gustafson (1976), Frei (1995), Hezarkhani and Williams-Jones (1998), Imai (2000), Kirkham and Sinclair (1995), Lange and Cheney (1971), Ohmoto and Rye (1979), Spry et al. (1996) and Zhang et al. (1996). *Solid squares* are averages, *thick bars* are ranges of most samples

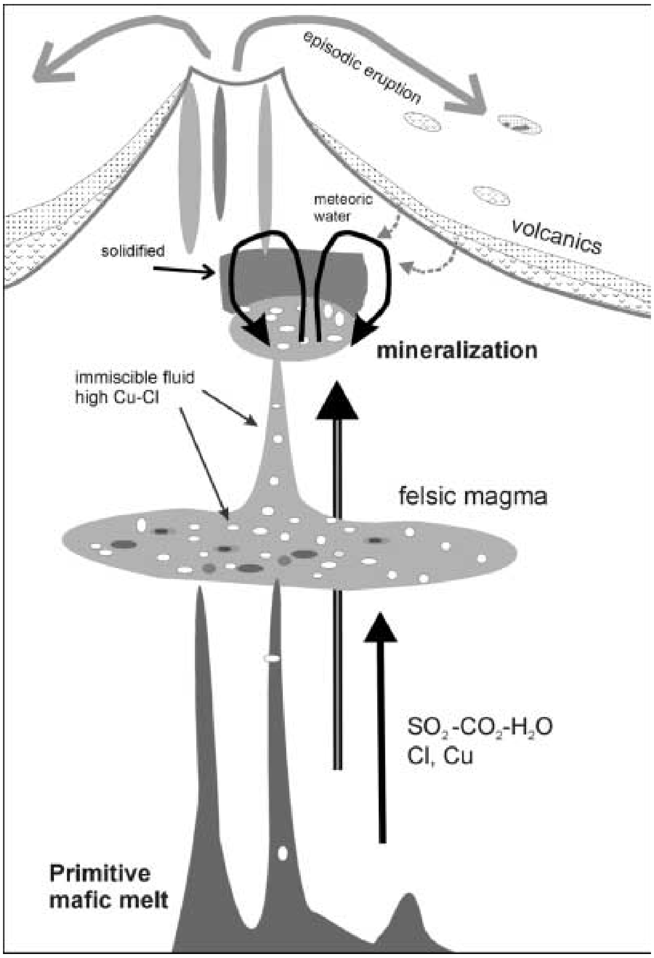

Fig. 4 Generalized geological setting for porphyry copper mineralization. Mafic melt at depth discharges SO_2–CO_2–H_2O–Cl together with metals having affinity with Cl and H_2O. These volatile elements are incorporated into an overlying felsic magma chamber and directly and indirectly included into an immiscible aqueous fluid phase in the magma chamber. The magmatic fluid generates a magmatic-hydrothermal activity for the copper–gold mineralization in already solidified igneous rocks. Periodic injections of mafic melt into a semi-solidified felsic magma chamber result in the destabilization of the felsic magma, forming dykes and extrusion of the mixed magma. Repeated processes formed the stratovolcano

Tertiary (Kay et al. 1999). Why have stratovolcanoes or other types of volcanoes not been universally accepted as the sites of porphyry copper mineralization? Topographic expressions of old (> 3 Ma) volcanoes are rarely preserved in arcs where erosion rates are high. Dome complexes overlie some porphyry deposits as noted by Sillitoe (2000), but are easily eroded. In addition, it is not easy to correlate pyroclastic rocks and lahars formed from pyroclastic eruptions, and even more difficult to correlate them with altered and mineralized intrusions.

Why have the apparent contributions of mafic magmas to porphyry copper deposits not been suggested by previous workers? Porphyry copper deposits form at shallow crustal depths, generally within 4 km of the surface. Mafic igneous rocks are uncommon at such shallow levels in arcs, and basalt lavas rarely erupt from volcanoes, even though many eruptions are triggered by the influx of mafic magmas (Sparks et al. 1977; Pallister et al. 1992). Mafic igneous rocks, however, predominate at lower crustal levels in dissected arcs (e.g. DeBari and Coleman 1989; Khan et al. 1989). Recent high-resolution aeromagnetic data from northern Chile show the clusters of porphyry copper deposits coincide with magnetic anomalies, which most likely reflect loci of mafic intrusions in mid to deep crustal levels (Behn et al. 2001). The dominant portion of mafic magmas from the mantle ponds and discharges its volatiles, solidifying at deep levels in arcs rather than erupting.

Summary

Porphyry copper deposits within the Mount Pinatubo volcano and at Bingham Canyon were formed beneath active stratovolcanoes characterized by periodic eruptions of pyroclastic rocks triggered by injections of mafic melt. The ascent of the mafic melt transfers substantial sulphur, together with other volatiles and copper, from the mantle to the shallow crust. These components then pass to hydrothermal fluid for deposition in, and as haloes surrounding the cupolas of shallow porphyry intrusions. Repeated eruptions and injections of mafic melt cause extensive fragmentation of semi-solidified and solidified rocks, generating the passage for hydrothermal systems for porphyry copper deposits.

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