

The Role of Magmatic Sulfides and Mafic Alkaline Magmas in the Bingham and Tintic Mining Districts, Utah

J. D. KEITH^{1*}, J. A. WHITNEY², K. HATTORI³, G. H. BALLANTYNE⁴,
E. H. CHRISTIANSEN¹, D. L. BARR^{1†}, T. M. CANNAN² AND
C. J. HOOK²

¹GEOLOGY DEPARTMENT, BRIGHAM YOUNG UNIVERSITY, PROVO, UT 84602, USA

²GEOLOGY DEPARTMENT, UNIVERSITY OF GEORGIA, ATHENS, GA 30602, USA

³OTTAWA-CARLETON GEOSCIENCE CENTRE, AND DEPARTMENT OF GEOLOGY, UNIVERSITY OF OTTAWA, OTTAWA, ONT., CANADA, K1N 6N5

⁴KENNECOTT UTAH COPPER, BINGHAM CANYON, UT 84006, USA

RECEIVED JANUARY 1997; ACCEPTED AUGUST 1997

This paper reports the existence of abundant magmatic sulfides in latite lava vitrophyres and vent-facies dikes from the Bingham and Tintic districts in central Utah. These dikes and flows appear to be comagmatic with the ore-related monzonite intrusions. In addition, analytical data suggest that the magmatic sulfides contain most of the Cu and Ag present in the latites. Magmatic sulfides are preserved only in the least oxidized and least degassed lavas and vitrophyres. Petrography of comagmatic dikes and intrusions suggests that resorption and oxidation (S-degassing) of the globules may make the metal content available to a magmatic ore-fluid. Minette and shoshonite lavas occur in subordinate amounts in the latitic volcanic fields associated with latite-monzonite intrusions and hydrothermal ore deposits of the Tintic (Ag–Pb–Zn–Cu–Au) and Bingham (porphyry Cu–Au–Mo) districts, Utah. The ages, chemical and modal compositions, and field relations of the mafic alkaline lavas suggest that such magmas mixed and fractionated at shallow crustal levels to form the ore-related latites and monzonites. The unaltered mafic alkaline lavas in these districts are some of the most Cu-rich lavas in the Great Basin province.

KEY WORDS: alkaline magma; Bingham; porphyry copper; magmatic sulfides; Utah

INTRODUCTION

The eruption of sulfur-rich magmas from El Chichon (Luhr *et al.*, 1984) and Mt Pinatubo (Westrich & Gerlach, 1992) in recent years has attracted attention to the limited solubility of sulfur in intermediate magmas and the factors potentially responsible for the formation of magmatic sulfides and anhydrite. However, the occurrence of magmatic sulfides in intermediate magmas is not universal; many volcanic suites appear to be sulfide unsaturated. Inasmuch as magmatic sulfides may sequester chalcophile metals, what would their presence signify in magmatic systems that formed porphyry Cu and mesothermal vein deposits? Do they sequester a significant portion of the magmatic Cu, Pb, Zn, Ag, and Au, thereby restricting metal availability of subsequent ore-forming fluids?

We have examined the volcanic rocks from the Tintic and Bingham mining districts (Fig. 1), Utah, and found that almost all of the volcanic units contain magmatic sulfides. Some quenched dikes and intrusion margins also have preserved magmatic sulfides comparable with those in the volcanic rocks. Several lines of evidence indicate that the volcanic and intrusive rocks are comagmatic (Keith *et al.*, 1989, 1991; Waite, 1996). The Tintic district and East Tintic sub-district in Utah have recorded over 100 years of production of Ag–Pb–Zn–Cu–Au ores from

*Corresponding author. Telephone: 801-378-2189. Fax: 801-378-8143.
e-mail: jeff_keith@byu.edu
Present address: US Bureau of Reclamation, Mercury, NV 89023, USA.

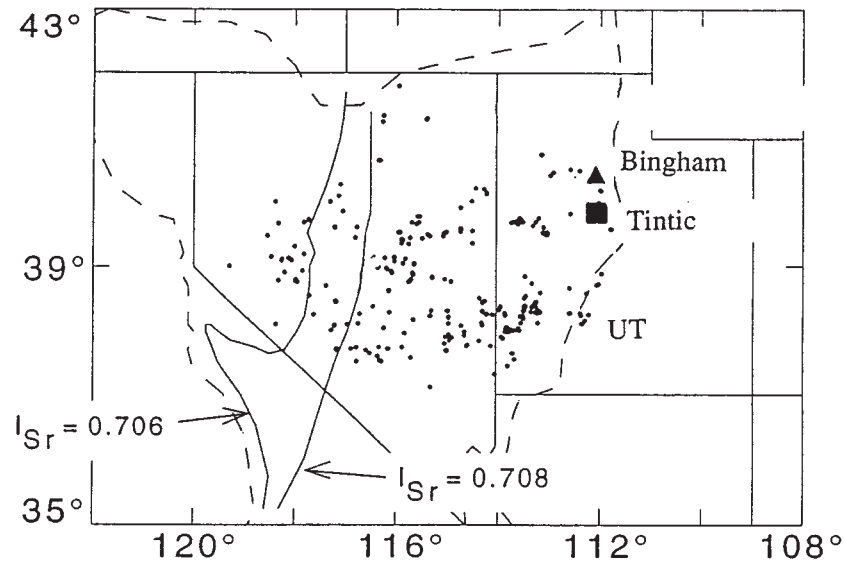


Fig. 1. Index map for location of the Bingham and Tintic districts in central Utah (UT). Also shown is the boundary of the Great Basin (dashed line), locations of mafic and intermediate lavas analyzed by Barr (1993; ●), and the $I_{Sr} = 0.7060$ line and the $I_{Sr} = 0.7080$ line of Farmer & DePaolo (1994), which approximately locate the concealed edge of Precambrian craton in western North America (after Barr, 1993).

vein and replacement deposits that are related to monzonite intrusions (Lindgren & Loughlin, 1919; Lovering, 1949; Morris & Lovering, 1979). The Bingham district hosts one of the most prolific porphyry Cu–Au–Mo (–Ag–Pb–Zn) deposits in the world, with combined reserves and production of over 20 million tons of copper (Babcock *et al.*, 1995). In this paper we examine the origin, abundance, and compositions of magmatic sulfides in each system, as well as their possible role in storing and releasing metals to the magmatic component of an ore fluid. The role of mafic alkaline magmas in forming the sulfide-rich latitic magmas of these giant ore-forming systems will also be investigated.

METHODS

We have collected, examined, and analyzed approximately 92 samples from the East Tintic Mountains and 94 samples from the Bingham district. Samples were collected with particular regard to obtaining flow vitrophyres and unaltered intrusions while still acquiring samples that represent the complete range of compositions and ages in each district. Details of magmatic sulfide preservation in quenched vs non-quenched or altered samples will be discussed below.

Major-element analysis and compositional mapping of the sulfides was done using a JEOL JXA-8600 Superprobe at the University of Georgia. Operating conditions consisted of an accelerating potential of 15

keV, a sample current of 15 nA, counting time of 20 s, and a beam diameter of 1 μm . Details of standardization, data reduction, and detection limits have been summarized by Cannan (1993).

Trace elements in sulfides were determined by proton-induced X-ray microprobe analysis. Operating conditions were 3 MeV of proton energy, 8 nA of specimen current, 600–900 s counting time, a 4 μm \times 5 μm beam, and an Al absorber of 352 μm thickness. Detection limits are three times the errors obtained from the background. Details of operation and accuracies have been given by Cabri *et al.* (1984).

Modal analysis of sulfides by automated electron microprobe methods was attempted, but found to be unsatisfactory because of the large amount of machine time required to analyze one sample and difficulty in discrimination by the microprobe between oxidized sulfides and magmatic Fe oxides. The preferred method of sulfide modal analysis used for this study was reflected light microscopy with a mechanical stage to measure and count every sulfide globule larger than 1 μm in a 2 cm \times 4 cm polished thin section. Modal volumes are reported, with the combined counting and measuring uncertainty estimated to be as large as 25%. No attempt was made to determine modal abundances of individual sulfide minerals by this method. The largest uncertainty in determining magmatic modal sulfide abundance is attributed to post-eruptive oxidation, which is readily apparent in almost every sample (as discussed below);

post-eruptive oxidation may decrease the modal abundance of sulfides by as much as two orders of magnitude.

GEOLOGICAL SETTING AND MAGMA PETROGENESIS

The East Tintic volcanic field, located in the East Tintic Mountains of central Utah, consists of intermediate-to-silicic volcanic and shallow intrusive rocks produced by composite volcanoes and small calderas (Hannah *et al.*, 1991; Keith *et al.*, 1991; Kim, 1992; Moore, 1993). Moore (1993) suggested that at least 100 km³ of magma were erupted during the life span (35–32 Ma) of the field. Compositions range from shoshonite to trachyte, with latitic lavas representing the dominant volcanic product. Petrogenetic modeling indicates that the early, amphibole-absent, latitic magmas, which are unrelated to mineralization, evolved by magma mixing and extensive high-pressure fractional crystallization of clinopyroxene. Younger, amphibole-bearing magmas also evolved by magma mixing and fractional crystallization, but these processes occurred at low pressures (Moore, 1993). Mapping and ⁴⁰Ar/³⁹Ar ages suggest a close temporal relationship between some of the younger amphibole-bearing latite flows and the ore-related monzonite intrusions (Moore, 1993).

Volcanic rocks that flank the eastern margin of the Bingham Canyon porphyry copper deposit range in composition from minette lavas to rhyolite domes and range in age from 39 to 33 Ma (Moore, 1973; Moore & Mckee, 1983). Debris avalanche and lahar deposits of latitic composition are the most abundant volcanic lithology. Moore (1973) suggested that of all the Bingham intrusions (39.8–37.5 Ma; Warnars *et al.*, 1978), the amphibole-bearing latite dikes most closely match the composition of some volcanic lithologies in the 1 km thick volcanic section. We concur with this observation and note that some debris avalanche deposits appear to have originated from small relict domes and shallowly eroded dikes. In addition, the radiometric age of the dikes does not differ significantly from that of the basal portion of the volcanic section and of the Bingham stock (Moore, 1973; Warnars *et al.*, 1978; Moore & Mckee, 1983). Some of these dikes cut the presumed mineralizing intrusive phase (quartz monzonite porphyry), but the alteration and weak mineralization present in portions of the dikes indicates that they are broadly synchronous with mineralization. It is possible that earlier phases of the Bingham intrusive complex also vented to the surface to form some of the older debris avalanche deposits, but additional work is needed to examine such correlations.

HYDROTHERMAL ALTERATION AND INTRUSIONS

Productive intrusions

Hydrothermal alteration of volcanic rocks in the East Tintic Mountains is spatially related to concealed faults, monzonite intrusions, and ore deposits (Lovering, 1949). Both equigranular monzonite intrusions and biotite latite dikes penetrate volcanic rocks that were part of a large stratovolcano. Latite and shoshonite dikes can often be traced to the shallowest levels of volcanic cover and certainly represent magma that vented. Ore-related monzonite intrusions cannot be traced to the shallowest levels of volcanic cover and may not have vented. Similarities in mode and bulk composition of some of the monzonite and latite suggest that they may represent comagmatic batches of magma. The ⁴⁰Ar/³⁹Ar ages of some units are also permissible evidence for correlation. For example, biotite from a glassy sample of vent-facies latite dike exhibits a plateau age of 34.5 ± 0.2 Ma (Keith *et al.*, 1991). A K–Ar age of 34.4 ± 1.2 Ma from biotite from a nearby alluvial-covered Cu–Mo prospect in the East Tintic Mountains also falls in this general time interval (Hannah & Macbeth, 1990). It is notable that the biotite latite dikes with abundant magmatic sulfides do not exhibit haloes of sulfide-rich alteration in the country rock; however, their more slowly cooled monzonite counterparts exhibit large sulfide-rich, argillic–phyllic alteration haloes, but contain few, if any, preserved magmatic sulfides (Keith *et al.*, in preparation). It appears that processes related to mineralization and alteration may also have effectively removed magmatic sulfides from magma that cooled to form monzonitic intrusions.

Waite (1996) examined the petrogenesis of ore-related latite and quartz latite dikes of the Bingham system. She noted that the unusually high contents of Cr and other compatible elements in the dikes require that the parental magma contained at least 10% primitive magma similar to the coeval minette dikes and flows.

Barren intrusions

The Sunrise Peak stock in the East Tintic district is notably barren and exhibits no spatially related alteration. Texturally, it is more analogous to the latite dikes than to the monzonite intrusions and the stock clearly vented to the surface (Lindgren & Loughlin, 1919). A vitrophyre sample from a flow related to the venting of this intrusion contains only trivial amounts of magmatic sulfides. The ⁴⁰Ar/³⁹Ar age of this flow, 34.7 ± 0.3 Ma, is correlative with the age of the stock of 34.7 ± 0.1 Ma (Moore, 1993).

The Last Chance stock of the Bingham district shows no direct spatial or temporal relationship to mineralization. The petrogenesis of this intrusion requires

less involvement of primitive magma via mixing (Waite, 1996).

MAFIC ALKALINE MAGMAS

Small amounts of minette, lamproite, and shoshonite magmas accompany the calc-alkaline Eocene–Oligocene magmatism in central Utah (Best *et al.*, 1968; Moore, 1973, 1993; Moore & Mckee, 1983; Keith *et al.*, 1991; Kim, 1992). Petrogenetic modeling of the Tintic and Bingham magmatism using both major- and trace-element whole-rock data, Nd–Sr isotopes, and phenocryst compositions indicates that shoshonite and minette were the most mafic magmas in these respective districts that mixed with intermediate magma to form the latites and monzonites (Moore, 1993; Waite *et al.*, 1997). A complete review of the evidence for participation of mafic alkaline magmas in the petrogenesis of the ore-related magmas in these districts is beyond the scope of this paper. However, the evidence for commingling of magmas in the Bingham district can be summarized as follows:

(1) Deino & Keith (in press) have documented the occurrence of minette dikes (37.74 ± 0.11 Ma) within the Bingham ore body that are the same age as late mineralized porphyry dikes (37.72 ± 0.09 Ma) and minette flows (37.84 ± 0.14 Ma) within the Bingham district volcanic rocks.

(2) Minette and late mineralized quartz latite dikes are intruded, side-by-side, into the core of the active ore-forming system (Waite *et al.*, 1997).

(3) In general, successive intrusions in the Bingham system become more silicic (increasing from 60 to 66% SiO₂) while also becoming richer in incompatible elements such as Cr (which increases from 40 to 180 ppm; Waite *et al.*, 1997).

(4) Unaltered latitic volcanic rocks that flank the range front also can be divided into two groups; namely, low-Cr latites (<40 ppm) that show little petrographic evidence of mixing and high-Cr latites (100–200 ppm Cr) that are similar to Bingham intrusions and show evidence of mixing (zoned amphibole, sieve-textured plagioclase, olivine–mica-rich clots; Waite *et al.*, 1997).

The Cu content of these mafic alkaline magmas is high compared with other Tertiary lavas that erupted across the Great Basin (Barr, 1993). Barr (1993) demonstrated that Cu concentrations in this suite of Tertiary lavas generally increase from west to east (Fig. 2). The Cu content of the Bingham minette lavas is also high compared with the average Cu content of other suites of alkaline rocks in western North America (Fig. 3). Copper in the Bingham and Tintic suites declines with increasing SiO₂ content as a result of mixing and fractionation of sulfide-saturated magmas (Moore, 1993; Waite, 1996).

SULFIDE DATA

Abundance and distribution of sulfides

Magmatic sulfides in rocks from both areas generally occur as globules that range in diameter from 1 to 500 µm. The modal abundance of magmatic sulfides varies from <0.0001 up to 0.1 modal % (Cannan, 1993; Hook, 1995). A biotite latite glass from the East Tintic Mountains contains globules up to 450 µm in diameter with a modal abundance of 0.02%; modal analysis reveals a total of 465 sulfide globules (in one thin section) over 1 µm in size. Titanomagnetite contains 36% of the globules, clinopyroxene contains 27%, the glassy matrix 22%, biotite 10%, and plagioclase contains 4%. Some lithologies from the East Tintic Mountains contain sulfide globules that are hosted almost entirely by the matrix. In addition, silicate melt inclusions commonly contain a small sulfide globule. Portions of the associated glass have S concentrations (~400 ppm) anticipated for sulfide saturation of this bulk composition (Carroll & Rutherford, 1985). By comparison, the sulfide-poor vitrophyre associated with the Sunrise Peak stock contains fewer than 10 globules per thin section with diameters in the 1–10 µm range. The only rocks in each district that are actually sulfide undersaturated are mafic lavas with <54% SiO₂ and no phenocrystic plagioclase. All plagioclase-bearing rocks were sulfide saturated as magmas, but oxidized lavas or non-quenched samples apparently lost most or all of their magmatic endowment of sulfides before solidification. Glassy or non-oxidized microcrystalline samples contain the highest proportion of preserved magmatic sulfides. As the SiO₂ content of magmas increases from 55% up to 75%, the abundance of magmatic sulfides also dramatically declines by two orders of magnitude (Fig. 4). Volcanic rocks from the Bingham district are slightly more silicic than those from the Tintic district and generally have smaller (<20 µm) and less abundant sulfides (0.01–0.001 vol. %).

Sulfide compositions

Most primary sulfide globules consist of mixtures of pyrite, pyrrhotite, and chalcopyrite. Magmatic sulfides from the Tintic and Bingham districts exhibit sulfur-rich compositions comparable with those from the Fish Canyon and Bishop Tuffs (Hildreth, 1977; Whitney & Stormer, 1983). No magnetite appears to have been exsolved from sulfide globules. Chalcopyrite is far more abundant than cubanite in the ISS (intermediate solid solution in the Cu–Fe–S system) portions of the grains. Microprobe analyses of the Tintic magmatic sulfides indicate moderate to low concentrations of Ni and Co (up to 1.0 wt %; Keith *et al.*, 1991; Cannan, 1993). However, magmatic sulfides from the Bingham district are distinctly more Ni rich, as evidenced by the common

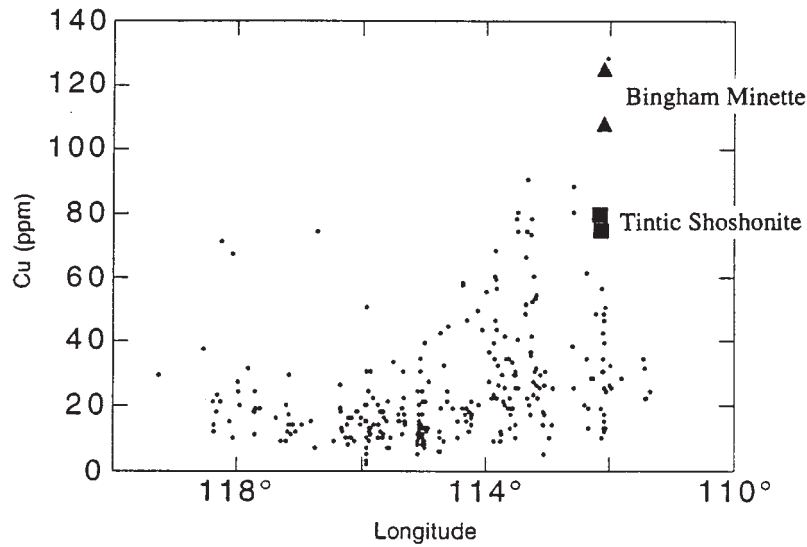


Fig. 2. Cu concentrations vs longitude for Great Basin intermediate and mafic lavas. Horizontal scale is the same as in Fig. 1 (after Barr, 1993).

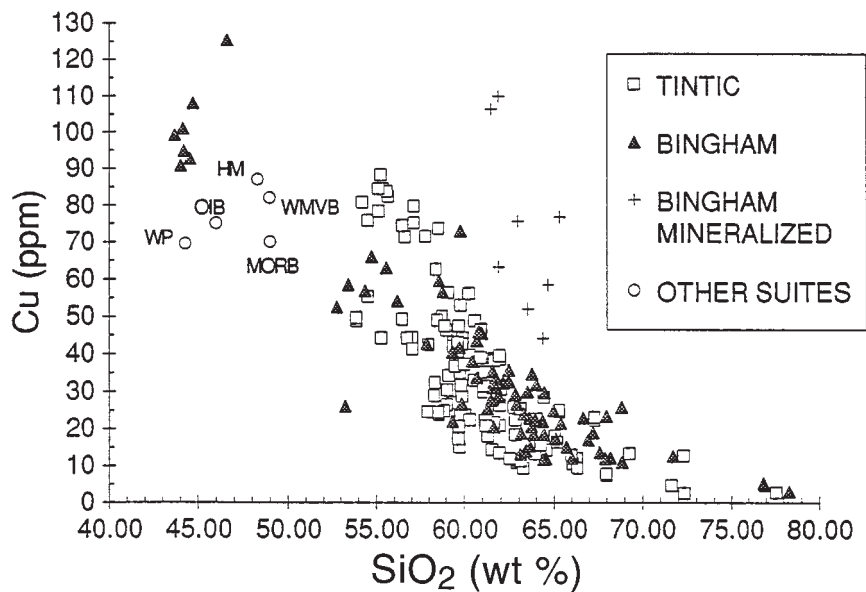


Fig. 3. Cu concentrations vs SiO_2 for Bingham and Tintic volcanic and intrusive rocks (Keith *et al.*, 1991; Kim, 1992; Moore, 1993; Waite, 1996). Also shown are the average Cu concentrations of: ocean island basalts (OIB); mid-ocean ridge basalts (MORB); Highwood, Montana, potassic lavas (HM; O'Brien, 1991); minette and melanephelinite dikes of the Wasatch Plateau, Utah (WP; Tingey *et al.*, 1991); and potassic lavas of the western Mexico volcanic belt (WMVB; Wallace & Carmichael, 1992).

occurrence of pentlandite and pyrrhotite with up to 2.38 wt % Ni (Hook, 1995).

The trace element contents of magmatic sulfides from these districts were also determined. A fresh sample (with perlitic glass as the matrix and no apparent hydrothermal alteration) of quenched latite dike from the Bingham intrusive complex (Bing-6; Table 1) was selected for analysis, as well as quenched (glassy) dikes and flows from the Tintic district (Table 2). Sample selection for trace

element analysis of sulfides was made on the basis of dikes and flows most closely related in time or space to mineralization, but still containing some pristine magmatic sulfides. The sulfides from the Bingham district latite dike contain higher concentrations of all analyzed chalcophile trace elements compared with the Tintic sulfides (Table 2). The large variations in trace element content from one globule to another within the same sample appear to be related to the mobility and behavior

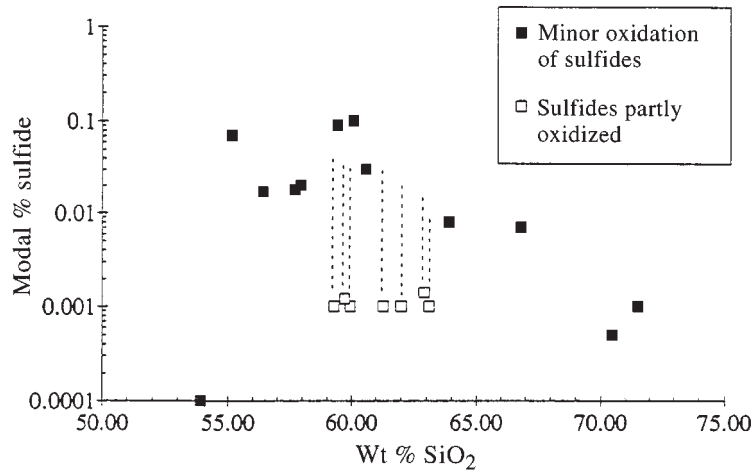


Fig. 4. Modal percent sulfide vs weight percent SiO₂ in lavas from the East Tintic volcanic field (Cannan, 1993). ■, lavas with minor amounts of oxidation of sulfide globules; □, lavas that have suffered more extensive oxidation of globules; primary magmatic sulfide content may lie somewhere along the dashed lines.

Table 1: Trace elements in magmatic sulfides from a quenched Bingham latite dyke

Sample	Zn	As	Se	Mo	Pd	Ag	Pb	Mineral
Bing-6	316	570	76	68	<10	162	4227	pyrrhotite
Bing-6	134	1751	58	95	14	496	3333	pyrrhotite
Bing-6	29	4430	124	12	<10	89	2620	pyrite
Bing-6	577	<10	30	na	<10	<10	<50	pyrrhotite
Bing-6	183	761	31	17	<10	144	471	pyrite
Bing-6	110	417	75	18	<10	126	1064	pyrrhotite
Bing-6	232	12115	na	16	39	58	1409	pyrite

Values (ppm) determined by proton-induced X-ray microprobe. Cd, Sn, Sb, Te, Au, and Hg were also analyzed, but resulting values were generally below detection limits. na, not analyzed.

Table 2: Trace elements in magmatic sulfides from Tintic latite and shoshonite

Sample	Host*	Zn	As	Se	Mo	Ag	Pb	Mineral
ET-121	60.32	305	56	34	<5	<10	180	pyrite
ET-121	60.32	40	89	27	<5	<10	130	pyrite
ET-121	60.32	57	123	3	<5	<10	400	pyrite
ET-121	60.32	130	78	7	<5	<10	345	pyrite
TJ-72	59.54	na	17	55	17	<10	99	pyrrhotite
TJ-72	59.54	1344	19	77	41	165	<50	chalcopyrite
TD-12	59.11	82	13	37	na	<10	<50	pyrrhotite
TJ-92	59.05	214	15	48	21	<10	na	pyrrhotite
TD-41	54.97	72	67	na	4	<10	<50	pyrrhotite
TJ-83	56.03	1930	4248	45	42	168	<50	chalcopyrite

Values (ppm) determined by proton-induced X-ray microprobe. Pd, Cd, Sn, Sb, Te, Au, and Hg were also analyzed, but resulting values were generally below detection limits. na, not analyzed.

*Host rock SiO₂ (wt %).

of these elements during exsolution of the globule. For example, Ag and Mo in Tintic sulfide samples are strongly partitioned into chalcopyrite rather than pyrite or pyrrhotite during exsolution (Table 2).

Sulfide exsolution, resorption and oxidation

Petrographic examination of magmatic sulfides from these districts reveals different episodes of exsolution, resorption, and oxidation (S-degassing) processes. Mono-sulfide solid solution globules are rarely preserved as pyrrhotite unless they are embedded: (1) near the centers of silicate phenocrysts (which are devoid of cracks to the crystal surface), (2) within titanomagnetite devoid of oxidation exsolution (or maghemitization) or (3) within some glomeroporphyritic clots. This may be due in part to the fact that S-rich pyrrhotite compositions spontaneously exsolve upon quenching, as noted by Craig & Scott (1974). Evidence for this process was also encountered by Whitney (1984) after examination of pyrrhotite globules in the Fish Canyon Tuff. However, the most apparent cause of sulfide oxidation in Tintic and Bingham samples appears to be oxidation associated with eruption.

If some sulfide oxidation occurs before eruption, as proposed by Hattori (1993) for fresh Pinatubo samples, then the behavior of some elements during the process may be important. X-ray maps for Fe and S document that the Fe distribution within the S-degassed sulfides is fairly homogeneous (Keith *et al.*, 1991; Cannan, 1993; Hook, 1995), as it would have been in the original iron mono-sulfide melt (MSS). However, X-ray maps for S indicate a very inhomogeneous distribution. Consequently, the degassing process consists of the outward migration of sulfur (and replacement with oxygen or hydroxyl). Continued degassing removes almost all of the S, As, and Cu (and probably Ag). The chalcopyrite often degasses last after the pyrrhotite, pyrite, and As-rich pyrite have completely degassed to an Fe oxide residue (Fe:O ratio lower than hematite). Co and Ni remain in the Fe oxide residue, showing evidence for less mobility during the oxidation–S-degassing process.

Sulfide globules that are not sequestered in other phenocrysts or phenocryst clots also show abundant evidence of resorption and disaggregation; these effects might be expected during depressurization involved with emplacement in shallow dikes and lavas. Samples which exhibit broken phenocrysts and strongly flow foliated glass also have sulfide globules which have been broken and form ‘trains’ of small sulfide fragments that parallel the foliation. Some latite dike samples with a holocrystalline fine-grained matrix exhibit spherical ‘spongy’ Fe oxides where >90% of the magmatic sulfur has been removed by dissolution and oxidation. The size, distribution, and modal abundance of the ‘spongy’ Fe

oxide grains mimic the occurrence of the magmatic sulfides.

Latite or monzonite dikes and intrusions with normal fine-grained or coarser-grained groundmass rarely preserve significant amounts of sulfides. If globules are present, they are generally <10 µm in size and embedded deep within phenocrysts. Globules of >10 µm, which occur as inclusions, consistently fracture their hosts and ‘erupt’ their contents to the melt during intrusion (Keith *et al.*, 1991).

DISCUSSION

Origin of sulfides

A variety of factors purportedly influence magmatic sulfur solubility, including temperature, pressure, oxygen fugacity, and iron content of the magma (Wendlandt, 1982; Wallace & Carmichael, 1992). In the Tintic and Bingham districts, only the most primitive lavas are not saturated with sulfides. Sulfide saturation apparently occurred as mafic magmas mixed and fractionated. Saturation occurred early relative to the growth of the observed phenocrysts inasmuch as sulfides occur as inclusions deep within all mineral phases. One potential mechanism that may have operated on a local scale to create the sulfides was reduction in the Fe content of the melt in the vicinity of growing Fe-oxides or Fe–Mg silicates (Bacon, 1989). This may explain why titanomagnetite and clinopyroxene are the most common host minerals for sulfide globules. On a larger scale, magma mixing is fundamentally important to the petrogenesis of magmas in both districts (Kim, 1992; Moore, 1993; Waite, 1996).

Others have proposed that a magma chamber may be enriched in magmatic sulfides or anhydrite by an upward flux of SO₂ released from underplated mafic magma. Evidence that SO₂ fluxing occurs is particularly compelling for recent eruptions of El Chichon (Luhr *et al.*, 1984) and Mt Pinatubo (Hattori, 1993), which contain abundant magmatic anhydrite. Hattori (1993) proposed that underplated mafic magmas may release supercritical fluids rich in SO₂ into overlying intermediate magmas. SO₂ may be initially reduced to form sulfides in the cooler, wetter magma; continued influx of SO₂ partially oxidizes the sulfides and then precipitates anhydrite. There is no evidence that this sulfide oxidation process exceeds the buffer capacity of the magma. However, the resulting net sulfur content of the magma exceeds what could have been dissolved in an intermediate melt. No magmatic anhydrite has been found in magmas from the Bingham and Tintic districts, but we cannot exclude the possibility that some volatile fluxing may have occurred to help create the high sulfide contents (0.1 modal %) of some magmas from these districts.

Metal content of sulfides

The magmatic sulfides from the Bingham and Tintic systems sequester critical amounts of ore-related metals. The copper content of a magma is strongly partitioned into a magmatic sulfide phase when it is present (Candela, 1989). Gold is probably sequestered to a similar (but undetectable) extent (Hattori, 1987). Although some loss of Cu, Ag, and Au from the magma may have occurred after eruption or intrusion, it is probably minor in these glassy rocks. Cu, Ag, and Au are similar chalcophile elements that would be expected to partition strongly into a sulfide phase. By contrast, the sulfide globules contain only a few percent or less of the Pb, Zn and Mo in the rock.

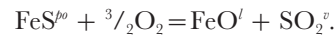
If the budget of metals hosted by the magmatic sulfides is readily contributed to an ore fluid by sulfide resorption or dissolution, then the ratio of metals in the sulfide globules may influence the ratio of metals in the hydrothermal deposits. Insufficient data are available to adequately examine this possibility, but the preliminary data are interesting. For example, the ratio of Cu/Pb/Zn in the Bingham magmatic sulfide globules has approximately the same magnitude as the Cu/Pb/Zn ratio in the Bingham deposit (Babcock *et al.*, 1995). This suggests that the small amount of Pb and Zn in the sulfide globules may be sufficient (relative to contributed Cu) to account for the Pb and Zn in the Bingham replacement deposits. As an additional example, sample ET-121 (Table 2) is from the glassy margin of a dike in the northern portion of the East Tintic district (Kim, 1992) where galena and sphalerite are the dominant ore minerals. The magmatic sulfides in ET-121 contain very little Cu and Ag, but do contain measurable Pb and Zn (Table 2). Slowly cooled portions of this intrusion and similar intrusions may have helped set the metal ratios in the adjacent replacement deposits.

If the metal ratios of the magmatic globules are partially inherited by the hydrothermal ores, then the significant concentrations of Ni and Co in the magmatic globules do not participate in the process. Possibly, the ligands in the magmatic ore fluid preferentially complex with Fe rather than Ni or Co; therefore the globules may be resorbed or dissolved, but Ni and Co remain in the melt or subsequent Fe–Mg silicates.

Removal of sulfides

One of the most significant characteristics of magmatic sulfides is the fact that they are not commonly preserved in slowly cooled lavas and intrusions. The timing, extent, and mechanisms for their removal from magmas may not be well known, but it is unlikely that significant amounts of Cu–Ag–Au-bearing ore fluids can be produced from sulfide-saturated magmas without at least

partial removal of the magmatic globules. Candela & Holland (1986) and Candela (1989) considered the possibility that magmatic pyrrhotite may sequester Cu and then become destabilized after vapor saturation. They proposed that removal of an SO₂-rich vapor from the magma would cause oxidation of pyrrhotite globules according to the following reaction:



We note that all oxidized globules that we have analyzed contain Fe₂O₃ rather than FeO, but the concept of magmatic oxidation of sulfides appears to be feasible.

Therefore, mechanisms for removal of magmatic sulfides include loss of sulfurous gases from the magma chamber, pressure decrease, and other oxidation processes in the magma chamber. Numerous lines of evidence indicate that an S-rich pre-eruptive fluid phase may be present in sub-volcanic magma chambers (Lühr *et al.*, 1984; Westrich & Gerlach, 1992; Lowenstern, 1993). Periodic loss of an S-rich fluid may lower the S and H₂O content of the melt and destabilize the sulfides. Upward volatile fluxing of an SO₂-rich fluid also may oxidize the sulfides (Hattori, 1993). Alternatively, the substantial pressure decrease and loss of sulfurous gases and H₂O that may accompany emplacement of sub-volcanic intrusions may also lead to resorption of sulfides. Lowenstern (1993) demonstrated that crystallization-induced volatile saturation, or 'second-boiling' may not be a necessary prerequisite for the creation of metal-bearing hydrothermal fluids. Instead, volatile saturation may occur because of depressurization combined with the presence of low-solubility gases such as CO₂ and SO₂. Clearly, magmatic sulfides that are composed of >50 mol % of a common volcanic gas may tend to be ephemeral.

Role of mafic alkaline magmas

Carmichael & Ghiorso (1986) noted that mafic alkaline magmas with high oxygen fugacities contain high concentrations of sulfur (2000–4000 ppm). The source region for minettes and highly oxidized potassic lavas may be phlogopite pyroxenite of the lithospheric mantle (Carmichael, 1991). Other lines of evidence indicate that lithospheric phlogopite pyroxenite may also be unusually Cu and S rich. Irving (1980) and Dromgoole & Pasteris (1987) noted that there is greater abundance of sulfides (up to 0.5 modal %) in mantle pyroxenites than in other mantle nodules that they examined. Clinopyroxenites, which probably represent high-pressure crystallization from alkalic basalts, may also be particularly rich in sulfides (0.06–0.26%, Salt Lake Crater, Hawaii; DeWaal & Clark, 1975). Mantle clinopyroxene megacrysts and clinopyroxenites from Kilbourne Hole contain sulfides

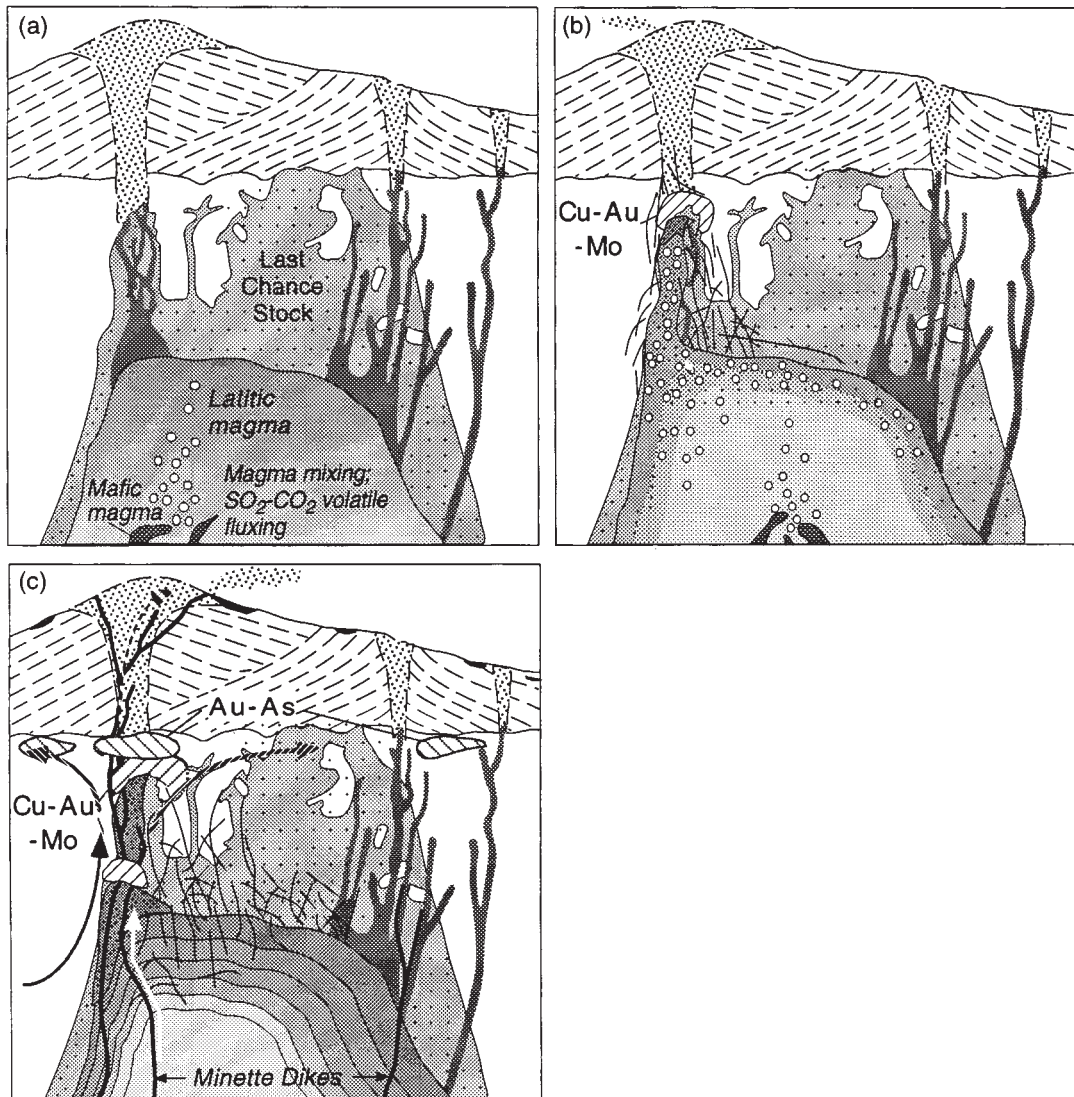


Fig. 5. Schematic cross-sections of the Bingham system. (a) Minette and shoshonitic magma supply above-average concentrations of SO₂, H₂O, Cu, and other chalcophile metals (and probably some H₂S and CO₂) to the sub-volcanic magma chamber. Some fluxed, insoluble SO₂ is reduced to form magmatic sulfides by interaction with cooler, wetter latitic magma. Magmatic sulfides sequester Cu, Au, Ag and some Mo, Pb, and Zn. (b) Crystallization along the walls of the magma chamber provides some water-rich fluid. Magma pressure decrease associated with stock emplacement or volatile loss causes oxidation and resorption of sulfides and releases chalcophile metals and sulfurous gases to the ore fluid. (c) After emplacement of the last silic porphyry dikes, minette dikes penetrate the batholith and are emplaced along the sides of porphyry dikes. Both types of dikes are only weakly fractured and mineralized, and contain half the mineralization of adjacent porphyry. Meteoric and magmatic fluids mix and do not readily penetrate into the volcanic rocks. Fluids are channeled through faulted and fractured intrusive rocks and Paleozoic rocks forming late Au-As mineralization.

that tend to be more Cu rich than sulfides from spinel lherzolites (Dromgoole & Pasteris, 1987). Biotite clinopyroxenite nodules from the potassic volcanic field of Highwood, Montana, are particularly Cu rich, with up to 260 ppm Cu (O'Brien, 1991). Cu-rich phlogopite pyroxenite may be generated by metasomatism of lithospheric mantle during subduction (Whitney & Stormer, 1983).

Wet, oxidized, mafic alkaline magmas generated from such mantle protoliths may be capable of delivering high concentrations of sulfur, water and chalcophile metals to the base of an ore-related magma chamber if they are allowed to rise rapidly through the crust without stagnating and fractionating sulfide-bearing magma. Even a mildly extensional tectonic regime, similar to that proposed for central Utah during the Eocene-Oligocene

(Presnell, 1992), may suffice to allow primitive magmas to erupt or underplate calc-alkaline magma chambers (Fig. 5). As a contrasting example, magma that formed the barren Sunrise Peak stock and associated flows in the Tintic district stagnated en route to the surface and fractionated clinopyroxene (Moore, 1993); this probably stripped some of the sulfides and chalcophile metals from the magma and may explain why the comagmatic fresh lavas contain relatively few sulfide globules and the stock has no related mineralization.

We do not imply that the ore-forming potential of magmatic systems can be evaluated solely on the basis of the fraction of lithospheric mantle input. Farmer & DePaolo (1984) noted that Nd isotopic data are useful to show that some ore-related plutons in the Great Basin contain a higher proportion of mantle material than barren systems; however, some systems such as Bingham were modeled by them to be derived primarily from felsic basement. For Bingham, we suggest that first, a wet, latitic magma formed from mixtures of crustal and mantle material and was emplaced in a high-level magma chamber; then, mild extensional tectonism allowed quick passage through the crust for some batches of primitive alkaline magma. The cooler, wet latitic magma may have served the critical role of converting SO₂ vapors, released from the minette magma, to H₂S and eventually to magmatic sulfides (Fig. 5; Hattori, 1993). In addition, some fluxed volatiles and metals may not be sequestered as sulfides, but simply reside in the roof-zone magma as a separate aqueous phase until mineralization occurs.

CONCLUSIONS

Several factors may have led to the formation of the world-class deposits associated with the Bingham and Tintic districts. Some of the following facets could be used as exploration criteria for similar deposits:

(1) All of the volcanic rocks from the Bingham and Tintic districts that we have examined are sulfide saturated except the most primitive (olivine-rich, plagioclase-absent) lavas.

(2) The primitive lavas exhibit the highest Cu concentrations in each volcanic suite. A minette flow (which is coeval with Bingham mineralization) contains the highest Cu content (125 ppm) of any of the unaltered lava flows from the Great Basin that have been analyzed by us or Barr (1993).

(3) Large (up to 500 µm), abundant (up to 0.1%) magmatic sulfides occur in some latite lava vitrophyres and vitric dikes from the East Tintic Mountains, Utah. Bingham district volcanic rocks are less sulfide rich, but the magmatic sulfides contain more chalcophile metals than those of the Tintic district. The volcanic rocks in

both districts appear to be comagmatic with ore-related intrusions.

(4) The S- and Cu-rich primitive alkaline magmas in both districts may have originated from partial melting of metasomatized lithospheric mantle. Sulfide saturation may not have occurred until the primitive magmas mixed with more silicic magmas or fractionated at mid- to upper-crustal levels. This would prevent any depletion in S and chalcophile metals.

(5) After emplacement of magmas in sub-volcanic chambers, sulfide saturation occurs early in the crystallization sequence of each volcanic suite. This indicates that almost all of the Cu and precious metals would be sequestered within sulfide globules.

(6) Comagmatic intrusions which fill the vents have no significant amount of preserved magmatic sulfides.

(7) Crystallization of the magma may not directly lead to formation of a metal-rich magmatic ore fluid. A pressure decrease, possibly associated with eruption, intrusion, or loss of magmatic volatiles, would initiate resorption of sulfide globules and release the sequestered metals and sulfur to the hydrothermal system (Fig. 5).

(8) The presence of Ni-rich magmatic sulfides in intermediate lavas may indicate that the lavas were formed by mixing of an S-rich mafic alkaline parent with latitic magmas. The implication might be that a large budget of mantle-derived S, Cu, Ag, and Au was also contributed in the process. Whole-rock trace element analysis of the intermediate lavas or porphyries may also reveal unusually high Cr and Ni contents.

(9) This process and model may be widely applicable to many porphyry systems, although the critical supporting evidence to verify the model may hinge on finding comagmatic glassy volcanic rocks or subtle evidence of intermixed primitive magma.

ACKNOWLEDGEMENTS

We thank Kennecott Corporation and Jaren Swenson in particular for guiding our sampling in collection of critical samples. We thank Jay Ague and Victor Kress for careful reviews of this paper. This work was supported by NSF Grant EAR-9114980.

REFERENCES

- Babcock, R. C., Jr, Ballantyne, G. H. & Phillips, C. H., 1995. Summary of the geology of the Bingham district, Utah. In: Pierce, F. W. & Bolm, J. G. (eds) *Porphyry Copper Deposits of the American Cordillera. Arizona Geological Society Digest* **20**, 316–335.
- Bacon, C. R., 1989. Crystallization of accessory phases in magmas by local saturation adjacent to phenocrysts. *Geochimica et Cosmochimica Acta* **53**, 1055–1066.
- Barr, D. L., 1993. Time, space, and composition patterns of middle Cenozoic mafic to intermediate composition lava flows of the Great

- Basin, western U.S.A. M.S. Thesis, Brigham Young University, Provo, UT.
- Best, M. G., Henage, L. F. & Adams, J. A. S., 1968. Mica peridotite, wyomingite, and associated potassic igneous rocks in northeastern Utah. *American Mineralogist* **53**, 1041–1048.
- Cabri, L. J., Blanck, H., El Goresy, A., LaFlamme, J. H. G., Nobiling, R., Sizgoric, M. B. & Traxel, K., 1984. Quantitative trace element analyses of sulfides from Sudbury and Stillwater by proton microprobe. *Canadian Mineralogist* **22**, 521–542.
- Candela, P. A., 1989. Felsic magmas, volatiles, and metallogenesis. In: Whitney, J. A. & Naldrett, A. J. (eds) *Ore Deposition Associated with Magmas. Reviews in Economic Geology* **4**, 223–233.
- Candela, P. A. & Holland, H. D., 1986. A mass transfer model for copper and molybdenum in magmatic hydrothermal systems: the origin of porphyry-type ore deposits. *Geochimica et Cosmochimica Acta* **81**, 1–19.
- Camman, T. M., 1993. Mineralogy and evolution of magmatic sulfides in ore-related magmas of the East Tintic Mountains, Utah. M.S. Thesis, University of Georgia, Athens.
- Carmichael, I. S. E., 1991. The redox states of basic and silicic magmas: a reflection of their source regions? *Contributions to Mineralogy and Petrology* **106**, 129–141.
- Carmichael, I. S. E. & Ghiorso, M. S., 1986. Oxidation–reduction relations in basic magma: a case for homogeneous equilibria. *Earth and Planetary Science Letters* **78**, 200–210.
- Carroll, M. R. & Rutherford, M. J., 1985. Sulfide and sulfate saturation in hydrous silicate melts. *Journal of Geophysical Research* **90**, Supplement C601–C612.
- Craig, J. R. & Scott, S. D., 1974. Sulphide phase equilibria. In: Ribbe, P. H. (ed.) *Sulphide Mineralogy. Mineralogical Society of America Short Course Notes* **1**, CS-1–CS-110.
- Deino, A. & Keith, J. D., 1997. Ages of volcanic and intrusive rocks in the Bingham district, Utah. *Society of Economic Geologists Oquirrh Symposium Special Volume*. In press.
- DeWaal, S. A. & Clark, L. C., 1975. The sulphides in the garnet pyroxenite xenoliths from Salt Lake Crater, Oahu. *Journal of Petrology* **16**, 134–153.
- Dromgoole, E. L. & Pasteris, J. D., 1987. Interpretation of sulfide assemblages in a suite of xenoliths from Kilbourne Hole, New Mexico. *Geological Society of America Special Paper* **215**, 25–46.
- Farmer, G. L. & DePaolo, D. J., 1994. Origin of Mesozoic and Tertiary granite in the western United States and implications for pre-Mesozoic crustal structure 2. Nd and Sr isotopic studies of unmineralized and Cu- and Mo-mineralized granite in the Precambrian craton. *Journal of Geophysical Research* **89**(B12), 10141–10160.
- Hannah, J. L. & Macbeth, A., 1990. Magmatic history of the East Tintic Mountains, Utah. *US Geological Survey Open-File Report* **90-0095**.
- Hannah, J. L., Macbeth, A. & Stein, H., 1991. Field relations between Tertiary magmatism and Tintic-type ore deposits, East Tintic Mountains, Utah. In: Raines, G. L., Lisle, R. E., Schafer, R. W. & Wilkinson, W. H. (eds) *Geology and Ore Deposits of the Great Basin*. Reno: Geological Society of Nevada, pp. 461–483.
- Hattori, K., 1987. Magnetic felsic intrusions associated with Canadian Archean gold deposits. *Geology* **15**, 1107–1111.
- Hattori, K., 1993. High-sulfur magma, a product of fluid discharge from underlying mafic magma: evidence from Mount Pinatubo, Philippines. *Geology* **21**, 1083–1086.
- Hildreth, E. W., 1977. The magma chamber of the Bishop Tuff: gradients in temperature, pressure, and composition. Ph.D. Dissertation, University of California, Berkeley.
- Hook, C. J., 1995. Magmatic sulfides in intermediate to mafic volcanic rocks contemporaneous with ore-related plutonism at Bingham, Utah. M.S. Thesis, University of Georgia, Athens.
- Irving, A. J., 1980. Petrology and geochemistry of composite ultramafic xenoliths in alkali basalts and implications for magmatic processes in the mantle. *American Journal of Science* **280-A**, 389–426.
- Keith, J. D., Dallmeyer, R. D. & Kowallis, B. J., 1989. Latite with magmatic pyrrhotite: a possible precursor to monzonite-related alteration/mineralization in the East Tintic Mountains, Utah. *Geological Society of America, Abstracts with Programs* **21**, 100.
- Keith, J. D., Dallmeyer, R. D., Kim, C. S. & Kowallis, B. J., 1991. The volcanic history and magmatic sulfide mineralogy of latites of the central East Tintic Mountains, Utah. In: Raines, G. L., Lisle, R. E., Schafer, R. W. & Wilkinson, W. H. (eds) *Geology and Ore Deposits of the Great Basin*. Reno: Geological Society of Nevada, pp. 461–483.
- Kim, C. S., 1992. Magmatic evolution of ore-related intrusions and associated volcanic rocks in the Tintic and East Tintic Mining Districts, Utah. Ph.D. Dissertation, University of Georgia, Athens.
- Lindgren, W. & Loughlin, G. F., 1919. Geology and ore deposits of the Tintic mining district, Utah. *US Geological Survey Professional Paper* **107**.
- Lovering, T. S., 1949. Rock alteration as a guide to ore—East Tintic district, Utah. *Economic Geology Monograph* **1**.
- Lowenstern, J. B., 1993. Evidence for a copper-bearing fluid in magma erupted at the Valley of Ten Thousand Smokes, Alaska. *Contributions to Mineralogy and Petrology* **114**, 409–421.
- Luhr, J. F., Carmichael, I. S. E. & Varecamp, J. C., 1984. The 1982 eruptions of El Chichon volcano, Chiapas, Mexico: mineralogy and petrology of the anhydrite-bearing pumices. *Journal of Volcanology and Geothermal Research* **23**, 69–108.
- Moore, W. J., 1973. Igneous rocks in the Bingham mining district, Utah. *US Geological Survey Professional Paper* **629-B**.
- Moore, D. K., 1993. Oligocene East Tintic volcanic field, Utah: geology and petrogenesis. M.S. Thesis, Brigham Young University, Provo, Utah.
- Moore, W. J. & Mckee, E. H., 1983. Phanerozoic magmatism and mineralization in the Tooele $1 \times 2^\circ$ quadrangle, Utah. *Geological Society of America Memoir* **157**, 183–190.
- Morris, H. T. & Lovering, T. S., 1979. General geology and mines of the East Tintic mining district, Utah and Juab Counties, Utah. *US Geological Survey Professional Paper* **1024**.
- O'Brien, H. E., 1991. Eocene potassic magmatism in the Highwood Mountains, Montana: petrology, geochemistry, and tectonic implications. *Journal of Geophysical Research* **96**(B8), 13237–13260.
- Presnell, R. D., 1992. Local and regional geology of the Oquirrh Mountains. In: Wilson, J. R. (ed.) *Field Guide to Geologic Excursions in Utah and Adjacent Areas of Nevada, Idaho, and Wyoming*. *Utah Geological Survey Miscellaneous Publication* **92-3**, 293–306.
- Tingey, D. G., Christiansen, E. H., Best, M. G., Ruiz, J. & Lux, D. R., 1991. Tertiary minette and melanephelinite dikes, Wasatch Plateau, Utah: records of mantle heterogeneities and changing tectonics. *Journal of Geophysical Research* **96**(B8), 13529–13544.
- Waite, K. A., 1996. Petrogenesis of the volcanic and intrusive rocks associated with the Bingham porphyry Cu–Mo deposit, Utah. M.S. Thesis, Brigham Young University, Provo, Utah.
- Waite, K. A., Keith, J. D., Christiansen, E. H., Whitney, J. A., Hattori, K., Tingey, D. G. & Hook, C. J., 1997. Petrogenesis of the volcanic and intrusive rocks associated with the Bingham porphyry Cu–Au–Mo deposit, Utah. *Society of Economic Geologists, Oquirrh Symposium, Special Volume*. In press.
- Wallace, P. & Carmichael, I. S. E., 1992. Sulfur in basaltic magmas. *Geochimica et Cosmochimica Acta* **56**, 1863–1874.
- Warnaars, F. W., Smith, W. H., Bray, R. E., Lanier, G. & Shafiqullah, M., 1978. Geochronology of igneous intrusions and porphyry copper mineralization at Bingham, Utah. *Economic Geology* **73**, 1242–1249.

- Wendlandt, R. F., 1982. Sulfide saturation of basalt and andesite melts at high pressures and temperatures. *American Mineralogist* **67**, 877–885.
- Westrich, H. R. & Gerlach, T. M., 1992. Magmatic gas source for the stratospheric SO₂ cloud from the June 15, 1991, eruption of Mount Pinatubo. *Geology* **20**, 867–870.
- Whitney, J. A., 1984. Fugacities of sulphurous gases in pyrrhotite-bearing silicic magmas. *American Mineralogist* **69**, 69–78.
- Whitney, J. A. & Stormer, J. C., Jr, 1983. Igneous sulfides in the Fish Canyon Tuff and the role of sulfur in calc-alkaline magmas. *Geology* **11**, 99–102.