Arizona Geological Society Digest 22
2008

# Exploration of genetic links between breccia pipes and porphyry copper deposits in a Laramide hydrothermal system, Sombrero Butte, Pinal County, Arizona, USA

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## ABSTRACT

**Breccia pipes represent relatively small but high-grade ore bodies that are also of interest because of their suspected link to an underlying porphyry copper deposit. There are more than one dozen breccia pipes in the Sombrero Butte area of the Copper Creek mining district of southern Arizona. Breccia pipes crop out with circular- to oval-shaped map patterns, 10-20 m in diameter, which extend over 0.5 km vertically and tend to narrow at depth. The rake of the pipes varies between vertical to plunging 10-20 degrees from vertical. Mineralization is concentrated within the pipes, with higher-grade material located at the outer edges just inside the highly fractured ring structures surrounding the pipe. Copper grades drop significantly in the surrounding unbrecciated granodiorite.**

**Detailed mineralogy and alteration evidence seen in a 645 m length of drill core and in thin sections provides support for the hypothesis that the breccia pipes are underlain by a porphyry copper system. The local presence of porphyry dikelets as breccia matrix, hypersaline fluid inclusions, K-feldspar + shreddy biotite + rutile ± andalusite alteration, and chalcopyrite + bornite mineralization are indications of a link to an underlying porphyry copper deposit.**

**Breccia pipe formation is related to evolution of an underlying magma chamber. In a favored model, magmatic fluids exsolve from the magma and rise and collect as one or more large bubbles at the roof of the chamber. As more fluid accumulates and the fluid bubble increases in size, the roof of the chamber eventually can no longer support the weight of the overlying rocks. Collapse of the overlying rocks begins, and the breccia pipe propagates upward toward the surface. This porous column of collapsed rock is a conduit of open spaces and fractures, through which aqueous magmatic fluids can easily travel and produce high concentrations of copper mineralization. The aqueous magmatic fluids are thought to be the same composition as those that produce porphyry copper deposits, leading to the conclusion that such a system might be present at depth beneath the breccia pipes.**

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Eichenlaub, A.B., and Seedorff, E., 2008, Exploration of genetic links between breccia pipes and porphyry copper deposits in a Laramide hydrothermal system, Sombrero Butte, Pinal County, Arizona, USA, *in* Spencer, J.E., and Titley, S.R., eds., Ores and orogenesis: Circum-Pacific tectonics, geologic evolution, and ore deposits: Arizona Geological Society Digest 22, p. 591-599.

## INTRODUCTION

Breccia pipes are common in porphyry systems, though classic porphyry-style mineralization has not yet been found in all districts where breccia pipes are known (Sillitoe, 1985). The abundance of breccias in porphyry systems ranges from absent to incidental occurrences to ubiquitous, but the controls on this variability are poorly understood. The descriptive types of breccias in porphyry systems vary widely, and genetic models for the various types have been proposed (e.g., Sillitoe, 1985; Seedorff et al., 2005). In terms of potential to host ore-grade mineralization, the most important type of breccia is open-space filling, hydrothermally cemented breccia, in which metals are precipitated from hydrothermal fluids of dominantly magmatic origin. The origin of this type of breccia remains speculative (e.g., Norton and Cathles, 1973), in part because there are relatively few detailed studies of breccia pipes (e.g., Perry, 1961; Zweng and Clark, 1995; Vargas et al., 1999; Marsh, 2001). Detailed studies of breccia pipes are needed to improve the understanding of the relationship between breccia pipes and potentially underlying porphyry systems and to predict the location of porphyry systems in districts that have dozens of breccia pipes.

The Sombrero Butte breccia pipe system is located at the southern end of the Copper Creek (Bunker Hill) mining district in the Laramide porphyry copper province of southwestern North America (Titley, 1982). The Copper Creek district is located 65 km north of Tucson, on the western side of the Galiuro Mountains in Pinal County, Arizona (Fig. 1). Copper Creek district is a classic breccia pipe district (Kuhn, 1941; Sillitoe, 1985) that contains more than 500 breccia pipes (Marsh, 2001). The breccia pipes that are known to contain high grades of copper and molybdenum include the Copper Creek, Childs-Aldwinkle, Mammoth, and Old Reliable pipes, all of which lie north of the Sombrero Butte part of the district. Deep drilling in the 1960s and 1990s also delineated large volumes of lower grade, porphyry copper mineralization (Guthrie and Moore, 1978; Marsh, 2001). Currently, Red Hawk Resources is attempting to develop the Copper Creek portion of the district, while Bell Resources is exploring the long-dormant Sombrero Butte end of the district.

The Sombrero Butte system offers strong indications that breccia pipes are genetically linked to larger hydrothermal systems. Breccia pipes at Sombrero Butte extend to depths of 0.5 km, at which point they enter a classic porphyry copper environment. These pipes are visible at the surface as circular to oval shaped outcrops and are nearly vertical to plunging 10-20 degrees from vertical. Breccia pipes are typically surrounded by a circular set of ring fractures that have captured and directed fluid flow in the breccia column and ultimately allowed for deposition of high-grade copper mineralization. Mineralization within the breccia pipes grades from a thick leached cap near the surface, to a zone of supergene mineralization containing chrysocolla + chalcocite, to deeper mixed supergene-hypogene mineralization with chalcocite + bornite + chalcopyrite, and finally into solely hypogene mineralization in the underlying granodiorite host rock. Alteration is dominated by hydrothermal K-feldspar, which becomes increasingly pervasive at depth. Although drilling to date is relatively limited in the Sombrero Butte area, evidence suggests that breccia-pipe formation, mineralization, and alteration resulted from deep underlying porphyry copper mineralization.

The Copper Creek mining district is underlain by Cretaceous sedimentary rocks which have been covered by a series of volcanic tuffs and flows, which were then intruded by a series of granitic to dioritic plutons. The Copper Creek Granodiorite intruded the Cretaceous rocks and is the main host rock for the breccia pipes and related porphyries at Sombrero Butte. Tertiary andesitic dikes and basaltic lava flows are the youngest, post-mineral rocks of the area. The district lies along a northwest to southeast trend of Laramide porphyry copper centers in Arizona. Structural features do not have a significant effect on the breccia pipe system. The main structures of importance are the syn-formation ring fractures that form a halo around the pipes and act as a trap for fluids circulating through the pipe and add to the localization of ore-grade mineralization.

## BRECCIA PIPES

There are numerous breccia pipes in the district. This section focuses on details of the Campstool and Magna breccia pipes at Sombrero Butte. An introduction to the abundance, geometry, and dimensions of the pipes is followed by sections detailing the weathering profile, fabric of breccias, hypogene alteration, and grade distribution.

### Abundance, geometry, and dimensions of breccia pipes

The >500 breccia pipes in the Copper Creek district range in width from 1 to 250 m (Marsh, 2001). At Sombrero Butte there are 12 breccia pipes that crop out at the surface (Fig. 1). The surface expression of the pipes is quite variable, ranging in diameter from <5 m to 20 m. At the surface several pipes crop out in conspicuous oxidized knobs, whereas other pipes are merely 1-m sized rocky veneers on the surface. The diameter of the breccia pipes tends to mimic the surface expression within the upper 100 m but then begins to narrow at depths of 200-300 m. In other cases, pipes can show signs of a bulge or thickening at depths of ~140 m. Due to the limited drilling at Sombrero Butte, this aspect is only a preliminary observation, but in general pipes elsewhere in the Copper Creek district tend to narrow with depth. In the majority of cases, the pipes are almost vertical, with fairly consistent cylindrical shapes (Fig 2).

This study focuses on the Campstool and Magna pipes located in the center of the Audacious claim (Fig. 1). The other known pipes in the Sombrero Butte area are the Audacious, Sunset, Rattler, Maverick, Victors, and Saguaro, along with four other unexplored pipes.

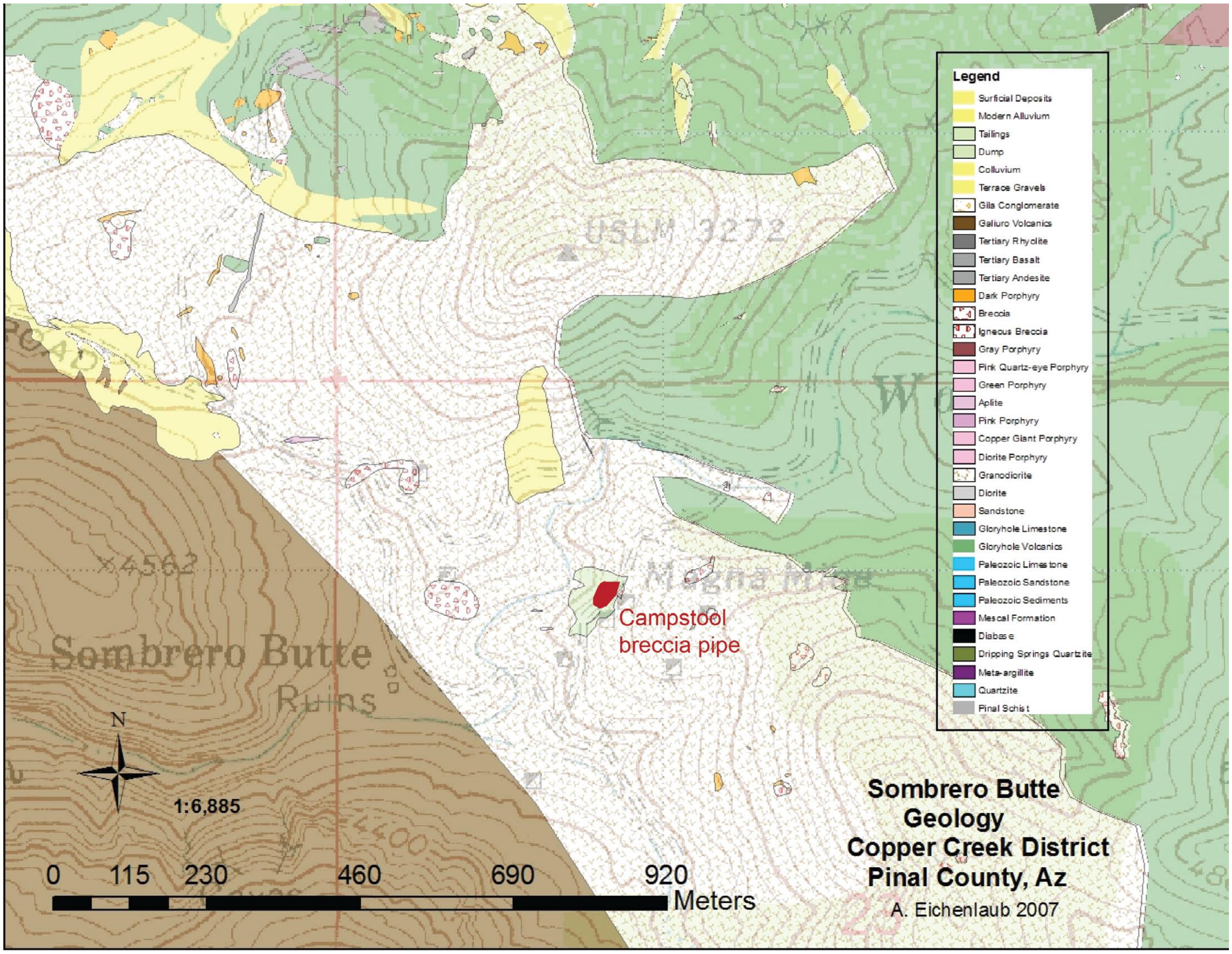


Figure 1. Geologic Map of Sombrero Butte, Copper Creek District, Pinal County, Arizona.

## Weathering profile

The sulfide and oxide mineralogy is consistent between several different pipes at Sombrero Butte. The majority of pipes have an upper leached cap that extends to a depth of approximately 270 m and that is composed of strong earthy, red hematite, purple to red specularite, and trace amounts of glassy cuprite. The relative amounts of these minerals vary between pipes. In most cases, there is only minor copper mineralization within the leached zone, occurring as sooty chalcocite and trace native copper. The extensive leached interval indicates that there has been strong weathering of the breccia and that supergene copper is likely to occur deeper in the breccia pipe. The granodiorite clasts within the leached cap show continued evidence of weathering with the plagioclase sites altering to white clays. Weathering of plagioclase sites is very common in the pipes, but is most prevalent in the leached zone.

Below the leached cap from 270 to 330 m there is a transition from weak hematite to hematite intermixed with moderately disseminated chalcocite. This zone is followed by a 90-m interval from 330-420 m of varying, minor amounts of bornite + chalcocite + chrysocolla ± cuprite. A 70-m interval of moderate chalcocite occurs from 420-490 m downhole with a 22-m-thick interval of 1.31% total copper. Below 490 m, the breccia has bornite – chalcopyrite – chalcocite mineralization at grades of 0.2-1% Cu that continues down into the granodiorite and does not taper off in grade until 610 m where grades decrease to <0.1% Cu.

## Fabric of breccias

The breccia pipes are composed of three major parts, the clasts, matrix, and cement. The clasts are the individual fragments from the surrounding or vertically transported wall rock and occur as rounded to angular slabs. The clasts are accompanied by either matrix or cement. The matrix is a fine

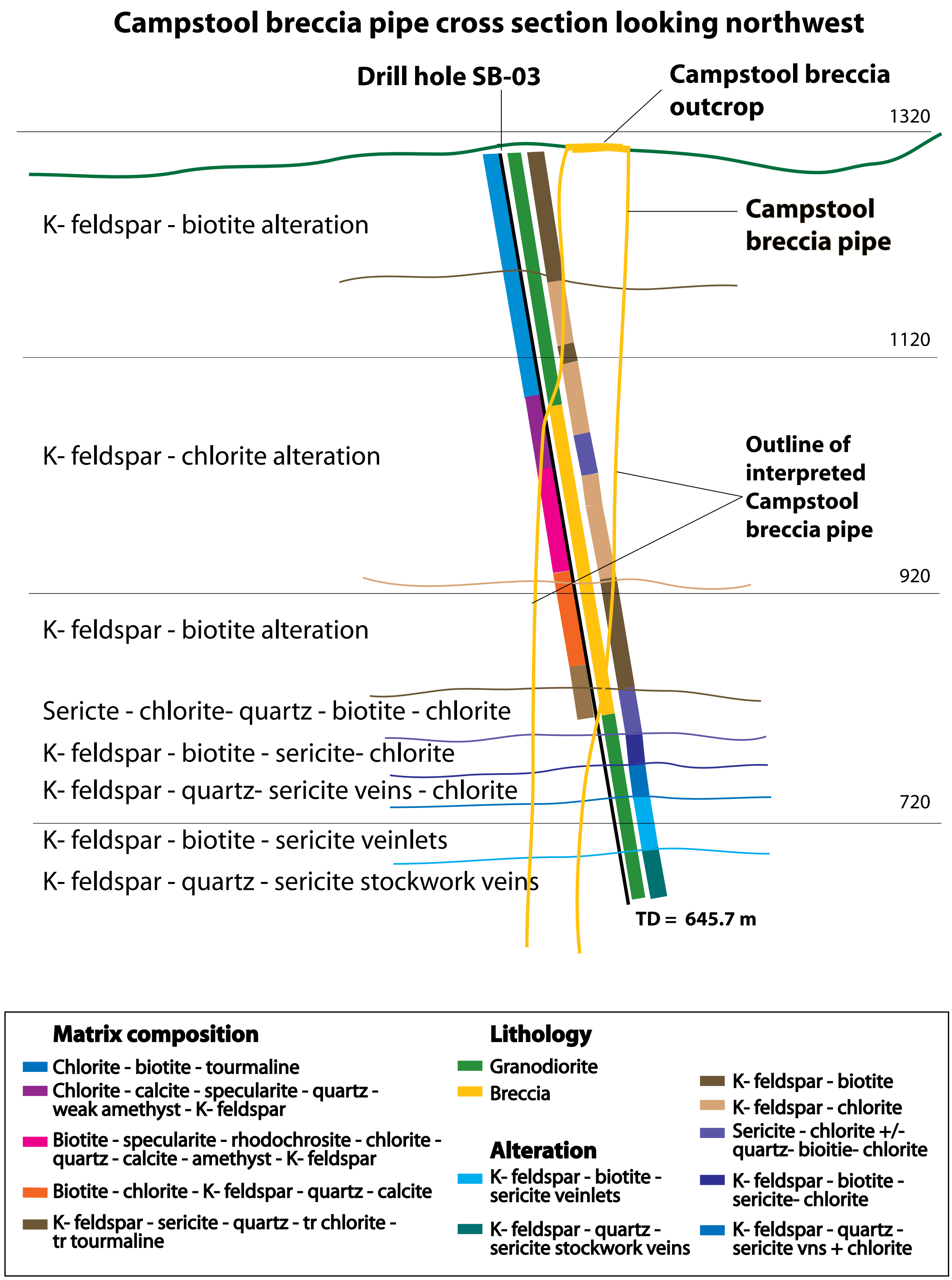


Figure 2. Generalized geologic cross section of the Campstool breccia pipe in the Sombrero Butte area, looking northwest. Center column represents lithology, left column represents matrix composition, and right column represents alteration. Horizontal colored lines outline interpretation of alteration zones and yellow line shows interpretation of pipe.

grained, clastic material derived from wall rock that encloses or fills the interstices between the larger clasts, whereas the cement precipitated in the interstices of the clasts and matrix is commonly fine grained, but coarse grained crystals occasionally line large, open-space cavities. The occurrence of clast- versus matrix-supported breccia is quite variable and does not appear to have any consistent pattern within the pipes, although current data shows that clast-supported breccia is more abundant.

**Clasts.** Clast composition in the pipes at Copper Creek can be heterogeneous, with clasts of both Copper Creek granodiorite and Glory Hole Volcanics (Marsh, 2001). At Sombrero Butte, clasts are dominantly composed of granodiorite. Clasts range in size from 2 cm to 20 m and can be rounded to angular in shape. In the core of the pipes, the clasts typically are rounded and show slight rotation, whereas the angular, slab-like clasts tend to occur at the margins of the pipes. It is also common to find 1-2 cm diameter clasts in the matrix surrounding larger, 10-cm diameter clasts. The margins of clasts can be sharp to ragged and either have K-feldspar or calcite rims. Clasts themselves can be fractured but overall do not show evidence of rotation or for the breccia pipes themselves having been affected by faulting. Clasts also contain veins that appear to be original to the rock in its previous state, because the veins are truncated at the margins of the clasts. In other cases, clasts are crosscut by veins of calcite or quartz that have developed within the breccia-pipe environment.

**Matrix-supported breccia.** Matrix-supported breccia is typical in the upper portions of the pipes. In the upper parts of pipes, the clast size is usually much smaller, 1-5 cm, with angular shapes and commonly exhibiting shingling. The clasts in matrix-supported breccia also tend to show clearer evidence of the effects of brecciation, pealing away the wall rock and piling up, hence creating the fabrics commonly referred to as shingle breccia (Sillitoe, 1985). Shingle and matrix-supported breccias are observed in other parts of the pipes but cannot be correlated between pipes in the area.

On average there tends to be 2-10 volume percent matrix. In the matrix-supported breccia, the common assemblage is dominantly chlorite + calcite + specular hematite + quartz ± K-feldspar ± tourmaline ± amethyst (Fig 2). Observation of drill core samples shows a medium to dark green matrix, reflecting a large amount of chlorite in the samples. The calcite + specular hematite + amethyst are cement that precipitated at a later stage within the breccia. Unfilled open-space between clasts is also common but typically is observed at deeper levels within the pipe. Open-spaces most often contain calcite lining vugs between clasts. Amethyst and rhodochrosite are also more common in open spaces at depths of 240-410 m. The presence of tourmaline has also been observed in several pipes occurring as matrix mixed with silica – quartz in non-mineralized pipes, as cement with bornite + chalcopyrite, as hairline veinlets, and blebs.

**Clast-supported breccia.** Clast-supported breccia is common throughout all the pipes at Sombrero Butte, but generally occurs below the upper 40-80-m thick interval of matrix-supported breccia. Clast-supported breccia contains clasts that are subrounded to angular and have a variety of sizes ranging from 2 cm to 20 m. In clast-supported breccia it appears that clasts were rotated, which accounts for their subrounded nature. There is only minimal evidence for splaying of wallrock, which occurs as narrow zones of shingle breccia within the main body of clast-supported breccia. The clasts are commonly crowded with little matrix between or occur with narrow mm-sized, calcite-lined cavities as cement.

### Hypogene alteration of clasts and wall rocks

The granodiorite wallrock surrounding the breccia pipes shows consistent alteration with depth. Plagioclase phenocrysts and groundmass that are K-feldspar altered to varying degrees compose the granodiorite. The mafic sites in the grandiorite show the most obvious alteration with hornblende phenocrysts altered to biotite and biotite phenocrysts altered to chlorite. In more extreme cases sericite alteration occurs along the edges of chlorite and biotite. The granodiorite does show increased alteration within 2-10 m of a breccia pipe and shows a strong magnetic signature. Granodiorite becomes increasingly altered, with biotite and chlorite altered to sericite, and the magnetic signature diminishes. This appears to be consistent with depth along the breccia pipes.

Alteration is mostly associated with the clasts and causes plagioclase to alter to K-feldspar and commonly sericite. Granodiorite clasts throughout the pipes have 0.2-0.5-cm-thick alteration rims, where plagioclase has been replaced by K-feldspar. These clasts are also strongly stained by hematite in their core, which grades outward to the altered rim. Rarely are granodiorite clasts unaltered. In the cases with the least alteration, biotite is slightly altered to hydrothermal biotite or to chlorite. Clasts can exhibit complete destruction of their shape by sericitic alteration with only faint ghosts of the clast remaining. Figure 2 shows a generalized cross section with matrix composition and alteration plotted downhole.

The magnetite that is typically present in the surrounding granodiorite host rock is completely destroyed in clasts within the pipes. Observations of drill core have revealed a characteristic magnetic signature in the system. The granodiorite surrounding pipes typically has a magnetic susceptibility of 20-40 SI, whereas breccia pipes show virtually no susceptibility. Leaching of the breccia pipes during weathering has altered the majority of the original magnetite within the granodiorite clasts. Magnetic susceptibility remains very high in the granodiorite host and begins to drop off significantly in altered granodiorite 1-2 m outside of the margin of a pipe. Within the breccia pipe the susceptibility is below 10 SI and typically undetectable.

Another important characteristic of breccia pipes is their associated tungsten halo. Drill hole SB-03 shows <4-10 ppm tungsten in granodiorite, but at 224 m there is an increase to 62 ppm tungsten which is associated with changing rock type and approach to a breccia pipe. Tungsten levels within the breccia pipe average 19 ppm, with a range of 10-62 ppm. At 492 m a decrease to <10 ppm in tungsten is observed and the drill hole enters the granodiorite host rock. The source of tungsten is presumed to be scheelite, but has not been identified.

Microprobe analysis was used to confirm alteration patterns within samples taken from the Magna and Campstool pipes (Eichenlaub, 2007). The matrix present in the Magna pipe from drill holes SB-02 and SB-06 was analyzed and shows fresh biotite along with hydrothermal biotite with increased magnesium, aluminum, and iron content. The secondary biotite is located at depths of 272-359 m within the Gray Porphyry matrix that occurs in the breccia. The Magna pipe also contains albite within the matrix, which indicates increased sodium content. This increase in sodium, iron, magnesium, and aluminum indicates that hydrothermal fluids have affected these rocks and may be associated with the sulfide-bearing fluids.

The alteration rims associated with clasts from the Magna pipe were also analyzed. The 4-mm thick alteration rims are K-feldspar with a 1 mm-thick chlorite alteration rim just inside. This granodiorite clast also contains chlorite-altered biotite with rutile.

Microprobe analyses for the Campstool pipe also confirmed hydrothermal alteration. At 231.43 m chlorite-rich matrix with minor rutile was confirmed. Deeper portions of the breccia at 457 m showed an increase in biotite content within matrix. By 475.2 m, clast alteration is dominated by K-feldspar with some fresh igneous biotite, with minor biotite altered to chlorite. Tourmaline was also found in the matrix at these depths indicating the presence of boron. The alteration shows slight variations downward, with various amounts of chlorite + biotite + K-feldspar + albite ± sericite ± tourmaline, with an increase in abundance of chalcopyrite. At depths of 598.8 m in the granodiorite, the K-feldspar is the dominant alteration mineral, with the abundance of chlorite + biotite diminished. Microprobe results also confirm an increase in aluminum at these depths, which is associated with aluminosilicates. The increased aluminum content along with observations of greenish kaolinite ± chalcopyrite ± pyrite suggests the possible presence of intermediate argillic alteration.

## Grade distribution

The copper grade within breccia pipes is variable vertically and horizontally. The pipes at Sombrero Butte show high concentrations of copper in the form of bornite, chalcocite, chalcopyrite, chrysocolla, and conichalcite. Pipes mineralized with chrysocolla and conichalcite typically occur near the surface, extend to depths of 80 m, and are contained within the oxidized portion of the supergene environment (e.g., Anderson, 1982). Disseminated chalcocite is present at greater depths in the supergene sulfide environment, but commonly in association with hypogene sulfides. Although the grades are locally enriched in chalcocite-bearing rocks, the lateral and vertical extent of enrichment is more limited than in most porphyry copper settings (e.g., Anderson, 1982; Sillitoe, 2005). From 272-294 m, grades of 0.58% Cu occur as a mixture of chalcocite + bornite + chrysocolla ± cuprite. From the oxidized portion of the supergene zone, the mineralization proceeds downward into a zone where supergene chalcocite occurs with hypogene minerals as bornite + chalcopyrite + chalcocite + pyrite. The highest grade mineralization in the Campstool pipe occurs at 470-492 m as 1.31% Cu in the form of bornite + chalcopyrite in clast-supported breccia. This interval also contains a smaller high grade interval from 480-492 m of 2.06% Cu as bornite + chalcopyrite. In this 22-m-wide zone, the majority of the bornite + chalcopyrite occurs disseminated in the cement between clasts, but also occurs within the clasts themselves to a limited extent.

There is limited data concerning the lateral distribution of mineralization due to the predominance of exposure by steep to vertical drill holes. From observations of outcrops, it is clear that mineralization along the edges of the pipes tends to be higher grade than within the core of the pipe. It appears in some cases where ring fractures are exposed that mineralization is strongly concentrated along these vertical fractures parallel to the pipes. This relationship is observed in several pipes at Sombrero Butte, including the Victors pipe, where the ring fractures contain tourmaline + bornite + chalcopyrite. Mineralization within the breccia pipes dominantly occurs as cement in the interstices between the clasts. In extreme cases, the combined matrix + cement can be entirely composed of sulfides ± quartz or calcite. There is minor mineralization observed in the clasts themselves although it is not uncommon to find sulfide veins crosscutting clasts, but disseminated sulfides are not typical within the clasts. This observation suggests that mineralization is closely associated with the cement that precipitated between the clasts.

The deepest drilled zone of mineralization, from 492-645 m, is composed of strong to moderate amounts of chalcopyrite with associated weak bornite. This deep zone of mineralization crosses from the breccia into the underlying granodiorite.

The underlying granodiorite continues to show consistent mineralization in the form of chalcopyrite as observed in the breccia. At depths of 500 m the granodiorite has stockwork style veins of quartz – K-feldspar – chalcopyrite, which extends to a depth of 610 m. From 610-645 m quartz – K-feldspar veins continue as thin, hairline veinlets with minor chalcopyrite. The veins present throughout the granodiorite are associated with pervasive K-feldspar flooding.

# DISCUSSION

This discussion addresses how breccia pipes are formed, how breccia pipes occur, what types of environments they may be associated with, the types of fluids that were associated with them, what the source of the fluid may have been, and the nature of copper-bearing breccia pipes.

### Mechanism of breccia pipe formation

Breccia pipes contain a considerable amount of open space, especially prior to precipitation of the hydrothermal minerals that are the cement. A fundamental problem in the formation of breccia pipes is the origin of this void space. Hypotheses for generating void space include (1) withdrawal of magma from beneath the site of the breccia pipe (Perry, 1961), (2) dissolution of roof rocks by a corrosive hydrothermal fluid released from an underlying magma chamber (Sillitoe and Sawkins, 1971), (3) doming of roof rocks during fluid release (Burnham, 1985), and (4) exsolution of magmatic fluids from a deep-seated magma body, first rising as dispersed bubbles and then collected in a large cavity near the roof of a magma chamber underlying the site of the breccia pipe (Norton and Cathles, 1973). Each model makes predictions that, in principle, can be tested by observations regarding, for instance, shape of the breccia pipe, directions of clast transport, relationship to porphyry mineralization, or fluid composition and properties. The fourth model shows that the roof of the cavity at some point could no longer withstand the weight of the overlying rocks, leading to collapse of the overlying rocks and associated brecciation, which propagated upward toward the surface.

In earlier studies of breccias in the Copper Creek district, Guthrie and Moore (1978) suggested that breccia pipes are formed by forceful injection of porphyry into brittle rock, whereas Kuhn (1941) proposed faulting as the cause of brecciation. Both interpretations lack an explanation for how void space was created for these circular- to oval-shaped bodies, 10-20 m in diameter, as faulting does not necessarily generate open-space, and magma withdrawal must follow forceful injection in order to generate a void. Among the hypotheses that do generate open space, (1) withdrawal of magma can be substantiated only if a lateral migration of the withdrawn magma can be demonstrated. One of the few compelling historical examples of lateral magma withdrawal was at the Valley of Ten Thousand Smokes, Alaska, in 1912, which produced crater (small caldera) collapse at Mt. Katmai during a 60-hr pyroclastic eruption at Novarupta 10 km to the east (Hildreth and Fierstein, 2000), with no obvious relationship to mineralized breccia-pipe formation. Hence, this first mechanism is, at best, an ad hoc explanation for Copper Creek. (2) Certain hydrothermal fluids are indeed corrosive, the mineralogic characteristics of Sombrero Butte show no evidence for massive dissolution, for instance of quartz, and indeed, the fluids that produced the breccia pipe appear similar to those that produce porphyry copper deposits with or without breccia formation. The final two mechanisms both involve localized separation of an aqueous phase, leading to (3) doming of the roof or (4) formation of a giant bubble. Although the geologic constraints are poor at the few pipes studied to date at Sombrero Butte, no evidence has been reported of doming of the roof at any of the hundreds of breccia pipes at Copper Creek; furthermore, mechanism (3) does not distinguish between formation of hydrothermally cemented breccia pipes such as the ones at Copper Creek and porphyry deposits without associated breccias. Thus mechanism (3) is rejected as a valid explanation, leaving mechanism (4)--or some other mechanism—as the most viable explanation. Mechanism (4), however, also requires a means of distinguishing between porphyry systems and breccia pipes, as explored further below.

### Separation and collection of an aqueous phase

Formation of ore deposits requires a mechanism for concentrating the ore elements, and formation of an aqueous phase provides for the opportunity to fractionate metals preferentially into a separate aqueous phase, for ultimate precipitation in a hydrothermal ore deposit (e.g., Candela and Piccoli, 2005).

The suite of magmatic-hydrothermal ore deposits, including porphyry systems, greisen deposits, and certain epithermal deposits, are ancient examples of formation of a separate aqueous phase of magmatic derivation, preferential fractionation of certain metals into the aqueous phase depending on the composition of the magma, and precipitation of metals as the hydrothermal fluid evolves in time, space, temperature, etc. (Rose and Burt, 1979; Barton, 1996; Seedorff et al., 2005). A present-day example of separation and collection of a separate, sulfur-rich vapor occurred in the pre-eruptive activity at Mount Pinatubo, Philippines, which was betrayed by the “excess sulfur” of the eruption, i.e., more sulfur in the eruptive cloud than can be accounted for by exsolution from an equivalent volume of magma (Hattori, 1993; Gerlach et al., 1996; Keppler, 1999). As noted by Hattori and Keith (2001), this accumulation of an aqueous phase is a forerunner of the formation of a porphyry system or other magmatic-hydrothermal deposit such as a breccia pipe. Furthermore, Mt. Pinatubo is a compositionally appropriate modern analogue of a porphyry copper or copper breccia pipe.

The nature of the distribution of the aqueous phase could determine whether or not the system leads to the formation of a breccia pipe, rather than a porphyry system.

### Conditions leading to preferential formation of breccia pipes

The distribution of the separate aqueous phase could exert a strong influence on the mechanical behavior of the two-phase mixture of magma and vapor. In the first case, the separate aqueous phase could be localized at the roof of the magma chamber but be dispersed at relatively low concentrations, forming a sponge-like distribution of bubbles. The bulk density and mechanical behavior of this mixture could be similar to magma prior to water saturation. This material would be likely to support the weight of overlying rocks, preventing eruption of the magmatic-hydrothermal system or formation of a breccia pipe but causing hydrofracturing of the surrounding rocks and formation of a porphyry system (Burnham, 1979). In a second case, the aqueous phase could be highly concentrated in the two-phase mixture at the roof of the magma chamber, forming a foam-like cap or consist of one or more large bubbles. The density and mechanical behavior of the second mixture may approximate that of the pure aqueous phase and be unable to support the weight of overlying rocks, leading to formation of an upward-propagating breccia pipe (Norton and Cathles, 1973).

The above hypothesis calls for an explanation for why the two types of systems might occur in nature. Perhaps a subtle magmatic compositional control favors formation of breccia pipes, rather than only porphyry systems. For example, an enriched concentration in a volatile, perhaps boron, could promote the aggregation of the aqueous phase into large bubbles, thus favoring formation of breccia pipes. Speculatively, the virtually ubiquitous presence of tourmaline, a boron-bearing mineral, in breccia pipes might be evidence for such a compositional control. On the other hand, may be there is no magmatic compositional control, and other factors, such as depth of emplacement or tectonic regime, could catalyze breccia-pipe formation.

A viable explanation for formation of breccia pipes must account for the similarity in fracturing characteristics in breccia pipes with those of porphyry systems, as well as the fact that some districts contain both breccia pipes and porphyry systems, as at Copper Creek (Marsh, 2001) and Cananea (Wodzicki, 2001). In addition, a mechanism must predict the occurrence of tens to hundreds of pipes, commonly in trends and clusters, in the classic breccia-pipe districts, such as Copper Creek (Marsh, 2001), Copper Basin (Johnston and Lowell, 1961), and Cumobabi (Scherkenbach et al., 1985). In any case, it remains unclear why some porphyry copper deposits have closely associated breccia pipes and other deposits in the same porphyry province do not have breccia occurrences.

### Significance of breccia pipes to exploration for porphyry systems

Breccia pipes represent relatively small but high-grade deposits that can be highly attractive exploration targets in their own right. Empirically, many breccia pipes do show a spatial, if not genetic, relationship to underlying porphyry mineralization (Bryner, 1961; Sillitoe, 1985). If there is a close genetic relationship between breccia pipes and porphyry systems, then mineralized breccia pipes potentially represent a valuable clue to the location of porphyry mineralization at depth. If a genetic link is weak or absent, however, then the breccia pipes have little or no relevance to exploration for deep porphyry copper deposits, as Sillitoe and Sawkins (1971) concluded for many of the breccia pipes in central and northern Chile.

As documented above, the present understanding of the geology of the Sombrero Butte pipes suggest a genetic link between the pipes and an underlying porphyry system, but further work is required to evaluate the strength of this relationship.

## CONCLUSIONS

There are more than one dozen breccia pipes in the Sombrero Butte area of the Copper Creek district that crop out with circular- to oval-shaped map patterns, 10-20 m in diameter, which extend over 0.5 km vertically and tend to narrow with depth. Mineralization is concentrated within the pipes, with the highest grades located at the outer edges just inside the highly fractured ring structures surrounding the pipe. The breccia pipes are dominated by angular to subangular clasts of granodiorite that vary between clast- and matrix-supported. The combined matrix and cement varies from chlorite + calcite + specular hematite + quartz + amethyst + K-feldspar + rhodochrosite, to tourmaline + biotite + chlorite, to chlorite + sericite + hematite. The dominant alteration throughout the Campstool pipe is K-feldspar alteration, which becomes increasingly pervasive in the granodiorite host below the breccia pipes.

Gray Porphyry occurs in the matrix composition of the Campstool and Magna pipes, providing additional evidence for linking the origin of breccia pipes to magmatism. The continuation of potassic alteration of the breccia pipe downward into unbrecciated Gray Porphyry and granodiorite is suggestive of a genetic link to porphyry systems, which is consistent with the similarity in fluid inclusion compositions in porphyry deposits and breccia pipes.

In a favored model for formation of mineralized breccia pipes, magmatic fluids exsolve from the magma and rise and collect as one or more large bubbles at the roof of the chamber. As more fluid accumulates and the fluid bubble increases in size, the roof of the chamber eventually can no longer support the weight of the overlying rocks. The roof collapses, and the breccia pipe propagates upward, terminating before reaching the surface. The porous column of collapsed rock is a conduit of open spaces and fractures, and the highest copper grades form in the areas of highest permeability.

## ACKNOWLEDGMENTS

We would like to thank Bell Resources for graduate funding and analytical costs. Thank you to Timothy Marsh and Glen Zinn for comments and support and Rex L. Evatt III for assistance on the Sombrero Butte Project.

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