The Cripple Creek district is renowned for epithermal gold telluride veins which have produced over 22 million ounces of gold from an intensely altered diatreme complex (total production + economic resources of >1000 tons). The district is also renowned for its association with a rare class of alkaline igneous rocks. The volcanism at Cripple Creek was part of a regionally extensive episode of Oligocene magmatism, including large volumes of calc-alkaline rocks and smaller, but widely distributed alkaline centers. Amongst the mid-Tertiary alkaline intrusive complexes, only Cripple Creek is associated with a giant (>500 ton) gold deposit. Further study of the magmatic and hydrothermal evolution of these systems will be necessary to explain this apparent disparity in gold enrichment.

Cripple Creek’s gold mineralization principally occurs as telluride minerals hosted by swarms of narrow veins. Most geological studies over the last century have focused on the high-grade veins and to a lesser degree, adjacent hydrothermal alteration, but metasomatism is now shown to be broadly developed and demonstrably accompanied many events throughout the evolution of the igneous complex. Alteration types ranged from minor early pyroxene-stable varieties through various biotite-bearing assemblages into voluminous K-feldspar stable types. Hydrolytic (acid) styles of alteration are present but minor. Economic gold mineralization is intimately associated only with late, voluminous K-feldspar-pyrite alteration which affected >5 km³ of the explored portion (upper 1 km) of the complex. Although similar to other gold deposits related to alkaline magmatism, Cripple Creek differs markedly from other epithermal systems in terms of its large volume of K-feldspar added and paucity of quartz and acid alteration.

**Keywords:** alkaline, epithermal, Cripple-Creek-Colorado, phonolite, metasomatism, hydrothermal-alteration, tellurides, diatreme
INTRODUCTION

The Cripple Creek gold deposit in central Colorado is hosted by an Oligocene alkaline diatreme complex. Cripple Creek is distinguished from the majority of epithermal ore deposits in the region by its remarkable production record (~930 t Au production + economic reserves, geologic resource >> 1000 tons), its association with a rare class of igneous rocks (phonolitic-lamprophyric magmatism), and its unusual styles of mineralization. While the association between alkaline rocks and gold mineralization has been long recognized (Lindgren, 1933; Mutschler and Mooney, 1993, Richards, 1995; Jensen and Burton, 2000), a key question remains: why do alkaline igneous centers show a disproportionate relationship with large (>100 Mt) gold resources? Further insight will be gained from detailed studies of individual deposits such as Cripple Creek, and these studies will also benefit our understanding of the petrogenesis and geodynamic significance of this unusual class of igneous rocks.

One hundred years of geologic studies have accompanied the history of mining in the Cripple Creek district, with most activity taking place in the early twentieth century. Recent renewal of mining activity in the district (1994) affords new exposures and a wealth of new information from recent drill programs. New work coupled with reinterpretation of existing data reveals a complex and dynamic history of magmatic and hydrothermal activity and provides insight into the geologic evolution of central Colorado, and how large gold deposits form.

This paper is divided into several sections. The first discusses the Cenozoic tectonic evolution of the part of Colorado which hosts the Cripple Creek district, as well as styles of magmatism that were active in the region; this provides a context for an appreciation of the styles of magmatism seen at Cripple Creek. The regional overview is followed by a brief description of the alkaline igneous rocks in the Cripple Creek district, and discussion and description of the styles of mineralization and alteration. The paper closes with a time-space synthesis of magmatic and hydrothermal activity and a general discussion and summary.

REGIONAL GEOLOGY AND OVERVIEW

The Late Oligocene Cripple Creek diatreme was emplaced at the junction of several Precambrian units along the margin of the Pikes Peak batholith, at a time when both widespread alkalic and calc-alkaline magmatism were active throughout the region (Fig. 1). This period of volcanic activity was the product of dynamic activity in the lower crust and upper mantle (Johnson et al., 1990; Ricuputi and Johnson, 1990; Colucci et al., 1991; Johnson, 1991) which saw widespread production of diverse magma types.

Regional mid-Tertiary magmatism (40–25 Ma) in and around Colorado took place during a time of tectonic reconfiguration. Laramide compression had largely waned by ca. 40 Ma (Coney, 1976, 1978), and was followed by periods of tectonic “quiescence” or relaxation. Regional extension began in the mid-Tertiary, although the exact timing of the onset of regional extension remains a matter of debate. It is clear from a wide variety of evidence that rift-related basaltic magmatism was active along the axis of the Rio Grande Rift by 26 Ma. Chapin and Seager (1975) bracket the onset of extension in the Rio Grande Rift between episodes of magmatism at 31 and 28 Ma, and it is recognized that the earliest alluvial basin deposits are possibly 3–4 m.y. younger (Christiansen et al., 1992). Kelley and Duncan (1986) interpret a cluster of fission track ages from 30 to 35 Ma to reflect disturbance of basement rocks in the Sandia Range and Sangre de Cristo Mountains of New Mexico, possibly dating the incipient phases of extension. Elsewhere in the region, 31 Ma olivine basalts were erupted along with rhyolites along the rift axis, which appears to signal a transition to bimodal rift-related volcanism (Chapin and Seager, 1975; Elston, 1984). Collectively, these data were interpreted by Christiansen et al. (1992) to reflect the onset of regional extension between 35 and 30 Ma, becoming widely developed by 26 Ma. Although broadly coeval with magmatism at Cripple Creek, this tectonism has no obvious expression in the district except perhaps indirectly in the hydrology of the evolving hydrothermal system.

Tertiary Magmatism

Following the close of the Laramide Orogeny, significant magmatism initiated in areas of Laramide uplift in central Colorado (Mount Princeton region) and the San Juan Mountains. At Mount Princeton, large ignimbritic eruptives were generated between 33 and 36 Ma (Lipman, 2007). Beginning at ca. 35 Ma, pre-caldera stratovolcanoes in the San Juan Mountains erupted mainly andesitic lavas, followed by later generations of voluminous rhyolitic to quartz latitic ash flow units erupted from a series of caldera centers throughout the region (Lipman et al., 1970; Mutschler et al., 1987; Lipman, 2007). This major magmatic event is referred to as the “ignimbrite flare-up,” and marked a significant period of magma generation and crustal modification in the region. Large volumes of calc-alkaline magmas were produced, with activity focused in four major volcanic fields (San Juan Mountains, Colorado, Mount Princeton, Colorado, Thirty-nine Mile volcanic field, Colorado, Latir volcanic field, New Mexico), and at numerous other calc-alkaline magmatic centers (Fig. 1).

At the time of the alkaline magmatic activity at Cripple Creek (ca. 31 Ma), calc alkaline magmatism (ca. 30 Ma) was continuing in both the San Juan volcanic field and the nearby Thirty-nine Mile volcanic field (Fig. 1). The initial phases of magmatism in the Guffey area (Thirty-nine Mile volcanic field) resembled the volcanic successions in the San Juan volcanic field in their intermediate (andesitic) compositions. In contrast to the San Juan volcanic field however, the Thirty-nine Mile magmas were more alkaline, and the eruptive centers of the Thirty-nine Mile Volcanic field did not evolve to produce the large volumes of ignimbritic eruptives seen in the San Juan volcanic field. Although small volumes of silicic eruptives are associated with some of the centers,
later stage shoshonitic basaltic to trachytic magmatism distinguishes the Thirtynine Mile field. In addition to the Cripple Creek area, alkaline magmatism was also widespread in the region, and is manifested as relatively small centers throughout Colorado, Utah, and New Mexico. These centers are compositionally diverse, ranging from oversaturated, high-K granites and/or rhyolites to ultramafic lamprophyres. Extension continued throughout the Miocene and Pliocene, with alkaline basalts and their differentiates emplaced along the axis of the Rio Grande rift (e.g., Raton-Clayton volcanic field, Española Basin). Sporadic potassic to ultrapotassic magmatism also took place, principally along the flanks of the rift (Gibson et al., 1993) but as far east as the Two Buttes intrusive complex along the Colorado-Kansas border and as far west as the Colorado Plateau (Hopi Buttes–Navajo province). Alkaline magmatism in the western United States continues to the present time with Pliocene ultrapotassic intrusions in the Sierra Nevada southeast of Yosemite, and Quaternary ultrapotassic lamproites in the Leucite Hills of Wyoming. Quaternary alkaline basaltic intrusions have also produced numerous maar craters along the axis of the Rio Grande rift near Las Cruces, New Mexico, and El Paso, Texas.

**Interpretation**

In the case of the San Juan volcanic field, calculations by Colucci et al. (1991) show that significant volumes of mantle-produced (basaltic) magmas underwent differentiation and assimilation–fractional crystallization (AFC) to produce magmas of intermediate compositions. Isotopic and geochemical data and petrogenesis models suggest that the magmas were largely derived from the crust, with 10%–30% contributed by more primitive, mantle derived melts (e.g., Johnson et al., 1990; Johnson, 1991; Riciputi and Johnson, 1990). The progressive increases of εNd seen in more evolved compositions are explicable by progressive hybridization of lower crust through injection of mantle derived basalts (Colucci et al., 1991). Similar histories are inferred for other major calc alkaline volcanic fields in Colorado.

The compositional diversity seen amongst the regional alkaline igneous centers must reflect a spectrum in modes of petrogenesis. Petrogenetic models range from fusion of lower crustal materials in the case of the high-K granites associated with Mo-rich styles of mineralization at Henderson-Urad (Bookstrom et al., 1988; Carten et al., 1993), to mantle-dominated compositions in the case of alkaline basalts erupted along the axis of the Rio Grande rift. The interpretation continues to be refined through ongoing research.

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**Figure 1.** Generalized map showing the distribution of Oligocene magmatic centers in the greater Colorado area.
Grande Rift (Gibson et al., 1993). These alkaline events lack the large volumes of magma like those responsible for the calc-alkaline batholith-ignimbrite centers (at least as seen in the upper crust). Nonetheless, these alkaline centers reflect regionally significant modification of the lower crust and upper mantle as well as melt generation in chemically anomalous (lithospheric) mantle.

### Cripple Creek District Geology

The Cripple Creek district has a gold inventory in excess of 900 t Au, principally hosted by high-grade veins and bulk-mineable, lower grade disseminated ores in an intensely altered alkaline diatreme. The diatreme complex consists of an upward flaring volcanic neck filled by heterolithic volcanic breccia. Evidence demonstrates significant upward and downward transport during volcanism, including charcoal from trees >200 m below the surface. The diatreme is elliptical in shape, and is ~5 km in diameter. Within the diatreme is a complex series of alkaline intrusions, totaling perhaps hundreds of individual intrusive bodies. These form composite flows, dikes, sills, laccoliths, and dome-shaped features intruding diatremal volcanic breccias and the surrounding Precambrian rocks. Figure 2 shows a generalized geologic map of the Cripple Creek district.

#### Cripple Creek's Alkaline Rocks

The alkaline intrusions at Cripple Creek belong to a rare class of distinctively composed volcanic and intrusive igneous rocks. Distinctive features include high alkali concentrations at given levels of silica, and high concentrations of large ion lithophile elements (LILE), high field strength elements (HFSE), light rare earth elements (LREE), and CO₂ (carbonate minerals). These chemical signatures provide important clues about the source regions and modes of evolution of the igneous system(s), and help constrain genetic relationships amongst the individual phases at Cripple Creek (discussed in greater detail in Jensen, 2003).

All intrusive phases within the diatreme are silica undersaturated, and intrusions span the entire range from felsic phonolites to ultramafic lamprophyres and silicocarbonatites (Figs. 3 and 4). The igneous rocks at Cripple Creek show evidence for a complex magmatic history that involved multiple cycles of magmatic recharge and resulted in a striking shift to more mafic compositions with time. This shift culminated with the emplacement of ultramafic lamprophyres and silicocarbonatites which are the intrusions closest in time to gold mineralization (Fig. 3; see also Jensen, 2003). Multiple episodes and types of hydrothermal activity accompanied this complex history of igneous

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**Figure 2.** Generalized geologic map of the Cripple Creek district showing distributions of major rock types and metasomatic features. Also shown is a plan view map of the 3100 ft (~1000 m) level of the Vindicator Mine; note abundance of biotite-rich (higher temperature) styles of alteration, and a cross section through the central portions of the Cresson open pit mine.
Figure 3. Synthesis of igneous evolution of the Cripple Creek volcanic complex

<table>
<thead>
<tr>
<th>Rock type</th>
<th>%SiO₂</th>
<th>volume</th>
<th>mineralogy</th>
<th>texture</th>
</tr>
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<tbody>
<tr>
<td>lamprophyre // dikes</td>
<td>30</td>
<td>1-2</td>
<td>(Ba,Sr,Rb,Cs)pl, af, el 30% //</td>
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<tr>
<td>quadra-southeast Cresson Pit and Cresson Pipe</td>
<td>40</td>
<td></td>
<td>ag, bi, ol, mt 65% //</td>
<td></td>
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<tr>
<td></td>
<td>50</td>
<td></td>
<td>ap, mz, CO₃</td>
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<td>60</td>
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<td>70</td>
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<td>porphyritic phonolite-tephriphonolite</td>
<td>&lt;1?</td>
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<td>pl, or &gt;&gt; sd, fd 40% //</td>
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<tr>
<td>// megacrystic phonolite dikes, Cresson Pit</td>
<td></td>
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<td>ag &gt; am, bi 55% //</td>
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<td></td>
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<td>ap, mz, sn</td>
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<td>late stage phonolites // various peripheral stocks, plug and flows</td>
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<td>in Precambrian, Bluebird dike, Cresson Pit, most fine grained</td>
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<td>nepheline monzosyenite* // Rose Nichol stock</td>
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<td>laphicphonolite-trachyandesite // stocks of hornblende phonolite in</td>
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<td>Vindicador Valley, biotite phonolite, South Cresson</td>
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<td></td>
<td>60</td>
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<tr>
<td>early, porphyritic series phonolite-tephriphonolite // upper phonolite in</td>
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<td>East Cresson and Cresson Pit</td>
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<td>phonolitic-tephriphonolitic heterolithic breccia // main mass of</td>
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<td>diatremal breccia</td>
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<tr>
<td>megacrystic, coarse grained syenite // xenoliths carried by</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>phonolite intrusions*</td>
<td></td>
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</tbody>
</table>

ac = acmite, af = alkali feldspar, ag = augite, al = analcime, am = kaersutitic amphibole, ap = apatite, bi = biotite, cp = clinopyroxene (aegirine-augite), fd = feldspathoids (undiff.), hn = hainite, m = magnetite, ne = nepheline, mz = monazite, ol = olivine, or = orthoclase, pl = plagioclase, sd = sanidine, sn = sphene

stock     dike     brecciated stock     diatreme
sill       plutons  domes, cryptovolcanic domes, laccoliths
evolution, culminating with the introduction of gold mineralization; the relationships between igneous and hydrothermal activity are described in greater detail later in this paper (time-space synthesis). This section focuses on description of the igneous rocks in the district.

**Volcanic Breccias**

Volcanic breccias occupy much of the volume of the diatreme and represent a diverse family of rocks. They are mainly poorly sorted agglomerates of heterolithic rock fragments supported by matrixes composed of rock flour and crystal fragments, which...
can locally grade into crystalline, feldspathic matrix materials with igneous textures. Rock fragments (clasts) range in size from microscopic to several meters in diameter. Clasts are typically equidimensional and subrounded, with the degree of rounding interpreted to reflect the amount of transport within the diatreme. The breccias have compositions that vary according to their clast types, but have a bulk composition that is generally phonolitic (see descriptions in Lindgren and Ransome, 1906, p. 97–100). Clast types include phonolites of various textures (porphyritic, aphanitic and trachytic), coarsely crystalline syenitic rocks and subordinate populations of mafic alkaline rocks. Precambrian rock fragments are common, and become progressively more abundant toward contacts with the surrounding Precambrian rocks.

Cross cutting relationships demonstrate that volcanic breccias were generated at multiple times during the evolution of the diatreme, and volcanic breccias commonly contain clasts of older breccias, indicating repetitive episodes of brecciation, or dynamic processes of emplacement. Several bodies of volcanic breccias are seen to grade laterally into bodies of coherent igneous rocks. Although some volumes of breccias in the near surface environment exhibit crystalline matrices (interlocking feldspar crystals with textures that bear greater resemblance to coherent igneous rocks), crystalline matrices become more abundant at depth, as seen in samples of deep drill core. At all levels of exposure, however, breccia matrices contain an abundance of xenocrystic feldspar fragments.

**Stratification in breccias.** Stratification within volcanic breccias is variably developed throughout the diatreme, but is most pronounced along its margins. Stratified volcanic facies range from the weakest suggestions of bedding and material sorting, to well-sorted lamellae that exhibit sedimentary-like structures such as cross-bedding and graded beds (both coarsening upward and downward sequences are observed). Lamellae contain pulverized rock fragments, crystal shards and volcanic ash or lapilli-sized fragments, some of which have accretionary textures (see also Lindgren and Ransome, 1906, p. 99, and Wood, 1990, p. 160–164). Soft sedimentary deformation structures (such as flame structures, slump blocks, and small-scale recumbent folding), and impact sags produced by volcanic ejecta are also common. In many exposures, these bedded volcanic rocks are nearly flat-lying, and some show low-angle cross-stratification or “dune structures,” but in some cases, bedding and stratification can occupy high angles or subvertical orientations.

Downfaulted or down-dropped blocks of bedded pyroclastic materials, and possibly epiclastic sediments, are occasionally seen at deep levels in the diatreme. These blocks are typically engulfed within the heterolithic diatreme breccia or within coherent volcanic units. Fragments of carbonaceous materials have also been observed at great depths in the diatreme. In two cases, bituminous coal (still exhibiting a woody structure) was recovered by miners at 200 m below the surface of the Doctor Jackpot and Morning Glory mines (see descriptions and analyses by Lindgren and Ransome, 1906, p. 31). A fragment of a conifer tree was discovered at a depth of 260 m by miners in the Indepen-
had high native permeabilities, making them particularly susceptible to alteration. In many areas, the original textures and compositions of breccias have been largely obscured by multiple episodes of hydrothermal alteration. Alteration types are diverse (as discussed below), but tend to be alkali-rich and range from high-temperature, biotite-stable assemblages to low-temperature adularia flooding. As part of this alteration, the breccias have also been variably sulfidized and carbonated, with sulfides and carbonate minerals replacing mafic igneous phases, occupying void spaces and, in some cases, flooding the matrix. Carbonate content increases with depth; many samples from deep exposures effervesce in dilute hydrochloric acid. This carbonate has important environmental implications, as these rocks can buffer large volumes of acidic groundwater.

Coherent Igneous Rocks

Diatremal breccias were successively intruded by a series of phonolites, tephriphonolites, phonotephrites, tephrites, and ultramafic lamprophyres (Figs. 3 and 4). The most common volcanic rock in the Cripple Creek district is phonolite, and close variants. At least two generations of phonolites are seen, which differ in terms of their mode of origin and geochemistry, but are otherwise similar in appearance. They are most readily distinguished in the field by their relative timing relationships. The repetition of voluminous phonolitic magmatism in the later stages of magmatic evolution is an example of recharge in the magmatic system(s). Distinctions in alkali index, trace element chemistry and isotope evolution is an example of recharge in the magmatic system(s). Alteration types are diverse (as discussed below), but tend to be alkali-rich and range from high-temperature, biotite-stable assemblages to low-temperature adularia flooding. As part of this alteration, the breccias have also been variably sulfidized and carbonated, with sulfides and carbonate minerals replacing mafic igneous phases, occupying void spaces and, in some cases, flooding the matrix. Carbonate content increases with depth; many samples from deep exposures effervesce in dilute hydrochloric acid. This carbonate has important environmental implications, as these rocks can buffer large volumes of acidic groundwater.

Geochemistry of Igneous Rocks

Figure 4 shows major element compositions for Cripple Creek’s igneous rocks. All fresh igneous rocks are strongly silica undersaturated (contain modal feldspathoids) and are distinctly sodic, with molar Na/K ranging from 1.3 to 2.5, with most rocks averaging ~2 (see Figure 4; molar Na versus K). Although the concentrations of both Na and K increase with SiO₂, Na/K does not change significantly over a broad range of SiO₂. Most rocks are metaluminous (mol. Na + K < Al₂O₃ < Na + K + Ca), except for late stage phonolites, which are peralkaline (mol. K + Na > Al₂O₃). A few mafic intrusions approach peraluminous chemical compositions, but remain strongly undersaturated with respect to silica. Compatible elements such as Mg, Ca, Fe, and Ti decrease with increasing SiO₂, while elements such as Al, K, and Na increase.

Figure 5A shows trace and rare earth element compositions for Cripple Creek’s rocks in comparison with other regional magmatic centers. The majority of Oligocene alkaline melts generated in the region exhibit depletions of Ta and Nb relative to other high field strength and rare earth elements, including shoshonitic magmatism at Guffey, Colorado (~30 km from Cripple Creek; e.g., Wobus et al., 1990), as well as the more primitive, mantle derived basalts along the axis of the Rio Grande Rift (Thompson et al., 1991). Exceptions to this geochemical signature include Cripple Creek, the Raton-Clayton volcanic field in northeastern New Mexico (Phelps et al., 1983), and basanitic lavas in the Española Basin, Colorado (Gibson et al., 1993).

On isotopic plots, Cripple Creek’s rocks plot near bulk earth, and share other chemical similarities with primitive rock types such as “type I” kimberlites (e.g., Smith, 1983), and are distinct from the alkaline igneous centers in central Montana and Boulder County, Colorado which host smaller volumes of gold mineralization (Fig. 6). The patterns of rare-earth element enrichment, lack of negative Ta-Nb anomalies, and sodic compositions of Cripple Creek’s rocks are most consistent with derivation from asthenospheric sources (Jensen, 2003). Similar modes of petrogenesis have been inferred for many rift-related phonolites, or phonolites associated with plume magmatism (oceanic-island basalt; OIB); these show remarkable chemical similarity with Cripple Creek’s igneous rock suites (Fig. 5B).

This combination of signatures differs from the calc-alkaline and most other alkaline igneous centers in the region, and suggests a mode of origin more symptomatic of global phonolitic magmatism rather than a regional control. The enrichment in LILE, HFSE, and LREE and similarity with numerous other phonolitic systems around the world suggests a link to specialized source regions in the mantle, and a mode of origin independent of crustal and possibly lithospheric mantle sources.

STYLES OF ALTERATION AND MINERALIZATION

Styles of alteration and mineralization at Cripple Creek are unusual for epithermal mineral deposits. The rocks at Cripple Creek have recorded numerous episodes of hydrothermal activity, ranging from high temperature pyroxene and biotite-rich assemblages, to low-temperature flooding by alkali feldspar with pyrite or specular hematite. K-metasomatism has affected large volumes of rocks in and around the diatreme complex (Fig. 2), altering the originally sodic igneous rocks to potassic and ultrapotassic compositions. Volumes of alkali feldspar + specular hematite alteration were developed throughout the evolution of the diatreme, while large volumes of K-feldspar + pyrite alteration and gold mineralization were developed late, following the emplacement of mafic rock types and lamprophyres. Although sulfate-bearing styles of alteration are abundant in certain areas of the district (especially at deeper levels), hydrolytic (acid) styles of alteration comprise relatively minor volumes overall. Although subordinate to the feldspar-stable alteration types at the district scale, white mica-phylllosilicate assemblages (products of hydrolytic alteration) appear most abundant in areas of late-stage, sulfate-rich alteration.

Economic gold mineralization is intimately associated with the late, voluminous K-feldspar-pyrite which makes up >5 km³ of the explored portion (upper 1 km) of the complex (Fig. 2).
Figure 5. (A) Spider diagrams from selected Tertiary alkaline and calc-alkaline igneous complexes from the greater Colorado area (data from various sources). These include examples of “shoshonitic” volcanism (Guffey and Two Buttes, Colorado), calc-alkaline volcanic fields (San Juan and Latir fields), ultrapotassic rocks (Leucite Hills, Wyoming, and other lamproites), alkaline basalts (San Luis Hills), and examples of alkaline magmatism in the Colorado Plateau (La Sal and Abajo Mountains, and lower crustal xenoliths transported by alkaline magmatism). Note the pronounced negative Ta-Nb anomalies in all of these examples, with the exception of the Cripple Creek system. Chondrite data from Thompson (1982).
Figure 5. (B) Examples of chemical signatures of sodic phonolitic magmatism from rift environments (top) and oceanic-island basalt complexes (bottom). Data from various sources.
The gold mineralization is principally hosted by thin seams of quartz (typically <5 cm) that contain variable fluorite, carbonate, pyrite, barite-celestite, and a suite of accessory minerals that include gold tellurides and, more rarely, the vanadiferous mica roscoelite. Also present in the district are mineralized hydrothermal breccias with quartz-fluorite-carbonate and rhodochrosite-celestite-fluorite matrixes; these show similar styles of wall rock alteration. Intriguing features include large masses of anhydrite-fluorite-pyrite ± galena-sphalerite-molybdenite and late stage, massive carbonate-sulfide veins and breccias in some parts of the district at deep levels.

Intense potassium metasomatism is broadly developed throughout the diatreme, the surrounding country rocks, and in satellite alkaline intrusions (variably developed over an area of 15 × 15 km), to the extent that it grossly exceeds the volumes of potassic alteration described in many other types of mineral deposits, including typical porphyry copper deposits. In zones of potassium metasomatism, K-feldspar has typically replaced alkali feldspar and sodic plagioclase, while illite and carbonate replace more calcic varieties of plagioclase. Mafic minerals are replaced by combinations of pyrite, carbonate, illite, and rutile (leucogne). A notable characteristic of this alteration type is its cryptic nature. Where sodic alkali feldspar (sanidine or albite) has been replaced by K-feldspar, feldspar grains are commonly bleached, and appear turbid and “dusty” in thin section, but retain original igneous grain boundaries. Many plagioclase crystals replaced by metasomatic K-feldspar have retained their original polysynthetic twinning, and show no obvious textural evidence for conversion to K-feldspar (Jensen and Barton, 2000). Only occasionally is the metasomatism seen to be texturally destructive in feldspathic rocks, whereas in mafic rocks (especially lamprophyres), the alteration tends to be more obvious in hand sample and in thin section and is commonly texturally destructive.

Although subtle in appearance, the chemical signatures of this style of alteration can be extreme, with many altered rocks having >14 wt% K₂O. K-feldspar rich styles of mineralization are intimately associated with gold mineralization, although earlier K-silicate events are also broadly developed throughout the district (e.g., zones of alkali feldspar + specularite alteration shown in Fig. 2). It is suggested that similar styles of alteration are under-recognized in many alkaline igneous centers.

Fluid compositions in the ore forming system were dominated by low temperature, dilute, CO₂-rich fluids (<225°C, <5 wt% NaCl; Thompson et al., 1985; Beaty et al., 1996). Most lines of evidence suggest that phase separation (boiling, effervescence) played a key role in precipitating gold in veins. The continuous effervescence of CO₂ over protracted vertical intervals may explain the continuous vertical extent of mineralization in some veins (e.g., Thompson et al., 1985). Away from veins, lesser amounts of gold were precipitated in alteration halos, mostly in
the sites of former mafic minerals. The preference for mafic mineral sites suggests that reaction with Fe-bearing phases in wall rocks also played a critical role in triggering gold precipitation.

The development of phlogopitic alteration halos around deep ore-stage veins, and an increasing abundance of anhydrite and base metal (sphalerite, galena, molybdenite) assemblages at deep levels (1000 m) is suggestive of transitions to higher-temperature, and base metal-rich environments at depth.

Compared to most epithermal districts, the mineralization at Cripple Creek appears to have been produced by fluids with high $\delta^{18}O$ (+3 to +9‰; Jensen, 2003 and Beaty et al. 1996). These data are consistent with fluids dominated by magmatically derived waters, recognizing that a significant component of externally derived fluids cannot be ruled out. High $\delta^{18}O$ signatures are seen in many other alkaline-related epithermal gold deposits, a characteristic that distinguishes them as a group from other epithermal deposits (c.f. data from Field and Fifarek, 1985). Sulfur isotopes are also broadly consistent with derivation from a magmatic source (Jensen, 2003).

According to our current understanding of precious metal geochemistry, alkaline hydrothermal fluids with moderate oxygen fugacities (as suggested by the coprecipitation of pyrite and sulfate minerals) have ideal chemistries for gold transport as a bisulfide complex (Seward, 1973; Shenberger and Barnes, 1989; Hayashi and Ohmoto, 1991; Benning and Seward, 1996; Wood and Samson, 1999). The large fluxes of these fluids suggested by the volumes of alteration at Cripple Creek, and the evidence for widespread phase separation and wall rock reaction during mineralization rationalize the large size of the Cripple Creek gold deposit.

**TIME-SPACE SYNTHESIS**

Figure 7 shows a time-space diagram which summarizes the magmatic and hydrothermal evolution of the Cripple Creek gold deposit. Hydrothermal systems were active from the onset of magmatism, as evidenced by xenoliths of altered rock entrained within early volcanic breccias and intrusions. Early styles of alteration include biotite and pyroxene-rich types (brown and green patterns on Fig. 7), variably accompanied by pyrite, carbonate minerals and alkali feldspar. These appear to represent styles of alteration developed at deep levels prior to the emplacement of the diatreme, and are not exposed in the near surface environment. Some of these early styles of alteration are gold bearing, according to secondary ion mass spectrometry analyses of sulfide grains (Jensen, 2003), but their extents and volumes are unknown.

Hydrothermal activity continued with the emplacement of diatremal and volcanic breccia, as evidenced by the phreatomagmatic(-phreatic) styles of volcanism. Large volumes of diatremal breccia, as well as many subsequent intrusions exhibit alkali-feldspar + specularite alteration (shown as down to the right slashed patterns on Fig. 7). Alkali feldspar + specularite alteration is also broadly developed in volcaniclastic sediments in the eastern sub-basin of the diatreme, and in some cases, is seen to cut discordantly across sedimentary units. The specularite-stable alteration and characteristics of metasomatism are consistent with the circulation of oxidized (hematite-stable) surficial fluids through a cooling volcanic pile, a phenomenon often seen in volcanic terranes (e.g., Lindley, 1985, and D’Andrea-Dinkeliman et al., 1983; Dunbar, et al., 1994), and as diagenetic alteration in sedimentary piles (Sheppard and Gude, 1968, and Sheppard and Gude, 1973). This appears to have been a recurring phenomenon throughout the evolution of the diatreme as shown by cross-cutting relationships, possibly in response to each major intrusive event.

Also present are small volumes of intrusion-related alteration, characterized by pyroxene and biotite-rich assemblages (again in green and brown patterns, respectively, in Fig. 7). Biotite-rich styles of alteration are most commonly developed around stocks and intrusions with igneous biotite, while pyroxene-rich styles of alteration appear to be related to the more felsic phonolites and tephriphonolites. Smaller volumes of peralkaline alteration (blue, sodic amphiboles) are specifically related to the emplacement of late stage, peralkaline phonolites. Lamprophyres appear to have exsolved low-density feldspar + carbonates phases, based on the immiscibility textures seen in some lamprophyre intrusions. Gold mineralization is generally not associated with these intrusion-related styles of alteration, which are limited to small volumes in the immediate vicinity of intrusive bodies.

In addition to the K-silicate styles of alteration, zones of albite and chloride-rich alteration are present around the periphery of the diatreme and in some outlying intrusions (not shown in Fig. 7). They contain variable amounts of pyrite, specular hematite, and in some cases, base metal sulfides. Cross-cutting relationships for these zones of alteration are not well exposed, and many timing relationships have been obscured by younger hydrothermal events. It is possible that some zones of sodic alteration represent Na-rich styles of alteration that compliment the much larger volumes of K-rich alteration. Further work is needed to constrain their timing, distribution, and significance.

Most (and possibly all) of the economically significant gold mineralization was developed after the emplacement of lamprophyres. Large volumes of hydrothermal alteration and mineralization were developed throughout the area (shown as light blue pattern in Figure 7, to right of lamprophyre events), causing large volumes of rocks to become altered and mineralized. Mineralization was characterized by the development of thin seams of quartz and carbonate with accessory pyrite, fluorite, adularia, celestite, and barite. Traces of base metal sulfides and gold ± silver tellurides were erratically deposited along the veins.

Gold mineralization was accompanied by the generation of voluminous low-temperature K-metasomatism in the near surface environment, with the largest volumes developed in volcanic breccias and phonolites. More restricted volumes of vein-related alteration are developed in less permeable host rocks such as monzosyenites, and in Precambrian rocks. In some deep exposures, evidence is seen for higher temperature styles of mineralization in the form of alteration assemblages rich in phlogopite, anhydrite and base metals (Mo, Pb, Zn, and minor Cu).
Fluids responsible for gold mineralization were especially concentrated in areas of favorable igneous plumbing. High densities of lamprophyre dikes, late stage phonolites, and to a lesser degree, monzosyenite intrusions appear to have been especially favorable for the development of mineralization. Areas with complex magmatic histories represent especially favorable structural conduits, in that they have been continuously utilized by magmas and hydrothermal fluids throughout the evolution of the diatreme.

Also developed during the process of mineralization were hydrothermal breccias (column with pink color in Fig. 7), some of which are characterized by Mn-rich carbonate matrices, but otherwise exhibit mineral assemblages and paragenetic relationships consistent with other types of mineralization developed throughout the district.

In a few areas of the district (Grassy Valley, Ironclad–Globe Hill and above the Dante Collapse Breccia) broad zones of phyllosilicate alteration and large volumes of hydrothermal sulfate (anhydrite) and carbonate cut earlier formed gold mineralization and K-alteration (Rosdeutscher, 1999; Jensen, 2003). These sulfate and carbonate-rich assemblages are commonly accompanied by pyrite, galena, sphalerite, and molybdenite. These are depicted as the late stage hydrothermal events on the far right in Figure 7.

Molybdenite appears to increase significantly with depth in the area of Globe Hill–Ironclad, possibly signaling a transition downward to a “porphyry-style” molybdenum deposit. Also present in the area are significant volumes of post-lamprophyre biotite-rich alteration, indicating the development of higher temperature styles of alteration during this event. Similar features have also been revealed in recent deep drilling in the vicinity of the Cresson Pipe, which shows evidence for late-stage biotite-rich alteration and anhydrite veining cutting zones of K-feldspar+pyrite alteration.

Following the cessation of hydrothermal activity, oxidation and hydrolytic alteration took place throughout the upper levels of the diatreme during subsequent 30 million years of weathering. In the near surface environment, sulfides have oxidized, feldspars have been partially altered to clay, and rocks have been bathed in variegated red, orange and yellow iron oxides. Although some erosion may have taken place (~500 m to 1 km according to most lines of evidence; Jensen, 2003), many features of the Cripple Creek volcanic complex and broad preservation of an Eocene-aged erosion
surface in the area suggest that post-magmatism erosion has been limited in the area. This appears to be a key factor in having preserved epithermal (i.e., high-level) precious metal mineralization in the Cripple Creek district.

**DISCUSSION AND SUMMARY**

The Cripple Creek magmatism appears to represent a primitive, alkalic end-member of widespread magmatic activity during the mid-Tertiary in Colorado, much in the way that the Missouri Breaks kimberlite pipes are thought to represent primitive end-members in the Eocene magmatic province of Montana (Scambos, 1991; Irving and O’Brien, 1991; O’Brien et al., 1991). Although distinguished by its gold mineralization, the magmatism at Cripple Creek closely resembles other small volumes of phonolitic magmatism seen along the trend of the Rio Grande rift (e.g., Raton-Clayton area, New Mexico; Phelps et al., 1983; Figs. 5A and 6). Collectively, these may represent deep-seated magmas that were emplaced in off-axis rift positions during the incipient stages of regional extension, similar to the styles of phonolitic magmatism in the East African rift (e.g., Mount Kilimanjaro and Mount Kenya).

Cripple Creek serves as an example of sodic phonolitic magmatism where the magmas have traversed a great thickness of continental crust with little chemical modification, and in this sense serves as an end-member in a continuum of geologic environments which host sodic phonolitic magmatism. These range from oceanic island centers to rift zones to back arc environments, but appear to operate independently of the type and thickness of overlying continental crust and lithospheric mantle. A consistent theme of sodic phonolitic magmatism is its association with active or incipient stages of extensional tectonic environments. The histories of evolution in their mantle source regions remain unclear, but either a specialized mantle source or source region modified by metasomatism prior to magmatism seem key, given their unusual chemical endowments and lack of time-integrated isotopic signatures suggestive of long-lived chemical anomalies.

Amongst the Tertiary alkaline systems of Colorado and surrounding regions, Cripple Creek is unusual in that it shows little evidence for crustal assimilation or derivation from modified lithospheric mantle source regions (metasomatically enriched mantle with negative Nb and Ta anomalies). Widespread evidence is seen for Nb-Ta depletions in many alkaline rocks and lithospheric mantle xenoliths in the region (Fig. 5A), and appears to be a long-lived characteristic of the region. Although generally thought to reflect influence of subduction-related processes, the persistence of this signature in a wide variety of rock types (both alkaline and subalkaline) suggests a more general characteristic of the lithospheric mantle ± lower crust in the region.

The distinctive compositions of Cripple Creek’s rocks and strong similarities with global OIB and rift zone phonolites suggest a fundamental link to processes acting in asthenospheric mantle. If so, Cripple Creek represents one of the earliest expressions of asthenosphere-derived melts emplaced along the axis of the Rio Grande Rift during the incipient phases of extension in the mid-Tertiary (c.f. Gibson et al., 1993). Lithospheric relaxation may have allowed small volumes of chemically exotic magmas to migrate to upper levels in the crust, and ultimately led to the development of the unusual styles of mineralization seen at Cripple Creek.

**Gold Mineralization**

Like many other epithermal districts, the alteration associated with gold mineralization at Cripple Creek is characterized by the development of K-silicate minerals such as K-feldspar (adularia), and illite ± sericite. However, K-metasomatism at Cripple Creek is much more intense, and the large volumes of altered rock more closely resemble the styles of K-rich fenitization commonly developed around many carbonatites and alkaline igneous complexes.

While a protracted and complex history of magmatism and hydrothermal activity pre-dated gold mineralization, it is clear that the economic mineralization only developed in the latest stages of magmatism (post-lamprophyre), and is characterized by thin veins that show remarkably consistent compositions, isotope signatures, mineralogies and textures throughout the district. Evidence for multiple pulses of ore-bearing fluids (thick and repetitively banded veins) is generally absent. Instead, veins follow a relatively simple and consistent pattern of mineral deposition throughout much of the district, and many ore-stage veins are characterized by only a single stage of mineral deposition. This suggests that the fluid or fluids responsible for mineralization followed a well-defined path of evolution, with little variation throughout the district.

While showing a close spatial and temporal association with phonolitic magmatism, the gold mineralization at Cripple Creek appears to be a product of complex processes of magmatic and hydrothermal evolution. In the Cripple Creek system, gold mineralization was not developed until several cycles of magmatism had taken place, many of which show evidence for related episodes of hydrothermal activity. Amongst the Tertiary alkaline magmatic centers along the Rio Grande rift, this may serve as a distinguishing feature at Cripple Creek and a symptom of prospectivity for gold mineralization in undereveloped systems; complex magmatic histories and evidence for multiple stages of recharge in the magmatic system. While relatively anhydrous phonolitic magmatism (characterized by rocks with pyroxene-rich compositions) was dominant at Cripple Creek, gold mineralization was not introduced until the emplacement of more diverse and volatile-rich magma compositions (e.g., lamprophyres and hydrous monzosyenitic intrusions), many of which demonstrably developed attendant magmatic-hydrothermal systems. Similar magmatic histories and clear evidence for voluminous alkali-metasomatism may be key characteristics for further exploration in the region.

The presence of tellurides, fluorite, and other minerals characteristic of alkaline-related gold deposits suggests that fluids
were enriched in chemical components derived from magmatic volatiles. The large fluxes of fluids with “magmatic” compositions, striking enrichment in tellurium, and other characteristics that distinguish these deposits from the more “classic” epithermal deposits (e.g., Bonham, 1984; Richards, 1995; Jensen and Barton, 2000). This argues for a fundamental control inherent to magmatic-hydrothermal systems related to alkaline magmatism.

FIELD TRIP STOPS

Field trip stop descriptions are available as item 2008144 in the GSA Data Repository at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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