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ARTICLE

The Sweet Home rhodochrosite specimen mine, Alma District, Central Colorado: the porphyry molybdenum–fluorine connection

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Abstract Intermediate sulfidation veins containing quartz–sphalerite–tetrahedrite–rhodochrosite–fluorite in the Sweet Home Mine, Alma District, Colorado were originally mined for silver starting in 1873. For the last 13 years up until 2004, however, the mine has produced world-class rhodochrosite specimens. Some of these specimens are considered to be among the finest mineral specimens ever produced and the finest of their species with values well over $1 million US dollars. The extraction, preparation, and marketing techniques pioneered at the Sweet Home operation have revolutionized the minerals specimen industry. The Sweet Home deposit is interpreted as a single pulse variant of a Climax-type hydrothermal system. Evidence for this includes (1) an age of mineralization (25.8±0.3 Ma) that coincides with the age of the end stages of mineralization of the Climax molybdenum deposit approximately 7.5 km to the northeast; (2) a geochemical (Mn, W, F) and mineralogical (topaz, fluorite, hubnerite, greisen muscovite) signature typically associated with Climax-type systems; (3) the presence of porphyry rhyolite dikes, a breccia dike, and local quartz–molybdenite veins in the nearby area; (4) a small pegmatite within the mine with an age (25.9±0.3 Ma) coincident with mineralization, which also contains minor amounts of disseminated molybdenite; and (5) the presence of similar-appearing gemmy, red rhodochrosites at Climax and other high-silica rhyolite systems. A significant difference is that unlike Climax-type systems, the Sweet Home hydrothermal system appears to have consisted of a single, relatively small pulse of magmatic fluid that slowly cooled and diluted with groundwater. This is inferred to have occurred at moderate depths in the order of 1.5–2.5 km below the surface. The fluids that formed the Sweet Home veins were dilute (salinity in the order of 2–4 wt% NaCl equivalent), high-temperature (temperatures of homogenization up to 370°C), and initially of magmatic origin. Gem quality ruby-red rhodochrosite at the Sweet Home Mine is nearly pure manganese carbonate with minimal solid solution with Fe^{+2}, Ca, or Mg. It formed at higher temperatures and salinities in comparison to lower value, pink rhodochrosite. Gemmy, ruby-red rhodochrosite is distinctly associated with highly evolved silica-rich igneous/hydrothermal systems. The high fluorine content typical of such systems suggests that Mn was transported in solution as fluoride complexes, which, in turn, favored rhodochrosite deposition at above-average temperatures and with minimal cation contamination.

Keywords Rhodochrosite · Climax-type system · Sweet Home mine · Fluorite

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Introduction

The Sweet Home Mine is located within the Alma mining district in the Mosquito Range of Central Colorado approximately 6 km northwest of the town of Alma. It occurs at the base of the Red Amphitheater in Buckskin Gulch at an elevation of 3,440 m. Other nearby mining districts include

Climax, Leadville, Breckenridge, and London; all are considered part of the central portion of the Colorado Mineral Belt (Fig. 1).

This paper presents a new geochemical model of formation for the Sweet Home deposit based on new quadrangle and mine scale mapping and additional paragenetic/alteration studies, as well as synthesizes the previously obtained fluid inclusion, stable isotope, and age data. The rhodochrosite deposit at Sweet Home is interpreted as being a variant to the mineralization seen at the porphyry molybdenum deposit at Climax, 7.5 km distant. This new model of origin links the formation of ruby-red gemmy rhodochrosite with the occurrence of hydrothermal systems associated with highly evolved silicic and fluorine-rich magmas.

District history

There has been a long history of mining within the Alma District featuring multiple-deposit types and ages of mineralization (Fig. 2). Placer gold was first discovered in 1859. Placer mining has continued to the present day, with peak production from 1935 to 1942 (Parker 1974). Hard-rock mining started in 1860 with the discovery of the Phillips (Buckskin Joe) lode, a gossan in quartzite and shale containing gold-bearing pyrite. Similar deposits such as the Paris (1861) and Orphan Boy (1862) were discovered nearby. The oxidized portions of these orebodies had been

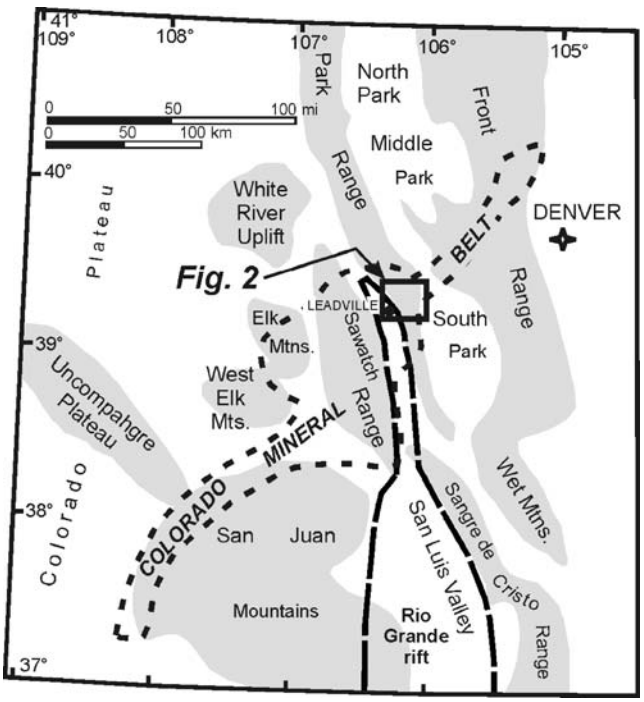

Fig. 1 Map of Colorado showing geographic and tectonic features. The location of the Alma District is *outlined* showing its relation to the Colorado Mineral Belt (*shaded*) and the Rio Grande Rift (*dark outline*). Modified from Tweto and Sims (1963)

mined out and the district essentially abandoned when, in 1871, silver was discovered high on the peaks of Mount Bross and Lincoln in supergene-enriched Ag–Zn–Pb–Ba manto bodies typically filling karst features in the Mississippian Leadville Formation dolomite. These are termed Sherman-type deposits (named after Mt. Sherman, approximately 8 km to the south), and their origin is controversial (see Beaty et al. 1990). One model suggests that these deposits formed during the Pennsylvanian from basinal brines; another suggests that they formed in the Paleocene related to quartz monzonite igneous activity. Regardless, field relations to the south indicate that Sherman-type mineralization preceded and was cut by Leadville mineralization dated at 39.6±1.7 Ma (Behre 1953; Thompson and Arehart 1990); these deposits preceded the veins at the Sweet Home Mine by at least 14 million years.

The quartz–pyrite–sphalerite–tetrahedrite–rhodochrosite–fluorite veins at the Sweet Home Mine were originally worked for silver on a small scale starting in 1873. In the first 20 years of operation, approximately $185,000 in ore was shipped (Voynick 1998). The mine then was dormant until the late 1910s when operations were renewed. Throughout the 1920s, there was some small-scale mining with minor production totaling $30,000 in then silver prices (Voynick 1998). Silver exploration was renewed in the mine during the 1960s through 1980s, but without significant metal production.

As early as 1876, deep ruby-red, translucent, large rhombohedral rhodochrosite crystals were noted from the Sweet Home Mine (Endlich 1878). There was very little interest in these, and they were principally discarded on the dumps. A few specimens made their way to museums in the USA and Europe. A small pocket of rhodochrosite was encountered in 1925 accompanying production from a major (16,000 oz) silver stope. Two lots were produced; one of which sold for $900 (Voynick 1998). At the time, there was very little interest in rhodochrosite specimens, and the mine faded into obscurity.

Circumstances changed in the 1960s. Mineral collecting had become more popular and broader-based. A major specimen, the Alma Queen, was discovered in 1966 as part of a failed mine reopening effort to find high-grade silver ore; limited specimen mining also occurred at that time. The Alma Queen was exhibited in 1967 at the Las Vegas Gem and Mineral Show where it created a sensation; it became the cover mineral for the book *The World's Finest Minerals and Crystals* (Bancroft 1973). In the mineral world, rhodochrosite from Sweet Home Mine became well known.

For the next 20 years after the discovery of the Alma Queen, various individuals (including some illicit miners) attempted to extract rhodochrosite crystals from the Sweet Home Mine, and some limited production occurred. In 1991, Bryan and Kathryne Lees formed a syndicate, raised

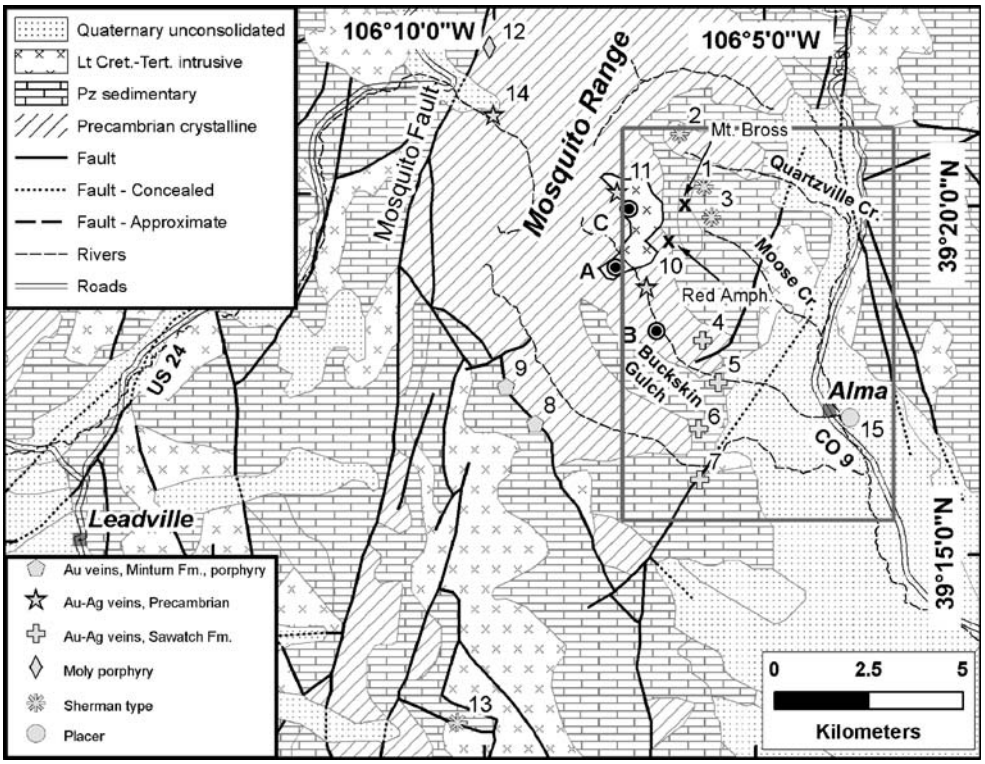

Fig. 2 Simplified geologic map of Alma and nearby mining districts showing mines, deposit types, major faults, tertiary intrusives, and drill holes. Selected mines in and near the Alma quadrangle are numbered: 1. Paris Mine, 2. Phillips Mine, 3. Hock Hocking Mine, 4. South London Mine, 5. North London Mine, 6. Tarryall district, 7. Upper Blue River district, 8. Kentucky Belle Mine, 9. Sweet Home Mine, 10. Dolly Varden Mine, 11. Champaign Mine, 12. Moose Mine, 13. Climax Mine, 14. New Orphan Boy Mine, 15. Russia Mine. Modified from figure 19 of Widmann et al. (2004) and Holmes and Kennedy (1983)

money, leased and later purchased the property, and formally opened the mine as a mineral specimen mine. For the next 13 years, their company, Collector's Edge Minerals, successfully mined rhodochrosite from open vug pockets using hydraulic splitters and diamond-tipped chainsaws.

This operation changed the mineral specimen industry not only in the development of new innovative extraction techniques but also in the fields of sample preparation and marketing. As a result of the activities at the Sweet Home Mine, there is now a better appreciation of mineral specimens. Individual Sweet Home rhodochrosite specimens have been sold for over $1 million, with many in the five- and six-figure dollar range (Fig. 3). Total gross production value of rhodochrosite specimens is estimated to be in the order of $15 million. All told, some 20,000 tons were mined in the course of extracting rhodochrosite specimens (Lees, 2003, personal communication).

In 2004, the Sweet Home Mine closed. The workings have been plugged, the mine entrance adit collapsed, and the hillside completely regraded and reclaimed. Future production of additional Sweet Home rhodochrosites is unlikely.

Previous work

The area encompassing the Sweet Home Mine was first described by Emmons (1886). Patton et al. (1912) provided the first district map. This work summarized what was then known about the Alma District, which at that time, had already faded from its peak production era of the 1870s. Singewald and Butler (1941) remapped part of the district focusing on deposits and mineralization associated with the London reverse fault to the south. The quadrangle encompassing the Sweet Home Mine was recently remapped at 1:24,000 scale by the lead author (and others) as part of the Colorado Geologic Survey's STATEMAP Program (Widmann et al. 2004). Topical studies associated with the recent quadrangle mapping include a structural thesis by Barbá (2004) and follow-up petrology studies by the lead author. Of particular note, a special issue of *The Mineralogical Record* (1998) was dedicated to the Sweet Home Mine at a point approximately halfway through its productive life as a rhodochrosite producer. This issue contains information and spectacular photos of interest to mineral collectors. It also includes abundant geologic and mineralogical data as well, collected in part by the third author who was a mine geologist at Sweet Home during its entire recent operation. The basic outline of the paragenetic sequence described in *The Mineralogical Record* still holds, although our studies allow for some additional refinements. Given that the mine is now permanently shut, these studies comprise the last record for the deposit.

Regional geology

The Sweet Home Mine is located in the Mosquito Range where it comprises part of a north–northeast striking, east dipping homoclinal sequence. Precambrian ortho- and paragenesis and large metamorphosed igneous intrusions

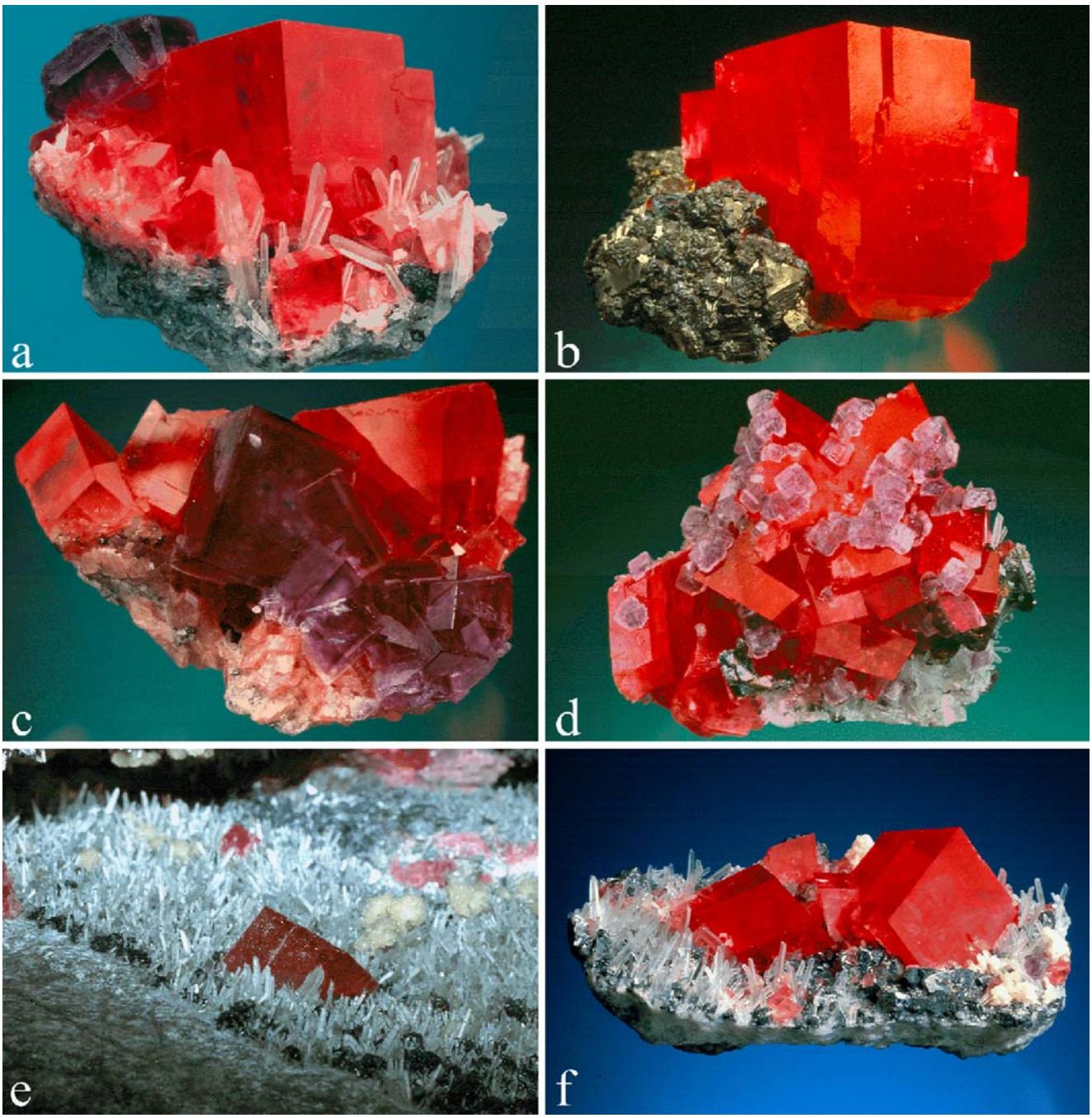

Fig. 3 Gemmy, ruby-red rhodochrosite specimens from the Sweet Home Mine, Alma District, Colorado. All photographs are by Jeff Scovil. **a** Rhodochrosite and fluorite (*upper left*), Strawberry pocket, fluorite raise, Sweet Home Mine. The specimen is 4.4 cm long. **b** Rhodochrosite perched on pyrite and black sphalerite, Sweet Home Mine. The specimen is 7.7 cm wide. **c** Rhodochrosite and fluorite, American pocket, fluorite raise, Sweet Home Mine. The specimen is 4.2 cm wide. **d** Rhodochrosite, purple fluorite, sphalerite (*bottom left*), Steve's pocket, fluorite raise, Sweet Home Mine. The specimen is 7.4 cm wide. **e** "Rhodo in the raw"; view of a just-opened (1992) pocket in the Sweet Home Mine showing red rhodochrosite, quartz needles, and yellow calcite. **f** Prepared specimen from nearby area; rhodochrosite, quartz needles, tetrahedrite, yellow calcite, and minor purple fluorite (*far right of specimen*), Calcite pocket, fluorite raise, Sweet Home Mine, 8.4 cm wide

form the core of the Mosquito Range and are the host rocks for the Sweet Home veins. The Precambrian rocks are overlain by a sequence of lower Paleozoic siliciclastic and platform carbonate rocks comprising inner shelf successions (Myrow et al. 2003). The lower Paleozoic sequence is overlain by a thick sequence of Pennsylvanian–Permian red bed arkosic sandstone and siltstone with rare minor carbonate interbeds.

The entire section was intruded by an extensive series (at least seven different rock units) of porphyritic sills, dikes, and small stocks starting in the latest Cretaceous–Paleocene and continuing through the Oligocene. Volcanic equivalents to these intrusives are not known. Within the district, sills are the predominant style of intrusion ranging in thickness from meters to hundreds of meters; strike lengths can exceed 1.5 km. Dikes tend to be much smaller and much less common.

In the Buckskin Gulch area, a series of monzonitic to granodioritic stocks, dikes, and sills ranging in age from 71 to 42 Ma (Bookstrom 1989) are exposed and related to a long-lived igneous center (Buckskin Gulch intrusive center) whose age significantly pre-dates Sweet Home mineralization (Fig. 2). Monzonite was emplaced early (between 72 and 67 Ma) followed by granodiorite (until 42 Ma); however, Bookstrom (1989) believes that magmas of both compositions were episodically emplaced during this approximately 30-million-year interval. Thin quartz monzonite and monzonite dikes occur within the Sweet Home Mine and are correlated to the Buckskin Gulch intrusive center. A broad pyritic halo is spatially associated with this intrusive center and comprised of very fine-grained pyrite disseminated in veinlets. This pyritic alteration is weathered on the surface to iron oxides plus sericite–clay. Sweet Home veins occur at the outer margin of the pyrite halo.

A series of rhyolite porphyry dikes, locally known as the later White porphyry (Patton et al. 1912; Singewald and Butler 1941; Behre 1953), is exposed in the district. Approximately 30 of these dikes are known in the greater Alma region, most in the adjacent Climax quadrangle (Bookstrom 1989). They are white to light gray, fine-grained rocks typically containing 2–5% phenocrysts of 1 to 2 mm rounded quartz and orthoclase in subequal amounts with lesser plagioclase in an aphanitic groundmass. A sample of a later white porphyry taken from Buckskin Gulch approximately 2 km from Sweet Home Mine yielded a fission track age of 34.9±3.8 Ma (Bookstrom 1989). The chemistry and age of these dikes are generally similar to that of early Climax magmas (Bookstrom 1983, 1989) that were the immediate magmatic precursor to the high-silica rhyolite associated with Climax molybdenum mineralization.

Another variety of rhyolite porphyry dike locally exposed in the area was termed the Climax late dikes by Bookstrom (1989). Rhyolite dikes of this type are exposed in Quartzville Creek 4 km from the Sweet Home Mine (where it was called the St. Louis dike by Singewald and Butler 1931), in the upper cliffs of Moose Creek 3 km from the Sweet Home Mine, and rarely, as talus blocks below the high wall above the Sweet Home Mine where it has been termed the square quartz porphyry. These dikes are light gray with 10–20%, 1- to 2-mm phenocrysts of subequal amounts of quartz, plagioclase, and oligioclase. Rare biotite and coarse, pink orthoclase phenocrysts distinguish the Climax late dikes from the later white porphyry (Singewald and Butler 1931). Fluorite is locally present at the dike ends, and other minerals noted include topaz, zircon, rutile,

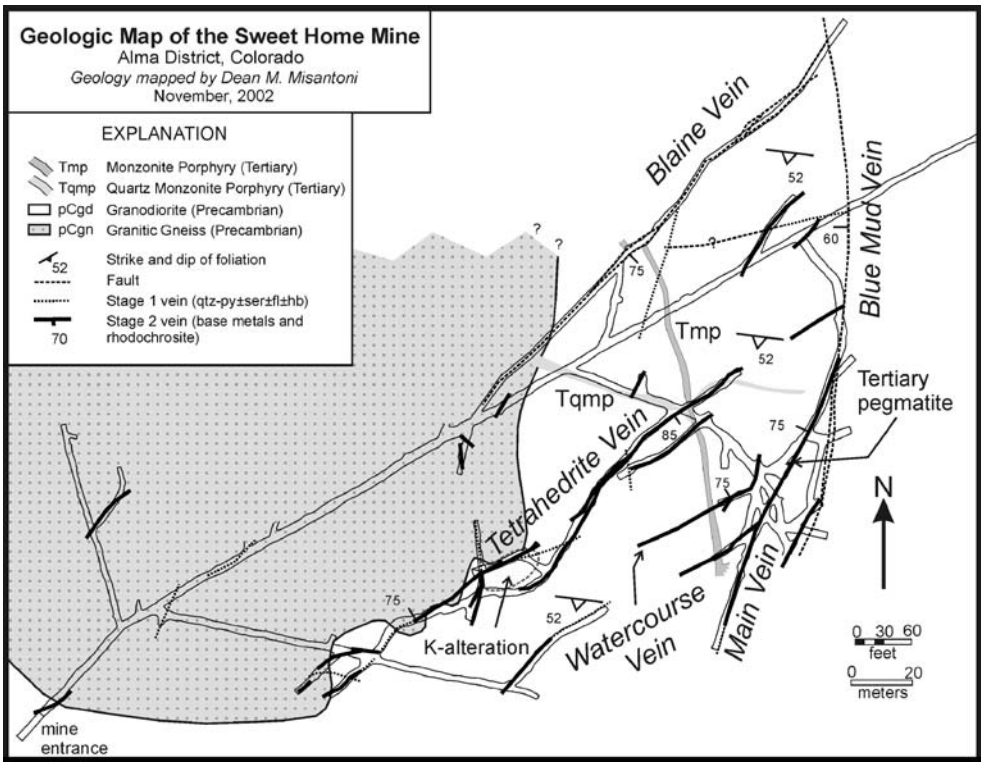

Fig. 4 Underground mine map of the Sweet Home Mine. This is the only level accessible in the modern mine. Dips given are average for the vein

and monazite (Bookstrom 1989), all of which suggest a chemical affinity to Climax high-silica rhyolite. These phases were not observed in the rare samples of rhyolite porphyry found directly above the Sweet Home Mine. At Climax, the Climax late dikes cut the major molybdenum orebodies but are weakly mineralized with quartz–molybdenite veinlets; they have been dated at 25.5±2 Ma (Bookstrom 1989). The rhyolite porphyry dike in Moose Creek has a similar age of ~25 Ma (error uncertainty unreported; Bookstrom 1983). The ages of these dikes correspond to the age of mineralization in the Sweet Home deposit of 25.8±0.3 Ma (40Ar/39Ar method; Barbá et al. 2005); this age is slightly younger than the previously reported K/Ar ages (27–31 Ma; Misantoni et al. 1998). The thinning, branching nature of these rhyolite porphyry dikes away from the Climax intrusive complex, as well as flow lineations on dike margins which plunge back towards Climax, have been interpreted by Bookstrom (1989) as indications that these dikes originated from the magmatic system at Climax.

Mine geology

Figure 4 summarizes the underground mapping of the Sweet Home Mine. Veins at the Sweet Home Mine are predominately hosted by Proterozoic meta-igneous and metamorphic rocks with minor mineralization in Tertiary porphyritic dikes and a syn-mineralization pegmatite. All units were altered and mineralized, indicating that all were emplaced before hydrothermal mineralization. These rocks are described in detail in Widmann et al. (2004); a brief summary follows. Proterozoic-banded gneiss is the principal vein host in the Sweet Home Mine and consists of quartz and K-feldspar-rich layers alternating with strongly foliated biotite rich bands. Biotite schist, migmatite, and aplite are present within the banded gneiss; these were not broken out during mapping. A small stock of granodiorite that intrudes the granite gneiss is weakly foliated, particularly near the contact. The foliation suggests that it was pre-metamorphic and, therefore, of Proterozoic age, which is the age of the metamorphic events in this part of Colorado (Tweto 1980).

Tertiary quartz monzonite and monzonite porphyry dikes are similar-appearing gray-green rocks with biotite, quartz, and orthoclase phenocrysts. Phenocrysts are typically 3 mm in diameter. Magnetite, apatite, and titanite are common accessories (Patton et al. 1912). The monzonite contains abundant hornblende rather than biotite and crosscuts the quartz monzonite porphyry. The dikes have no associated alteration haloes or mineralogical zonation; mineralized veins cut the dikes (Fig. 4).

The pegmatite, exposed near the central portion of the main vein with no cross-cutting relations (Fig. 5), consists of coarse quartz and K-feldspar crystals with very minor muscovite. The minor quantity of muscovite in the pegmatite is in marked contrast to the typical Precambrian pegmatite dikes in the region, which locally contain as much as 10% muscovite. The pegmatite also locally contains disseminated clots of molybdenite, suggesting a possible link to Climax-style mineralization. The pegmatite has been dated at 25.9±0.3 Ma (Barbá et al. 2005), coincident with hydrothermal vein formation. There are numerous small occurrences of the pegmatite within various stopes; it is more prevalent than suggested by Fig. 4.

A 3- to 7-m-wide, vertical, pebble dike was found on the western side of Buckskin Gulch close to the Sweet Home Mine. The pebble dike consists of rounded elliptical to spherical, pebble to cobble-sized clasts of Precambrian gneiss and granite cemented by hydrothermal quartz, rock flour, and minor fluorite. Distinctive clasts of Tertiary age were not noted within the dike. Strong limonite staining is associated with the breccia dike.

A series of isolated, thin quartz–pyrite–molybdenite veins are exposed 2 km northwest of the Sweet Home Mine at Kite Lake. This area was drilled by Climax Molybdenum Company in 1978–1980 (three drill holes), and weak chloritic, phyllic, propylitic, and potassic alterations were encountered. Pyrite, sphalerite–galena–chalcopyrite, and fluorite–molybdenite–rhodochrosite veinlets

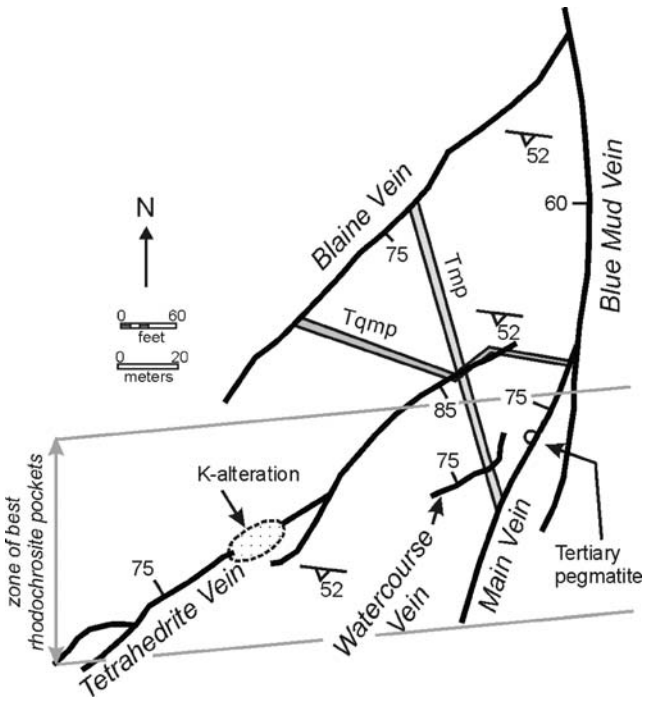

Fig. 5 Schematic underground plan map showing principal veins, pegmatite, and zone of potassic alteration. The zone of potassic alteration has been projected upwards from the side walls to the intersection with the tetrahedrite vein in the back; no field relations between the two were observed

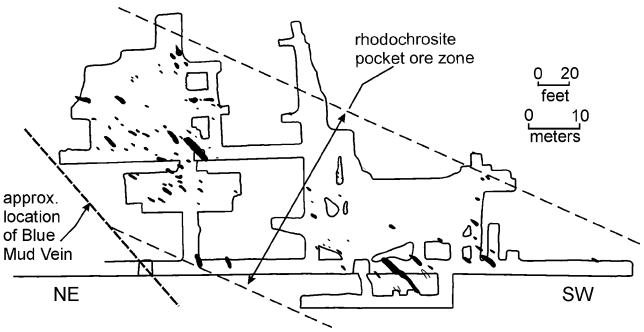

Fig. 6 Longitudinal section of the Main vein showing mine workings and rhodochrosite pockets (*in black*). Limits of the rhodochrosite "ore shell" shown by *dashed lines*. The intersection with barren Blue Mud vein is shown as heavy *dashed line*

were widely and sparsely scattered throughout the drill holes, and no significant molybdenite mineralization was encountered (Bookstrom 1983).

Five main veins are distinguished in the Sweet Home Mine: Main, Tetrahedrite, Watercourse, Blaine, and Blue Mud (Figs. 4 and 5). Principal rhodochrosite production was from the Main vein, with lesser amounts from the Tetrahedrite and Watercourse veins. The Blue Mud vein is a barren post-mineralization fault-vein. Production from the Blaine vein was extremely minor.

The Sweet Home Mine workings cover a relatively small area (~300×120 m; Fig. 5). The overall hydrothermal system appears larger. Red rhodochrosite has been historically reported from the collapsed Tanner Boy workings directly across Buckskin Gulch (Emmons 1886). These veins are likely the on-strike continuation of the Sweet Home veins. Nonetheless, the Sweet Home hydrothermal system as a whole appears to be relatively small.

Even within a vein, the volume of rhodochrosite produced was quite limited, as demonstrated in a longitudinal section showing the location of vug pockets along the Main vein that actually yielded specimen rhodochrosite (Fig. 6). Of all these vug pockets, five contributed the majority of production value in the mine. Specimen mining is very much a bonanza, "feast or famine" operation.

Most of the mine workings shown in Fig. 4 existed before rhodochrosite production as a result of silver mining and exploration. The economics of specimen mining simply do not allow for significant mine development and exploration. Utilization of preexisting mining operations appears required for a profitable specimen mining operation.

Structural vein controls

Three, steeply dipping (between 70 and 80°) fault and fracture sets have been mapped within the mine workings; these have WNW, NE, and N strikes. All three structural trends contain Tertiary porphyry dikes, which are altered and mineralized, and all are inferred to be pre-mineralization. The Precambrian foliation also strikes WNW, but has a shallower dip approximately 50°SW (Barbá et al. 2005). The NE-striking faults crosscut the WNW-striking structures; they also host the majority of silver-base metal-rhodochrosite mineralization in the mine (Misantoni et al. 1998). North-striking faults formed last and crosscut all other vein sets. Field relations and kinematic analysis suggest that these faults originally formed in Laramide time under a compressional regime, and later extension reopened the faults, providing the open space necessary for vug formation (Barbá et al. 2005; this study). Extension in this part of Colorado coincided with early phases of Rio Grande rifting at approximately 30 to 24 Ma (Wallace 1990; Dickinson 2003). The age of mineralization at Sweet Home (25.8±0.3 Ma; Barbá et al. 2005) nicely coincides with the early phase of Rio Grande rifting, and the structural style and orientation of faulting during mineralization is generally the same as Rio Grande rift-related faulting. Minor offsets on some veins suggest a minor post-mineralization movement.

A detailed structural analysis (Barbá 2004) determined the controls upon vug formation (and thus, location of rhodochrosite pockets) within the mine. Three vug occurrences were noted: at changes with strike and dip of a given vein, at the intersection of two vein structures, and at openings formed by fault bends controlled by host rock foliation (Barbá 2004; Barbá et al. 2005). In general, the fault/vein intersections were responsible for the major pockets and refraction due to metamorphic foliation accounts for most of the smaller pockets (Misantoni et al. 1998).

Rhodochrosite pockets rake dominantly to the SW (Fig. 6). An upper limit to gemmy rhodochrosite deposition has been established in the workings of the Main vein. Several years of unprofitable, barren, upward raise development were undertaken before this relationship was understood. A lower limit to rhodochrosite pocket formation was inferred by mine management to be present beneath the main workings southwest of the intersection with the barren Blue Mud fault vein. The Sweet Home Mine was closed in 2004, in large part, because it was believed that the principal structure, the Main vein, had been mined out.

The inclined ore zone, if not rotated, would imply a fluid source to the northeast or toward the zone of pyritic alteration in the Red Amphitheater. However, it is not completely clear if this is the original structural orientation. Farther to the northeast (toward Mt. Bross; Fig. 2), Widmann et al. (2004) documented a series of wedge-shaped fault blocks with differing strikes and dips. Bookstrom (1989) interpreted these as reflecting the apex of a broad buried intrusive which he termed the Alma dome.

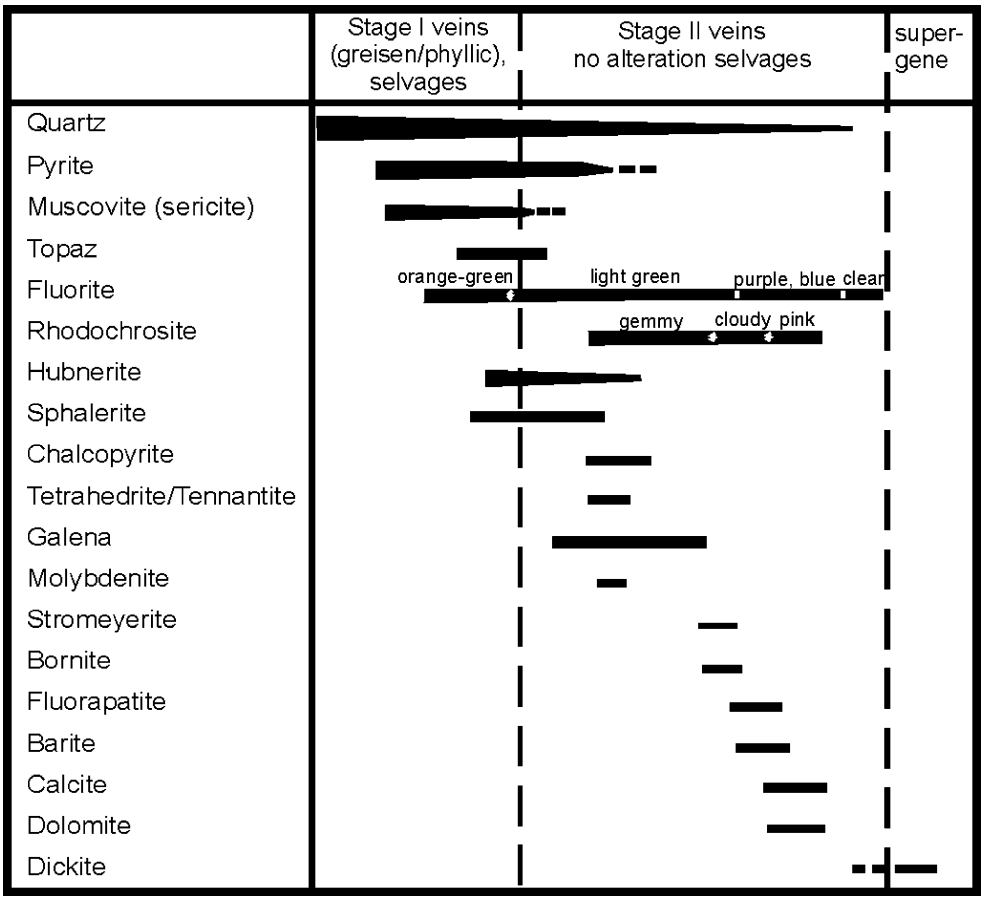

Fig. 7 Paragenetic diagram of Sweet Home vein filling minerals; earliest formed minerals to the *left*

Paragenesis

A typical vein in the Sweet Home Mine is 2 to 25 cm in width. There are two main styles (stages) of veins at Sweet Home (Misantoni et al. 1998; Wenrich and Aumente-Modreski 1998; Fig. 7). Vein fillings of the earliest stage (stage 1) consist of quartz, pyrite, green fluorite, sericite rosettes, ±hubnerite, topaz, and/or sphalerite. Stage 2 veins contain base metal and silver minerals (galena, sphalerite, tetrahedrite, chalcopyrite, pyrite, and stromeyerite), rhodochrosite, and blue to purple fluorite, as well as local accumulations of apatite, barite, and calcite. Rhodochrosite is relatively late in the paragenetic sequence of stage 2 veins. Within the middle portions of banded veins, the rhodochrosite is commonly pink and massive. It is only in isolated vug pockets that the rhodochrosite takes on a redder color, particularly when the crystals are well formed and isolated (Misantoni et al. 1998). When paragenetic relations are available, the red gemmy rhodochrosite precedes cloudy pink rhodochrosite (Wenrich and Aumente-Modreski 1998). Purple or colorless fluorite crystals can be seen perched on rhodochrosite crystals, although fluorite deposition occurs throughout the entire paragenetic sequence (Misantoni et al. 1998). Silver principally occurred in stromeyerite or tetrahedrite. Sphalerite at Sweet Home is commonly opaque and black. The iron content of Sweet Home sphalerite is typically minimal, ranging from 0.01 to 0.06 wt% Fe, although a 1.43-wt% Fe content was noted in one sample (Wenrich and Aumente-Modreski 1998). These authors noted that areas containing rhodochrosite with the purest (low iron) composition also contained the sphalerite with the lowest iron contents; these sphalerites tended toward being clear or light golden orange in color.

Key paragenetic observations are as follows: tetrahedrite, early (but not continuous) deposition of pyrite, and chalcopyrite rather than bornite+pyrite. All told, the paragenetic sequence defines an intermediate sulfidation assemblage (Sillitoe and Hedenquist 2003). The overall sequence of metal deposition is tungsten first, then zinc, then lead, then copper-silver, and finally, manganese.

Alteration

All rocks within the mine are altered to some extent. Propylitic alteration is widespread, particularly in biotite-rich rocks such as local biotite schist or biotite-rich bands within the gneiss. Thin veinlets of epidote–chlorite–pyrite–hematite are common. Biotite is commonly sulfidized to pyrite, and subsequent oxidation yields the bright iron

oxide staining seen on the surface in the Red Amphitheater above the mine. The propylitic alteration does not appear to be vein-controlled; rather, it is interpreted as resulting from the intrusions of the Buckskin Gulch igneous center that were emplaced approximately 15 million years before Sweet Home mineralization. Timing of the pyritization event is unclear.

Two types of hydrothermal alteration are directly associated with vein mineralization: potassic and greisen/phyllic. Potassic alteration is present in a limited area near the central portion of the Tetrahedrite vein (Fig. 5). In the granitic gneiss host rock, K-feldspar replaced plagioclase, and coarse metamorphic biotite crystals are replaced by fine aggregates of 1-mm-long biotite blades. Rare 1- to 2-cm-wide pink K-feldspar veinlets radiate from this area and are cut by mineralized veins (Barbá et al. 2005). This area and the area of the nearby pegmatite dike are interpreted as centers of (magmatic) fluid flow at the onset of the hydrothermal system.

The dominant style of vein-related alteration consists of coarse, white (greisen) muscovite, fine-grained fluorite, pyrite, and quartz. In places, only quartz and pyrite with minor fine-grained sericite are seen. Alteration selvages are 2 to 13 cm in width, approximately equal to vein widths (Misantoni et al. 1998). No time relations between the two alteration styles were observed; both are associated with early quartz–pyrite–fluorite–hubnerite–sphalerite veins. Later sphalerite–galena–tetrahedrite–rhodochrosite veins, in structures that were not open during the early greisen stage, typically lack alteration selvages. Rather, their contact with the K-feldspar-rich wall rock is knife-sharp, and the wall rock is unaltered.

Late-stage clay is present in open faults and fractures throughout the mine. This clay is post-mineral and interpreted as a supergene effect from the oxidation of pyrite by downward percolating meteoric water. Rhodochrosite fragments in the otherwise barren clay veins suggest post-rhodochrosite brecciation and fault movement followed by clay formation.

Fluid inclusions

A reconnaissance fluid inclusion study (approximately 20 samples) was performed on Sweet Home samples by Reynolds (1998). His results are summarized below. All inclusions encountered were two-phase, liquid-rich aqueous inclusions whose vapor bubble disappeared upon heating. No vapor-rich inclusions were noted (thus, no evidence for boiling) nor were halite-bearing inclusions seen. The highest temperatures of homogenization (360–370°C) came from the earliest quartz of stage 1 veins. Later stage 1 quartz associated with hubnerite, muscovite, and/or topaz yielded homogenization temperatures of 325–340°C. Early stage 1 fluorite yielded homogenization temperatures up to 325°C. Sphalerite-hosted inclusions at the end of stage 1 deposition yielded homogenization temperatures of 260–305°C. All stage 1 fluids had salinities estimated to be in the order of 2–4 wt% NaCl equivalent, as well as containing an estimated 1–2 mol% CO_2.

Stage 2 rhodochrosite contained fluid inclusions that yielded homogenization temperatures of 280–310°C. These temperatures were found in the most transparent, deepest red rhodochrosite. Cloudy but still bright red rhodochrosite yielded lower homogenization temperatures of 255–280°C. These two fluids also had salinities estimated to be in the order of 2–4 wt% NaCl equivalent as well as an estimated 1–2 mol% CO_2. The latest opaque pink rhodochrosite contained inclusions, which yielded homogenization temperatures of 135–145°C. The latest fluorite crystals contained inclusions, which yielded homogenization temperatures as low as 112°C.

Salinities of the fluid inclusion decreased rapidly with temperature. Below 250°C, there was no evidence of CO_2, and estimated salinities fell from approximately 3.5 wt% NaCl equivalent at the onset of ruby-red rhodochrosite deposition to virtually pure water at the close of fluorite deposition.

Stable isotope data

A limited oxygen and deuterium isotope study was performed on four samples (Misantoni et al. 1998). Early stage 1 quartz–pyrite–sericite–hubnerite veins yielded oxygen isotope compositions of +7.7 and +8.5‰; this falls within the range of water of magmatic origin (Taylor 1974). The muscovite yielded an estimated deuterium composition of −82‰; again, this overlaps the range of magmatic water composition (Taylor 1974). Stage 2 quartz–rhodochrosite veins had oxygen isotope compositions in the range of +4.4 to +5.6‰. These results were interpreted as indicating fluids dominantly of magmatic origin but with a dilution by meteoric water in the order of 10 to 20% (Misantoni et al. 1998).

Discussion of isotope and fluid inclusion data

A combined interpretation of the isotopic and fluid inclusion data suggests that a low salinity magmatic fluid started precipitating vein fill minerals at least at 370°C (the 370°C has not been corrected for pressure; the actual highest temperature of formation is higher). This fluid was cooled, and mineralization continued through the interaction of increasing, but modest amounts of meteoric water culminating in an extremely dilute, relatively low-temperature hydrothermal fluid (112°C, again, the actual depositional temperature is higher owing to pressure corrections).

Although there are indications of very minor dilution by meteoric water at higher temperatures, significant dilution did not start until the system had cooled below 250°C. There was no boiling or phase separation throughout the mineralization sequence, nor were there high salinity fluids present.

The high temperatures, minimal groundwater dilution, and absence of boiling suggest a relatively deep hydrothermal system believed to be in the order of at least 1.5- to 2.5-km depth. The absence of broad alteration haloes, the coarse crystals, and the apparent lack of vertical zoning also support precipitation at relatively great depths.

This combination of fluid inclusion characteristics is unusual (Reynolds 1998). Either the magmatic fluid at Sweet Home had characteristics different from most porphyry systems, or the fluid traveled considerable distance from the source porphyry pluton, cooling, and becoming less saline. However, the pegmatite and small zone of potassic alteration in the center of the Sweet Home system suggest that the fluid upflow point and overall thermal center of the hydrothermal system were relatively close beneath the present workings. Thus, a significant vertical transport distance for the hydrothermal system would appear to be ruled out. It is worth pointing out that a comparable spatial position at Climax (pegmatite pods and small amounts of potassic feldspar veining) would correspond to approximately the upper portion of the orebody or just above the top of the molybdenite ore shell (Wallace et al. 1968; White et al. 1981). The Sweet Home system, although probably porphyry molybdenum related, is not a direct analog to a Climax-type molybdenum system. The John Reed prospect, which contains ruby-red rhodochrosite and which lies on the periphery (1.5 km from the center) of the Climax system but not directly above it, is a more probable analog for the Sweet Home deposit. Somewhere, another Climax-type molybdenum orebody may well lie buried in the greater Alma District.

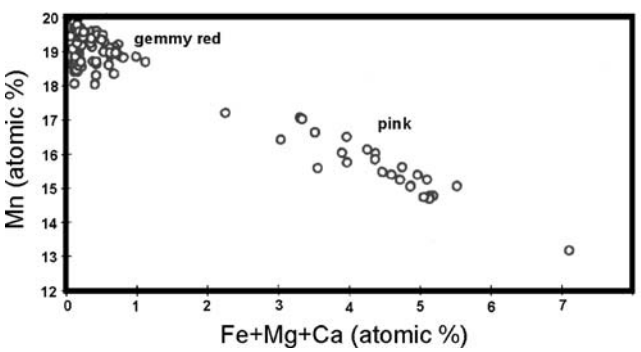

Fig. 8 Compositional analysis of Sweet Home rhodochrosites. The ruby-red, gemmy rhodochrosites are essentially pure manganese carbonate. Lower value pink rhodochrosites contain 2–7 at.% Fe^{+2}, Ca Mg contaminants. Modified from Wenrich (1998)

Rhodochrosite geochemistry

The crystal structure of rhodochrosite is similar to that of calcite or siderite. The typical contaminants in rhodochrosite are ferrous iron, calcium, magnesium, and to a much lesser degree, zinc. Ferrous iron substitutes for manganese through a continuous solid solution series to the iron carbonate siderite (Deer et al. 1962). There is a debate as to whether a continuous solid solution series between rhodochrosite and calcite exists (Goldsmith and Graf 1957; Fubini and Stone 1983); nonetheless, the rhodochrosite crystal lattice can accept considerable quantities of calcium ions.

Microprobe analysis of approximately 20 Sweet Home rhodochrosite specimens was performed by Wenrich (1998) to assess the chemical control for the color of the rhodochrosite. Her results (Fig. 8) clearly show that the brightest ruby-red, gem quality rhodochrosite is pure manganese carbonate with essentially no dilution by other elements. Later stage pink rhodochrosite has a consistent contamination of 2–7 wt% Fe^{+2}+Mg+Ca. Of the three ions, Fe^{+2} appears to be the "bad actor" at Sweet Home (Wenrich 1998), transforming ruby-red gem quality rhodochrosite to opaque bubblegum-pink rhodochrosite (with a significantly lower market value).

Gemmy rhodochrosite, in general, is marked by the apparent absence of contamination by other ions. In this regard, Sweet Home rhodochrosite is among the purest recorded in the world. By comparison, a rhodochrosite from Ljubija district, Bosnia, considered at the time to be among the purest recorded (Deer et al. 1962), contained 0.60 wt% Fe and 0.36 wt% Ca. In contrast, a ruby-red rhodochrosite from the Good Luck pocket (generally considered among the best quality rhodochrosite from the entire Sweet Home Mine) contained 0.14 wt% Fe and 0.03 wt% Ca.

Discussion

The Sweet Home Mine is interpreted as related to a Climax-type porphyry molybdenum system. Supporting evidence includes the following: (1) an age (25.8±0.3 Ma) that coincides with that of the end stages of molybdenum mineralization at Climax, approximately 7.5 km to the northwest; (2) a geochemical (Mn, W, F) and mineralogical (topaz, fluorine, hubnerite, greisen muscovite) signature typically associated with Climax-type systems (White et al. 1981); (3) the occurrence of porphyry rhyolite dikes, a breccia dike, and local quartz–molybdenite veinlets (although not in the mine per se), all suggestive of a Climax-type system in the general area; (4) a small pegmatite occurring within the mine with an age coincident with mineralization that also contains minor clots and

disseminations of molybdenite; and (5) occurrence of ruby-red rhodochrosites at Climax and other high-silica rhyolite systems (discussed further below).

One important distinction is that Climax-type systems typically feature multiple igneous events and multiple hydrothermal events. As documented by Seedorff and Einaudi (2004a,b), at the Henderson porphyry molybdenum deposit in the northeastern Colorado Mineral Belt, a dozen igneous events were focused on three, closely spaced intrusive centers. Each intrusion supplied its own magmatic fluid pulse, which coalesced into a molybdenite ore shell above the individual intrusive centers. At the Sweet Home Mine, however, there is only evidence for a single, relatively small, pulse of dilute magmatic fluid.

The isotopic and fluid inclusion evidence at Sweet Home suggests magmatic input early in the paragenesis followed by consistently declining temperatures and salinities. This is suggestive of a single, continuously evolving system. Note that the stage 1 and stage 2 vein assemblages are only found in the limited Sweet Home Mine area and not elsewhere on Mt. Bross. In addition, the rhodochrosite-bearing veins are apparently centered upon the potassic alternation and pegmatite, suggesting a linkage between the two; this is supported by the synchronous age dates. At Sweet Home, evidence for multiple magmatic hydrothermal events is lacking.

Bookstrom (1989) suggested that the Climax and Alma hydrothermal systems were genetically linked and proposed that a single granitic batholith (termed the Climax–Alma granite batholith) underlies both districts. The late White and Climax rhyolite porphyry dikes that are most likely associated with Sweet Home mineralization vector back toward Climax (Bookstrom 1989). Overall, the Climax–Alma igneous system (which includes the batholith and the dikes) appears quite broad with lateral dimensions in excess of 8 km, but so far, only one cupola/igneous center is known (located at its far northern end), and that is precisely where the molybdenum orebodies specifically are located. Thus, whereas the Sweet Home deposit is broadly associated with a Climax-type hydrothermal system, at present, there is no supporting evidence that a molybdenite orebody underlies, or is in close proximity to, the deposit. Having said this, we acknowledge that drilling has directly tested neither the Sweet Home deposit at depth nor the heart of the pyritic halo it abuts. Of the three drill holes placed in the general area by Climax Molybdenum Company in the late 1980s, one (A in Fig. 2) tested a small quartz–molybdenite vein cluster to the north at Kite Lake, another (B in Fig. 2) tested a rock chip Mo geochemical anomaly on the periphery of the Red Amphitheater, and the third (C in Fig. 2) tested a lower order gravity anomaly near Kite Lake. None of the drill holes had any great success (Bookstrom 1983).

Table 1 Homogenization temperatures of fluid inclusions in rhodochrosite from various intermediate sulfidation vein deposits

Deposit	Homogenization temperature range (°C)	Reference
Butte, Montana	200–268	Gorman-Lewis et al. 2002
Creede, Colorado	204–208	Robinson and Norman 1984
Mountain Queen, Colorado	180–230	Powell 1992
Pasto Bueno, Perú	238–245	Landis and Rye 1974
Sultan Mountain, Colorado	209–227	Musgrave and Thompson 1991
Sunnyside, Colorado	203–237	Casadeval and Ohmoto 1977
Sweet Home, Colorado		Reynolds 1998
Ruby red	280–310	
Cloudy red	255–280	
Pink	135–145	

Why is the Sweet Home Mine such a famous mineral collecting locality? It is because its rhodochrosite is among the best in world in color, clarity, and crystal form. But what caused this? The electron microprobe analyses indicate that these rhodochrosites are remarkably pure and free from other ion contaminants. Temperatures of deposition, particularly for the gemmy varieties of rhodochrosite, are elevated, and the isotopic evidence suggests derivation from magmatic fluids.

Rhodochrosite is a common mineral in intermediate sulfidation vein deposits; Sillitoe and Hedenquist (2003) use it as a defining mineral for this type of deposit. While rhodochrosite is quite common in vein deposits, it is typically of the bubblegum-pink variety. Ruby-red gem quality rhodochrosite is, in fact, quite rare. Moreover, rhodochrosite from most vein deposits typically formed at temperatures significantly below those seen at Sweet Home. A compilation of rhodochrosite fluid inclusion homogenization temperatures (Table 1) reveals that from those deposits where data are available, rhodochrosite has fluid inclusion homogenization temperatures typically between 180 and 250°C, with most in the 200–225°C range. In contrast, Sweet Home rhodochrosites have homogenization temperatures significantly higher, 280–310°C for the ruby-red variety and 255–280°C for the cloudy red variety. Thus, Sweet Home rhodochrosite stands out in two basic ways: its remarkable purity (which leads directly to its ruby-red color) and its inferred temperature of formation at temperatures significantly above that of "normal" rhodochrosite.

Table 2 Worldwide occurrences of gemmy red rhodochrosite

Locality	Deposit type	Associated igneous rocks	Rhodochrosite occurrence	Associated minerals	Reference[a]
Capillitas, Argentina	Polymetallic veins in diatreme	Granite/monzonite	Stalactites	?	1
Climax, Colorado	Porphyry molybdenum	High silica rhyolite	Late veinlets	w-qtz, fl[b]	2, 3
Henderson, Colorado	Porphyry molybdenum	High silica rhyolite	Late veinlets	w-qtz, sph, gal, fl[c]	2, 3
Hotazel, South Africa	Metamorphosed sedimentary Mn	None?	Isolated vugs	?	4, 5
John Reed, Colorado	Veins (distal Climax)	?	Veins	qtz, py, fl[b]	2, 3
Moose, Colorado	Veins, central Central City	Quartz bostonite, alkali rhyolite	Veins	qtz, py, pur-fl[c]	2, 3
N'Chwaning, South Africa	Metamorphosed sedimentary Mn	None?	Isolated vugs	fl[c]	4, 5
Pachapaqui, Perú	Polymetallic veins and mantos	Rhyolite porphyry	Late vugs in veins	fl[b]	6, 7
Pasto Buena, Perú	Tungsten greisen	Quartz monzonite	Late vugs in veins	qtz, hub, gn fl[b]	7, 8
Sweet Home, Colorado	Intermediate sulfidation veins	Rhyolite porphyry?	Vugs in veins	qtz, fl[b], tet	9
Uchucchacua, Perú	Ag, Mn skarn, replacements, veins	Dacite porphyry	Reaction rims on Mn–Fe silicates	qtz-fl[b]	7, 10
Urad, Colorado	Porphyry molybdenum	High silica rhyolite	Late veinlets	qtz-py, mo, fl[b]	2, 3

[a] 1, Colombo 2003; 2, Miller 1971; 3, Eckel et al. 1997; 4, Wilson and Dunn 1978; 5, Von Bezing et al. 1991; 6, Diaz 1975; 7, Crowley et al. 1997a–c; 8, Landis and Rye 1974; 9, this paper; 10, Bussel et al. 1990

[b] Syn-deposition with ruby red rhodochrosite

[c] Uncertain if syn-depositional

qtz quartz; *py* pyrite; *sph* sphalerite; *tet* tetrahedrite; *hub* hubnerite; *mo* molybdenite; *w* white; *gn* green; *pur* purple; *fl* fluorite; *?* not known

Table 2 is a compilation of deposits in which ruby-red, gemmy rhodochrosite is known to occur. In certain deposits such as Uchucchacua, Perú, N'Chwaning and Hotazel, South Africa, ruby-red rhodochrosite is a result of the recrystallization of a Mn-rich "protore". The latter two mines are part of the Kalahari Manganese Field, the world's largest sedimentary manganese deposit. This field was subjected to an alkalic hydrothermal/metamorphic event at its northern end; temperatures are estimated to have reached 450°C (Von Bezing et al. 1991). At the N'Chwaning Mine, gemmy-red rhodochrosite scalehedrons were locally found in one small area of the mine contained in isolated vugs within high-grade bixbyite–braunite ore (Wilson and Dunn 1978). Stringers and veinlets to the vugs are absent; the inference is that the elements for the rhodochrosite were mobilized from the immediately adjacent wall rock. The rhodochrosite at Hotazel formed in a similar setting in isolated vugs and fissures, with ruby-red rhodochrosite associated with quartz and manganite (Von Bezing et al. 1991). Like at Sweet Home, the South African rhodochrosites are chemically pure. One N'Chwaning rhodochrosite was reported to contain FeO and CaO contents of 0.2 and 0.1 mol%, respectively; a Hotazel rhodochrosite contained more CaO, 2.0 mol% but similar low FeO and MgO contents, 0.2 and 0.13 mol%, respectively (Wilson and Dunn 1978; Von Bezing et al. 1991).

Uchucchacua, Perú is a silver–manganese replacement vein and skarn district (Bussell et al. 1990). At this locale, ruby-red rhodochrosite locally occurs as a late reaction front replacing manganese–iron silicates (Crowley et al. 1997a–c). A dark manganese oxide matrix is typical. The gemmy-red rhodochrosites from Uchucchacua typically have quartz and water-clear fluorite associated with them. As in the South African occurrences, the constituents for the ruby-red rhodochrosites at Uchucchacua are inferred to have been derived from the immediate Mn-enriched wall rocks with preferential leaching and precipitation of manganese.

Several Andean base metal vein districts, such as Pasto Buena, Perú; Capillitas, Argentina; and Pachapaqui, Perú are known to contain ruby-red rhodochrosite, at least in limited quantities. Pasto Buena is a tungsten-base metal greisen system centered about a quartz monzonite stock. At the core of this quartz monzonite stock is a low-grade molybdenite–wolframite–chalcopyrite stockwork (Landis and Rye 1974). Limited quantities of gemmy, ruby-red rhodochrosite (perhaps two dozen truly outstanding specimens) were produced from the Huayllapon Mine during the 1970s to mid 1980s. Rhodochrosite typically occurred in a very late vug stage of mineralization that was synchronous with large amounts of fluorite deposition (Crowley et al. 1997a–c). The ruby-red rhodochrosite typically occurred perched on quartz needles, but

was also seen associated with pale green fluorite or hubnerite.

The Pachapaqui, Perú district contains a series of Ag–(Pb–Zn–Mn) veins and small mantos-cutting Cretaceous limestone and quartzite. The veins are located proximal to a series of rhyolite porphyry intrusions. The center of the district is a large breccia pipe that is cut by bipyramidal quartz porphyry dikes (Diaz 1975; Copemisca, 1974, private reports). Pachapaqui is well known for its specimens of pale pink rhodochrosite and manganoan calcite. In 1993, a limited quantity of raspberry-red rhodochrosite was collected from this district (Crowley et al. 1997a–c). Unfortunately, detailed information about these rhodochrosites and their associations is lacking. Fluorite has been noted in the district, but in uncertain relations to the rhodochrosite.

Capillitas, Argentina is noted for fine rhodochrosite stalactites, the inner cores of which are commonly ruby-red. Geologically, Capillitas is sulfide-rich polymetallic [Pb–Zn–Mn–Cu (As, Sb, Ag, Au)] vein system cutting a diatreme comprised of rhyolitic and dacitic volcanic rocks and granitic breccias overlying and surrounding a granite–monzonitic batholith (Colombo 2003).

Of perhaps greater interest is the strong association of high-silica (Climax-type) porphyry molybdenum deposits with ruby-red rhodochrosite. The Climax, Urad, and Henderson deposits all have produced ruby-red rhodochrosite specimens (Miller 1971; Eckel et al. 1997). However, the bulk-tonnage mining practiced at Henderson, Climax, and Urad precluded production of significant quantities of specimen rhodochrosite. These specimens are comparable to much of the Sweet Home material, if not quite the quality of its very best. At Urad, specimens have been reported that consist of deep red, transparent rhodochrosite rhombohedrons up to 5 cm on edge on milky quartz crystals. Pyrite, molybdenite, and green or purple fluorite also are associated with rhodochrosite (Miller 1971; Eckel et al. 1997). Henderson rhodochrosite is similarly associated with white quartz; an association with molybdenite or pyrite has not been noted. Lighter pink-red rhodochrosite from Henderson with associated sphalerite-galena or clear to light green fluorite is also known. At Climax, rich, red cloudy to transparent rhodochrosite rhombohedra up to 5 cm are found associated with white quartz crystals and green, blue, or purple fluorite crystals. Rhodochrosite at Climax was particularly common in the underground workings near Ceresco Ridge (the southern boundary of the deposit; Eckel et al. 1997) where it is rumored that several rhodochrosite-bearing stopes were closed by management concerned about excessive specimen-collecting by workers.

Other Colorado rhodochrosite occurrences are clearly related to porphyry molybdenum mineralization or highly evolved silicic igneous intrusions. The John Reed Mine is a small mine located approximately 1.5 km southwest from the Climax open pit in Alicante Gulch. Deep, rose-red gemmy rhodochrosite crystals perched on associated quartz and pyrite matrix have been reported from this locality

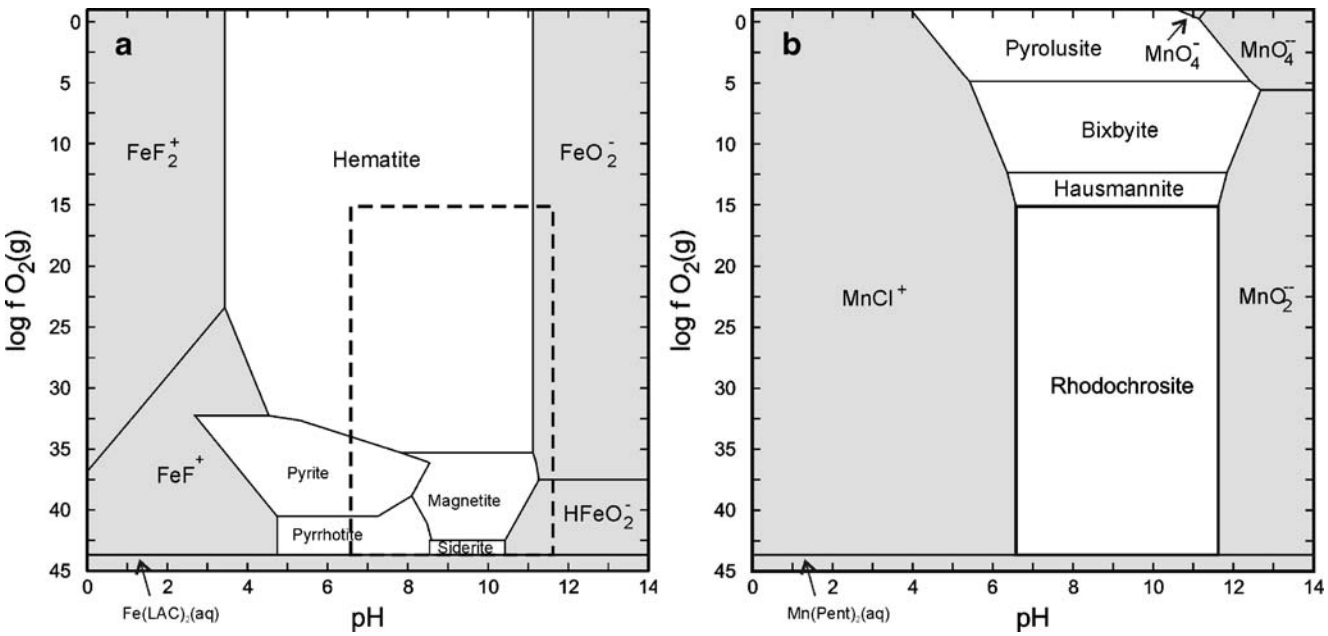

Fig. 9 Log fO2/pH diagrams for **a** Fe^{+2} and **b** Mn^{+2} constructed for temperatures of 250°C and the conditions listed below (courtesy of J. Brugger). Aqueous phase fields are *shaded* and solid phase fields are *white*. The *heavy dashed line* in **a** represents the rhodochrosite field taken from **b**. These diagrams were calculated using The Geochemist's Workbench and the thermodynamic properties in the database distributed by the Lawrence Livermore National Laboratory (Version 8, Revision 6). Other assumptions: vapor-saturated pressure P=39.83 bars, a[main]=10^{-4}, a[H2O]=1, f [CO2(g)]=10 bars, a[S]=10^{-2}, a[Cl]=1, a[F]=10^{-1}

(Miller 1971); most likely, John Reed is a distal portion of the overall Climax hydrothermal system. The Moose Mine is a small vein occurrence in the central potion of the Central City district (Sims et al. 1963), a district that has been proposed as an alkaline porphyry molybdenite system by Rice et al. (1985). At the Moose and nearby Gem and Belman Mines, Miller (1971) reported bright red gemmy rhodochrosite rhombohedral crystals associated with purple fluorite, quartz, and pyrite.

So what was it about the Sweet Home hydrothermal system that favored rhodochrosite deposition at high temperatures and with minimal contamination by Fe^{+2}? The high temperatures were favored by formation at relatively deep levels with little groundwater contamination, thus, promoting large crystal sizes from slowly cooling fluids.

The minimal contamination by Fe^{+2} possibly was related to Sweet Home being an abnormally low-Fe system. This is suggested by the minimal amount of pyrite (which was only deposited early in the paragenesis) and the absence of other significant iron phases. This possibility can be further explored through log fO2/pH diagrams for Fe^{+2} and Mn^{+2} constructed for 250°C (Fig. 9). If a pH change of a near-neutral fluid was the precipitation mechanism, then most (nearly all?) of the iron would be removed from the fluid as pyrite by the time rhodochrosite precipitated. This is supported by the paragenesis at Sweet Home. However, this cannot be the only explanation, as this paragenesis is observed in other rhodochrosite deposits, which lack ruby-red rhodochrosite (Table 1).

Alternatively, the hydrothermal fluids at Sweet Home could have been so highly oxidized such that no Fe^{+2} was present in solution, only Fe^{+3}. This, too, is permissible by fO2/pH relationships (Fig. 9). However, there is no hypogene hematite associated with the Sweet Home system, and high-sulfidation/oxidation phases such as alunite, dickite, and native sulfur are absent.

It may be significant that rhodochrosite deposition at Sweet Home occurred in relatively neutral pH conditions. This is suggested by the apparent lack of wall rock alteration accompanying rhodochrosite deposition after the strong greisen and sericitic alteration of the early stages of vein filling. The inference is that by the time of rhodochrosite deposition at Sweet Home, excess hydrogen ions were consumed through wall rock interactions. Thus, the quality of the rhodochrosite in a hydrothermal system may be a function of the overall acidity of the system; more neutral solutions may favor rhodochrosite deposition at higher temperatures that, in turn, favors end-member rhodochrosite.

Two associations with gemmy red rhodochrosite stand out: (1) an association with highly evolved silicic igneous rocks such as the high-silica rhyolites of Climax-type molybdenum deposits and (2) a strong association of fluorite co-deposited with the ruby-red rhodochrosite. Even in systems not as highly evolved as the Climax-type rhyolites such as Pasto Bueno (Landis and Rye 1974), there is evidence of substantial fluorine in the hydrothermal system. Fluorine typically complexes with high-field strength elements such as tin, uranium, and thorium, but unfortunately, there is limited data on Mn-fluoride or Fe-fluoride complexes (see Sverjensky et al. 1997 for what is available).

We propose a model in which the manganese at Sweet Home was carried as a mangano–fluoride complex that had a solubility significantly lower than either iron–chloride or iron–fluoride complexes at the relatively high temperatures of ruby-red rhodochrosite deposition. This allowed the precipitation of Fe-free rhodochrosite at relatively high temperatures followed by Fe-bearing rhodochrosite at lower temperatures more typical of other rhodochrosite occurrences (Table 1). In contrast to Sweet Home, most base metal hydrothermal systems are chlorine-dominated (Sillitoe and Hedenquist 2003), and their rhodochrosites are pink and iron-bearing. What makes Sweet Home special is that it is a fluorine-dominated hydrothermal system. Exploration for ruby-red rhodochrosite deposits should thus take the fluorine-dominated geochemistry into account.

Conclusions

The quartz–pyrite–sphalerite–rhodochrosite–fluorite veins in the Sweet Home deposit are interpreted as a distal variant of a Climax-type porphyry molybdenum system. It is not clear whether the Sweet Home deposit represents a distal limited fluid pulse of the overall Climax magmatic/hydrothermal system or a distal portion of a separate molybdenum-bearing hydrothermal system. Regardless, the strong association of gemmy-red rhodochrosite with fluorine-rich silicic igneous hydrothermal systems suggests that opportunities exist for specimen grade rhodochrosite at other Climax-type molybdenum deposits, as well as in fluorine-enriched silicic igneous-related hydrothermal systems in general.

Acknowledgment Kate Barbá provided some vein and wall rock samples from her work at the Sweet Home Mine; the use of these samples is greatly appreciated. The other mappers of the Alma quadrangle, Beth Widdman and Richard Madole, along with field assistants Kate Barbá and Marilyn Moll, provided much useful feedback in the field and office. Joel Brugger constructed and provided the log fO2/pH diagrams. Reviews by Graham Closs, Kalin Kouzmanov, and Joel Brugger greatly improved the paper.

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