BULLETIN DE L'ASSOCIATION MINERALOGIQUE DU CANADA
THE CANADIAN MINERALOGIST
JOURNAL OF THE MINERALOGICAL ASSOCIATION OF CANADA

Volume 34 October 1996 Part 5

The Canadian Mineralogist
Vol. 34, pp. 905-930 (1996)

OCCURRENCE AND SIGNIFICANCE OF STALACTITES WITHIN THE EPITHERMAL DEPOSITS AT CREEDE, COLORADO

WAYNE R. CAMPBELL

11 Manzanita, Littleton, Colorado 80127, U.S.A.

PAUL B. BARTON, Jr.*

U.S. Geological Survey, M.S. 954, Reston, Virginia 20192, U.S.A.

ABSTRACT

In addition to the common and abundant features in karst terranes, stalactites involving a wide variety of minerals have also been found in other settings, including epigenetic mineral deposits, but these are almost always associated with supergene stages. Here we describe a different mode of occurrence from the Creede epithermal ore deposits, in Colorado, wherein stalactites of silica, sphalerite, galena, or pyrite formed in a vapor-dominated setting, below the paleo-water table, and except possibly for pyrite, as part of the hypogene mineralization. Axial cavities may, or may not, be present. No stalagmites have been recognized. The stalactites are small, from a few millimeters to a few centimeters long and a few millimeters in outer diameter. They represent only a small fraction of one percent of the total mineralization, and are covered by later crystals. Their growth orientation usually is unobservable; however, the parallel arrangement of all stalactites in a given specimen, consistency with indicators of gravitational settling, and the common presence of axial structures make the stalactitic interpretation almost unavoidable. In contrast with common carbonate stalactites, the growth mechanism for the sulfide and silica stalactites requires extensive evaporation. Stalactitic forms have also been reported from other deposits, mostly epithermal or Mississippi-Valley-type occurrences, but we caution that stalactite-like features can form by alternative processes.

Keywords: stalactites, speleothems, quartz, chalcedony, pyrite, sphalerite, galena, Creede, Colorado, vapor-dominated, ore deposits.

SOMMAIRE

En plus des stalactites que l'on retrouve en abondance dans les terrains karstiques, il s'en trouve aussi faits d'une grande variété de minéraux dans d'autres milieux, y inclus les gîtes minéraux épigénétiques. Dans ce milieu, il s'agit presque toujours de stalactites associées aux stades supergènes. Nous décrivons ici un mode de formation différent, applicable au cas du gisement épithermal de Creede, au Colorado, dans lequel des stalactites de silice, de sphalérite, de galène ou de pyrite signalent un milieu à dominance de phase vapeur. Ces stalactites se seraient formées sous le niveau des nappes d'eau et, sauf peut-être dans le cas de la pyrite, feraient partie de la minéralisation hypogène. Une cavité axiale peut être présente ou non. Par contre, nous n'avons

---

* To whom correspondence about this contribution should be addressed.

pas trouvé de stalagmites. Ces stalactites sont petites, leur longueur allant de quelques millimètres à quelques centimètres, et leur diamètre externe étant millimétrique. Elles représentent seulement une fraction d'un pourcent de la minéralisation totale, et leur surface est tapissée de cristaux tardifs. L'orientation de leur croissance n'est généralement pas observable; toutefois, l'agencement parallèle des stalactites dans un échantillon donné, la concordance de cette orientation avec les indicateurs d'accumulation par gravité, et la présence courante d'un canal axial rend quasi inévitable l'interprétation qu'il s'agit bien de stalactites. Au contraire du cas des stalactites courantes composées de carbonate, le mécanisme de croissance des stalactites à sulfures et à silice semble indiquer une évaporation poussée. Des formes stalactitiques ont aussi été décrites dans d'autres gisements, mais il faut se rappeler que des mécanismes alternatifs de formation ont pu en être responsables.

(Traduit par la Rédaction)

Mots-clés: stalactites, spéléothèmes, quartz, calcédoine, pyrite, sphalérite, galène, Creede, Colorado, dominance de vapeur, gîtes minéraux.

INTRODUCTION

Stalactites in karst and cave environments are well recognized, and stalactites of oxides and carbonates also are common in the supergene setting of ore deposits. Documentation of stalactites related to primary hydrothermal systems is rare (Barton & Campbell 1994). Most of the occurrences reported from hydrothermal deposits are in Mississippi-Valley-type (MVT) ores (Hicks 1950, Hill & Forti 1986); however, comments by colleagues indicate that stalactitic features also are observed within other types of hydrothermal deposits, even though they are not generally reported in the literature. A list of known occurrences of non-karstic stalactitic or similar structures (Table 1) supplements the occurrences listed in Hicks (1950). The main purposes of this paper are to draw attention to the existence of these features by reporting on the occurrences of stalactites within the epithermal ore deposits at Creede, Colorado and to interpret their significance in demonstrating former vapor-dominant conditions in hydrothermal deposits in general.

Hill & Forti (1986) defined a stalactite as "a vertically-hanging speleothem formed by dripping water and generally having a tube or remnant of a tube at its center. Variant shapes may be tubular, conical, bulbous, deflected, or a combination thereof." In this paper, we shall apply the term "stalactite" to pendant speleothems formed by dripping water, regardless of whether the openings are solution caverns or tectonic openings, whether the occurrence is in a cavern in limestone or in a fissure in an ore deposit, and whether an axial channel is present or not.

In contrast, Peck (1978) used the term "stalactite" to include speleothems having axial tubes, regardless of their orientation, specifically referring to those from the Upper Mississippi Valley lead–zinc district that he reasonably interpreted to have formed as collars around former points of mixing of liquids. We prefer the term "chimney" (named for the sulfide structures marking the venting of hot submarine springs into cold seawater) for sites of local mixing where two liquids, or a liquid and a vapor, mix by injection of one into the other.

Our emphasis here is on stalactites as primary depositional features in ore deposits, but related features such as "draped" deposits, suggestive of sagged paint, and "chimney-like" features that formed as collars around orifices localizing mixing are included in our discussion for completeness. "Flowstone" is a term denoting mineral matter deposited as "a smooth, sheet-like speleothem formed by films of flowing water" (Hill & Forti 1986); it forms on the walls of a vapor-filled cavity, whereas ordinary vein minerals are deposited from a fluid that completely fills the cavity. Whereas we have little trouble in recognizing stalactites, flowstone is much less easily distinguished from simple vein-filling. In almost every instance, stalactites in ore deposits serve as substrata for additional deposition, either as a flowstone deposit from a water film or as a site for precipitation from a surrounding massive liquid.

We extend the term "stalactite" to include flowstone that has pendant forms suggestive (or even demonstrative) of deposition from downward-flowing films of water in contact with vapor, a process shared with icicles (Makkonen 1988). The stalactites of carbonates, oxides, sulfates, *etc.*, so commonly noted in the supergene zone of mineral deposits, are not of concern here.

OCCURRENCES OF STALACTITES IN THE CREEDE DISTRICT

Geological background

The Creede district has been the object of intensive study (summarized by Bethke & Lipman 1987) for several decades. The district has been a major producer of silver (about 2500 tonnes produced since 1891), with minor lead, gold, zinc, and copper, over the past century; although production has ceased, a substantial amount of mineralized ground remains. The mineralization is an adularia–sericite type of epithermal deposit (Heald *et al.* 1987) contained in steeply

TABLE 1. OCCURRENCES OF SILICA OR SULFIDE SPELEOTHEM-LIKE FEATURES WITHIN CAVES AND ORE DEPOSITS

Location	Mineralogy	Morphology[1]	Occurrence	Reference
		"EPITHERMAL DEPOSITS"		
Creede District, Colorado, USA	Ch	'stalactitic'	vein, subsinter?	Plumlee (1989); this study
	Sp, Gn	stalactitic	vein	" " " "
	Py	stalactitic	vein & travertine	" " " "
	Py	"drape"	vein	" " " "
Andalgala district, Catamarca, Argentina	Rhs + traces of late Py	'stalactitic'	vein	Shaub (1972), Brodkorb & Brodkorb (1979) (excellent specimens are common at mineral dealers)
Camp Bird Mine Colorado, USA	"Silica" + Qtz	'stalactitic', 'helictitic'	vein	Lees (1990; pers. comm., 1991)
Cinola mine, B. C., Canada	"Silica"	'drape'		P. Bethke (pers. comm., 1988)
Cirotan, West Java, Indonesia	Au-+ W-bearing Qtz	stalactites + stalagmites	vein	Jébrak et al. (1996)
Divide, Nevada, USA	"Silica"	'drape'	subsinter conduit	B. Berger (pers. comm., 1988)
Kvaison, Caucasus, Russia	Sp	stalactitic	vein?	Zhabin (1983)
Mahogany mine, Oregon, USA	"Silica"	stalactitic	subsinter conduit	J. Rytuba (pers. comm., 1989)
Mount Painter, South Australia	Qtz	"nailhole"		Coats & Blissett (1971)
Oe mine, Japan	Rhs	stalagmitic	vein (?)	Kojima & Sugaki (1983)
Osarizawa, Japan	Mrc	stalactitic	vein	P. Barton, (pers. obs., 1970)
Porco mine, Bolivia	Sp	stalactitic	vein	C.G. Cunningham et al. (1994)
Central Peru	Pb-As minerals	stalactitic	vein, late stage leaching	Lacy & Hosmer (1956)
San Cristobal, Peru	Carb + Sulf	stalactitic	vein, replacement	Dalheimer et al. (1983)
Taxco, Mexico	Mrc	stalactitic	vein	M. Barton, (pers. comm., 1993)
	KARST & MISSISSIPPI	VALLEY-TYPE	DEPOSITS	
Location	Mineralogy	Morphology[1]	Occurrence	Reference
Djebel Hallouf, Tunisia	Gn + Sp + Py + Cal + Jor	stalactitic	karst/MVT	Rouvier (1971); Zuffardi (1976)
Laurium, Greece	Carb + Py + Mrc + Gn + Sp + Cer + Cal	stalactitic	karst after limestone replacement	Leleu & Morikis (1967)
Nanisivik mine, N.W.T. Canada	Py + Mrc	stalactitic	karst	Gait et al. (1990)
Pine Point, N.W.T. Canada	Sp + Gn	stalactitic	MVT	Kyle (1981)
Salafossa, Italy	Py	stalactiform	karst/Alpine vein	Bernard et al. (1972)
Largentiera, Auronzo, Italy	Sp	stalactiform	karst/Alpine vein	Lagny (1971)

Table 1, continued

Location	Mineralogy	Morphology[1]	Occurrence	Reference
Southeast Missouri, USA				
Fletcher mine	Py	chimney	MVT	A.V. Heyl (pers. comm., 1990)
Magmont mine	Mrc + Gn	stalactitic	MVT	Hagni & Trancygner (1977)
West Fork mine	Fe-sulfide	stalactitic & stalagmitic	MVT	Mavrogenes & Hagni (1992)
	Fe-sulfide	chimney		Marikos et al. (1986)
Silesia, Poland	Sp + Gn	stalactitic	MVT	Sass-Gustkiewicz et al. (1982)
Trzebionka, Silesia, Poland	Sp + Cal Gn + Mrc	stalactitic & rare stalagmititic	MVT	Sobczynski & Szuwarzynski (1975)
Upper Miss. Valley,	Mrc	chimney	MVT	Heyl et al. (1959)
Wis., Ill., USA	Py	stalactitic	MVT	R.V. Kirkham (pers. comm., 1990)
Shullsburg mine	Py + Mrc + Gn	stalactitic	MVT	LaBerge (1984)
Amelia mine	Py + Mrc	stalactitic	MVT	Kucha & Barnes (1995)
Marsden (Black Jack)	Mrc + Gn + Sp	stalact., chimney	MVT	Peck (1978)
NON-ORE (or POST-ORE) KARST/CAVE ENVIRONMENT				
Amaltheus Clay, Germany	Py	stalactitic	diagenetic	Hudson (1982)
Jewel Cave, South Dakota, USA	Ch + Qtz	stalactitic	karst cave	Deal (1964)
Lava Beds Nat. Mon. California, USA	Opal	coralloidal	lava tube	Anderson (1930)
Wheal Julia mine Namaqualand, S.A.	Cc, Bn, Ccp	stalactitic	supergene	Cornelissen (1958)
Raibl mine, Italy	Cal	"stalactitic" (inverted chimney)	post-mining subaqueous "karstic"	DiColbertaldo (1947)
Montevecchio, Sardinia	Mrc	stalactitic	supergene	Zuffardi & Salvadori (1964)
Rio De Janeiro, Brazil	"Siliceous"	stalactitic	faulted gneiss overhang	Caldcleugh (1829)
Geysers, California	Opal	stalactitic	overhang	Vonsen (1941)
Rock Creek, Oregon, USA	Ch + Qtz	stalactitic	diabase vugs	Housley (1952)
Wyoming, USA	Ch	stalactitic	karst cave	Broughton (1974)
OTHER DEPOSIT TYPES, (EXCEPT EPITHERMAL, KARST AND MVT)				
Ballynoe, Silvermines, Ireland	Py	'chimney'	SEDEX	Larter et al. (1981)
Leadville, Colorado, Tucson mine	Gn	stalactitic	mesothermal	Emmons et al. (1927)
Mid ocean ridges	Py + Ccp + Sp + Silica + Anh + others	chimney	Massive sulfide	many descriptions
Choroque, Bolivia	Cassiterite?	stalactitic	tin vein	Currier (1995)

Symbols and abbreviations: Anh anhydrite, Bn bornite, Carb carbonate, Cal calcite, Cer cerussite, Ch chalcedony, Cpy chalcopyrite, Cc chalcocite (white and blue), Gn galena, Jor jordanite, Mrc marcasite, MVT: Mississippi-Valley-type deposit, Py pyrite, Qtz quartz, Rhs rhodochrosite, SEDEX: sediment-hosted exhalative deposit, Sp sphalerite, Sulf sulfosalt.

[1] The single quotation marks denote material resembling stalactites (or chimneys) in all respects, but collected from unoriented specimens, without visual proof of pendent (or upward) growth.

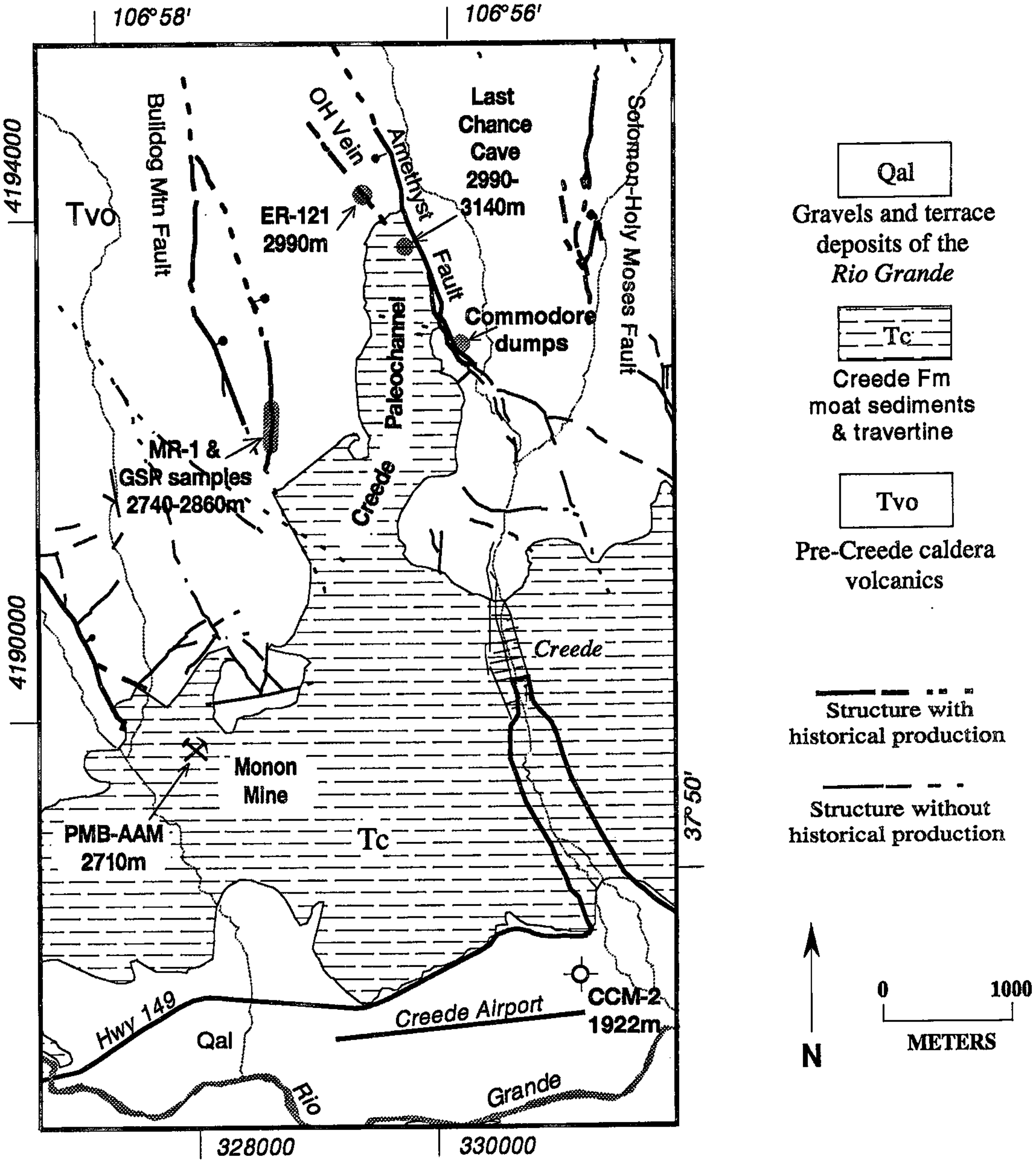


FIG. 1. Location map for stalactite samples within the Creede mining district, Colorado. Value below sample number is the elevation in meters. CCM–2 is the site of the U.S. Geological Survey's "Creede Caldera Moat Drilling Project" bore hole that contains pyrite stalactites in calcite veins.

dipping, northwest-trending fissure veins (Fig. 1). The veins displace thick, welded, rhyolitic ash flows constituting the intracaldera fill of the resurgently domed late Oligocene Bachelor caldera (the second of at least six major middle Tertiary calderas) in the central San Juan Mountains of southwestern Colorado. The mineral association is characterized by base- and precious-metal sulfides, native silver, and minor sulfosalts in a gangue that includes quartz (locally chalcedonic), barite, rhodochrosite, pyrite, chlorite, fluorite, and hematite. The brines of the Creede hydrothermal system are considered to have come from fluids residing in the lacustrine facies of the Creede Formation to the south; additional recharge was contributed from meteoric solutions derived from former highlands in the vicinity of the Continental Divide north of Creede, and with possible contributions of magmatic fluid as well (Bethke & Rye 1979). The Creede Formation is just over one kilometer thick and consists of local stream conglomerate and a wide variety of lacustrine clastic sediments, ash flows, and waterlain silicic tuff, all of which are intercalated with travertine and deposited within an annular lake or moat surrounding the resurgent dome inside the Creede caldera. The latest local igneous event was about 1 m.y. prior to the Creede hydrothermal event (Bethke *et al.* 1976).

Mineral deposition was almost entirely as open-space filling, and extensive, interconnected, crystal-lined open spaces remain today, 25 m.y. after the event. Mineralization varied in both time and space, as is summarized in Table 2; the speleothem-like features described in this paper constitute a minuscule part of the total record. Fluid inclusion evidence for boiling from quartz from the OH vein places the paleo-water table about 500 meters above the sample sites (Barton *et al.* 1977, Hayba 1992), which is similar to depths estimated from postulated level of the land surface at the time of mineralization (Steven & Eaton 1975). Plumlee (1989) estimated a depth as shallow as 350 meters for the Bulldog Mountain vein system. Along the top of the ore, condensation of acidic vapors produced an impermeable cap of sericitic alteration (Barton *et al.* 1977).

Location and orientation of samples

The locations and elevations of samples are shown on the map (Fig. 1). The samples are diverse in mineralogy, morphology, and paragenesis. There is no evidence, or even a suggestion, that they formed in a single, district-wide stalactite-forming event.

Many 'stalactites' were collected from unoriented "dump" material; thus we lack absolute proof of their original orientation. However, their usual rigorously parallel orientation within each specimen and consistent arrangement relative to other geopetal criteria, such as sedimented mineral grains, make it inconceivable to us that they could be any feature other than stalactites. Nonetheless, we use single quotes to enclose all references to materials having undocumented orientation from the field.

Description of stalactites: general considerations

Stalactites[1] are found "hanging" in former open spaces within piles of breccia fragments, from irregularities along vein walls, or from older layers of relatively large euhedral crystals. Silica 'stalactites', including many with an axial cavity, "hang" from earlier silica, even from the tips of euhedral quartz, without evidence of feeder channels. Unfortunately, none of the sulfide specimens that have a well-developed axial tube contain the basal substrate-attachment portion. Thus, evidence for feeder channels in the form of cracks extending into the overhanging rock or vein matter is absent for sulfide stalactites. In most instances, non-stalactitic overgrowths of hydrothermal quartz, chalcedony, or sulfides have overgrown the original 'stalactites'; their presence unequivocally demonstrates that the 'stalactites' belong to the hydrothermal event, and not to a subsequent process.

Individual stalactitic features are surprisingly monomineralic, but they have a variety of mineral compositions: silica, sphalerite, galena, or pyrite. However, it is significant that we have found no "mixed populations"; that is, silica 'stalactites' are associated with other silica 'stalactites' and never with sphalerite or pyrite 'stalactites'.

Description of silica 'stalactites'

Chalcedony-free, well-crystallized quartz or amethyst is abundant and widespread throughout the Creede district, and it constitutes one of the major gangue minerals. Locally there is much chalcedony. Some large specimens (up to several tens of centimeters across) on the dumps are as much as 50% or more chalcedony interlayered with quartz, but such samples usually show repetition of layers; an estimate of the total stratigraphic thickness of banded silica would be 5 to 10 (rarely as much as 20) cm. Banded chalcedonic silica is strongly concentrated in a small fraction of the district within one or two hundred meters of the Last Chance Cave (also known as the Chance Cave; see Fig. 1). Some similar material is found on the Commodore 3 and Commodore 4 dumps a kilometer south of the Last Chance Cave, but these materials are suspected to have come, *via* interconnected workings, from farther north in the vicinity of the Last Chance Cave; nevertheless, the actual source of the Commodore dump silica has little bearing on our interpretation. Thin seams (usually less than a few cm wide) of banded chalcedonic (now recrystallized) silica occur elsewhere in the district, usually early in the paragenetic sequence, but such deposits are small, local, and volumetrically insignificant.

The Last Chance Cave is a chambered hanging-wall zone that was shattered prior to and during mineralization; the silver values were principally in the later fine-grained materials that surround blocks of broken banded silica. The Last Chance Cave formed, and is so named, as a consequence of collapse during mining,

TABLE 2. SUMMARY OF MINERALOGY[1], ZONING, AND TENTATIVE CORRELATION OF PARAGENETIC SEQUENCE FOR THE MAIN CREEDE MINING DISTRICT

	Southern Area: Bulldog Mtn. vein South Amethyst vein Monon Hill	Central Amethyst Area: Central Amethyst vein OH vein P vein
⇑ Younger		
	V stage	E stage
	bot Py[5], Mrc, Sp, Stib, Sulf	bot Py, Mrc, Sp, Stib, Sulf
	IV stage (minor)	D stage
	Sp, Gn, Ccp	Sp, Gn, Ccp
	III stage	C stage
	Fl, Qtz	Fl, Qtz, Sd
	II stage	B stage
	Brt, Qtz, *Gn*, *Sp*, Tet, Sulf, Silver	Qtz, *Sp*, *Gn*, Ccp, Chl, Hem, Tet
	I stage	A stage
	Rhs, *Qtz*[6], Ad	*Qtz*[6], Chl, Ad
⇓ Older		
	Travertine	
	Cal, *Py*[5]	

Abbreviations: Ad = adularia, bot Py = botryoidal pyrite, Brt = barite, Cal = calcite, Chl = chlorite, Ccp = chalcopyrite, Fl = fluorite, Gn = galena, Hem = hematite, Mrc = marcasite, Py = pyrite, Qtz = quartz or chalcedony or banded silica, Rhs = rhodochrosite, Sd = siderite, Sp = sphalerite, Stib = stibnite, Sulf = sulfosalts, Tet = tetrahedrite.

[1] Principal minerals in each stage listed in order of abundance. Additional minerals are generally present, but in much smaller amonts. Italicized abbreviations of minerals indicate those exhibiting local stalactitic morphologies.

[2] The North Amethyst area is not included here as no speleothems have been recognized there.

[3] The paragenesis for Southern Area is from Plumlee (1989).

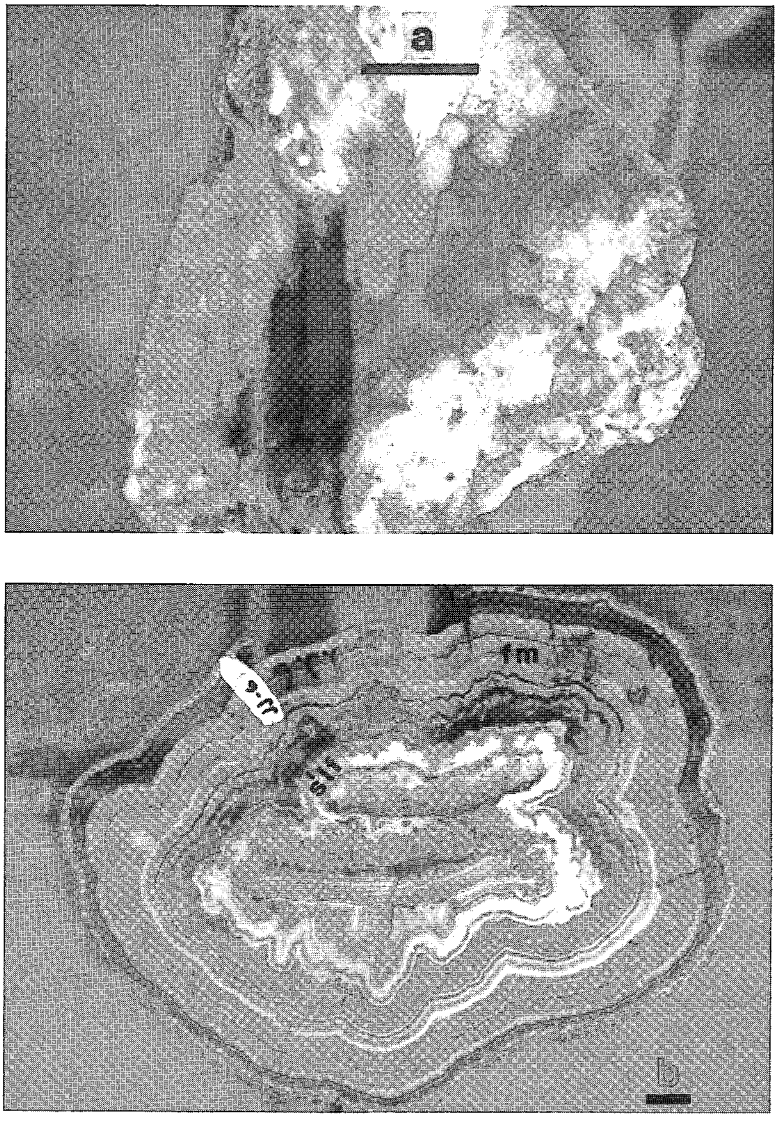
[4] The paragenesis for Central Amethyst Area is from Bethke and Rye (1979).

[5] Pyrite stalactites from Monon Hill mine may have been deposited either at this stage or during the older, travertine-forming event.

[6] Banded silica deposition is first observed in this stage, but may also have been deposited during later stages, especially II and B. The exact stage of silica 'stalactite' formation is ambiguous.

not as a pre-mining solution feature. It is similar to the bonanza bodies in the hanging wall of the famous Comstock Lode in Nevada (Vikre 1989). The Last Chance Cave is located at a major structural plexus of shattering where the footwall of the major structure, the Amethyst vein normal fault, is more convex toward the hanging wall near the surface than it is a few hundred meters down dip. Thus, during movement on the normal fault, the hanging wall became an unsupported arch that collapsed, with attendant localized brecciation (Cannaday 1950; for further discussion, see Steven & Ratté 1965). Two major veins, the OH and P, emanate from the swarm of minor structures in this plexus. In addition, a paleocanyon (filled by coarse conglomerate of the pre-ore Creede Formation) crosses above the ore zone and enters the Creede moat to the south. The former canyon is truncated by the Amethyst fault in the vicinity of the Last Chance Cave, and the sediments are situated so that they almost certainly served as an aquifer for discharging hot fluids rising along the Amethyst vein-fault system. Thus, the area in which the banded silica is found was a focus for fluid flow during mineralization. The underground workings in this area are inaccessible, and the 'stalactite'-bearing banded silica samples were collected from surface or underground dumps of material believed to have been mined from the vicinity of the Last Chance Cave.

Although amethyst is a common variant of silica throughout the Creede district, the majority of the quartz layers and almost all of the chalcedony bands are colorless or white to gray. A minor amount of the



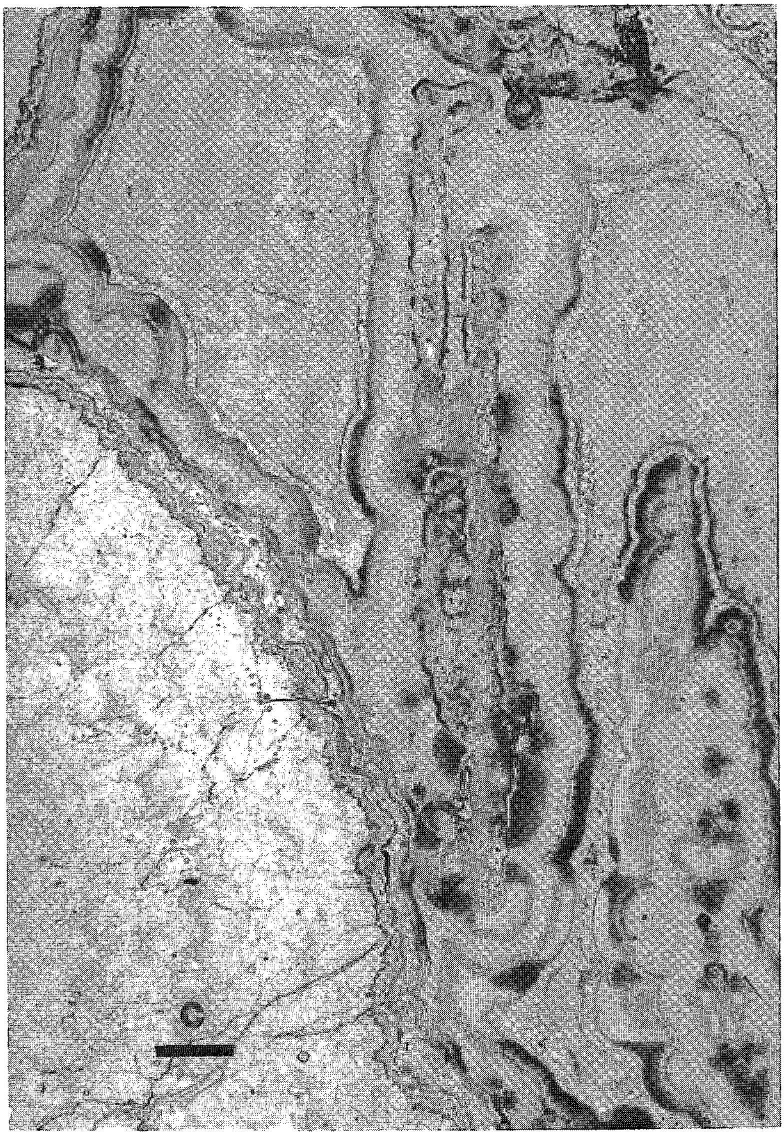


FIG. 2. Representative samples of silica 'stalactites' collected from the mining dumps of the Last Chance Cave. Photos are oriented to agree with their inferred geopetal orientation. Each of these samples is >99% silica. a) Silica 'stalactites' hanging within a banded silica vein. Sample C–97, from Last Chance dump. Bar = 1 cm. b) Sawn slab showing silica 'stalactites' hanging from the underside of a platy fragment of breccia composed of older banded silica layers, which projected into an open space along the vein. Subsequent layers of banded silica envelop the breccia fragments and silica 'stalactites'; that is, the entire array of concentric layers becomes younger outward. Sulfides (slf) and arborescent fluorite (now represented by molds visible as "smudges", fm) coprecipitated with the banded silica and are only present on the 'upward-facing side', presumably due to gravitational settling of crystal nuclei. Sample JJ–6, Last Chance dump; collected by J. Jackson. Bar = 1 cm. c) Nearly longitudinal section through silica 'stalactites'. Note the "linked" microspheres of lamellar silica forming the cores of the silica 'stalactites'. The "stalagmite" is an illusion and is actually a 'stalactite' crossing the plane of the section at an angle. Transmitted, plane-polarized light. Sample C–86, Last Chance dump. Bar = 1 mm.

chalcedony and its associated quartz is amethystine, and amethyst and white to clear quartz are commonly intergrown so that no pervasive natural process of selective coloring or bleaching of amethyst is likely. The chalcedony layers are composed of radiating fibers, which may be either length-fast or length-slow, with the former more common. All chalcedony layers are colloform and display fiber elongation oriented perpendicular to growth banding. The microcrystalline quartz shows crystal terminations pointing toward the former open vein, and it obviously grew from true solution. In contrast, the cryptocrystalline quartz and chalcedony show no evidence of growing from an ionic or molecular solution; indeed, some textures are characterized by tiny spherules (now mostly recrystallized to microgranular quartz) a few micrometers in diameter. Locally, these spherules display soft-sediment-like, deformation-induced features; in all probability, they represent deposits of flocs of silica. However, because most of the chalcedony bands remain of constant thickness regardless of their orientation as linings within formerly open spaces, we must conclude that there was usually negligible sedimentation or slumping of silica, and the issue of solution *versus* sol remains enigmatic.

Much of the chalcedony has undergone recrystallization, resulting in a "feather"-textured microcrystalline quartz that is invariably length-fast. As determined by the procedure described by Murata & Norman (1976), recrystallized chalcedony has a higher crystallinity index (4.0–4.1) than the chalcedony (1.8–2.2); large euhedral crystals have a crystallinity index in the range 7.0–9.8. Thin bands of chalcedony are locally completely recrystallized, whereas thicker bands with coarser fibers are unchanged or only partially recrystallized. The recrystallization process destroys growth banding and changes the color of the chalcedony from white or amethystine to colorless.

All silica 'stalactites' within each sample have parallel axes and grew in the same direction (Fig. 2). In samples of banded silica that have upper and lower walls present, sulfides, chlorite, flakes of hematite, and arborescent fluorite are distributed asymmetrically. They (especially chlorite and hematite flakes) are almost always observed to have been deposited on what we interpret to have been upward-facing surfaces and are apparently localized by the gravitational sedimentation of crystallites. An excellent example of this is found in sample JJ–6 (donated by J. Jackson), in which almost all of the sulfides (dark material) and arborescent fluorite occur in the banded silica on one set of surfaces. These accumulated on the upward-facing side of a platy breccia fragment (composed of older layers of banded silica, Fig. 2b) that had projected into open space. Growth of the layers was outward. The fragment and its overgrowths acted as an umbrella and shielded the banded silica layers below the fragment from accumulation of settling nuclei of sulfides and fluorite. This geometry is consistent with the slightly earlier silica 'stalactites' hanging from beneath the breccia fragment (illustrated below by occurrence IV: Fig. 5).

Out of 253 samples of banded silica collected from the Last Chance Cave mining area, only 15 contain recognizable 'stalactites'. The silica 'stalactites' occupy two brief intervals amid a multitextured paragenesis that is characterized volumetrically by more than 99% banded silica. Minor hypogene constituents in the banded silica include platy or skeletal galena, euhedral sphalerite, trace amounts of probable sulfosalts, "leaf" native silver, and lithified, fine-grained siliceous sediment. Also present are: fine-grained arborescent white fluorite (in part etched away), a few remnants of coarse (up to several cm), green and white, euhedral to anhedral fluorite, and numerous empty molds representing former (now leached away) coarse-grained sphalerite and octahedra of fluorite. The leaching of the fluorite and sphalerite was among the latest events in the deposit, because the molds are devoid of filling by later minerals. Other minerals common elsewhere in the Creede paragenesis, such as rhodochrosite, pyrite, marcasite, chalcopyrite, and chlorite, are rare. Even the locally abundant barite is sparsely represented, mostly by platy molds, that, alternatively, are suggestive of etched out lamellar calcite rather than barite; however, no remnants of lamellar calcite, or any other morphology of calcite, are found in the ore. In a few specimens, silica clearly occupies space that was once occupied by barite.

The banded silica is entirely open-space filling, and many openings remain (*e.g.*, Fig. 2a). Repeated breaking of the banded silica occurred during deposition, and a laboriously reconstructed stratigraphy of the silica shows that the fracturing events were local rather than pervasive. There are remarkably few fragments of wallrock or vein deposits other than older parts of the same local sequence of banded silica. We tentatively assign the silica 'stalactites' to the early part of the "B stage" in Table 2, because the minor chalcedonic silica found in the nearby P vein is clearly of early B stage and because the B-stage silver values, for which the deposit was mined, were in the fine-grained material surrounding the broken blocks of banded silica.

The silica 'stalactites' have lengths as great as 7 cm and diameters less than 1 cm. A rounded, conical shape is the predominant morphology observed; cylindrical morphologies also are present, but less commonly. All conical silica 'stalactites' occur as drip structures with straight, parallel axes pointing the same way. The 'stalactites' usually occur in clusters, commonly forming coalescent curtains or masses. Some cylindrical silica 'stalactites' have axes that are very slightly curved and diverge a few degrees from parallel. No feeder channels are observed in any of the material from which the 'stalactites' are suspended.

Unusual, tiny 'stalactites' that may be better described as "helictites" have been noted hanging from thin (1 mm) layers of banded silica that coats coarse crystals of amethyst. They are ~1 mm in diameter and are up to 5 mm long, and they have no visible feeder channels. They twist and turn at odd angles, but have the same geopetal orientation as the conical forms. The process by which these features formed is not obvious. Layers of chalcedony surround the "helictites", creating a botryoidal surface from which hang more typical conical 'stalactites' of silica.

No recognizable stalagmites or thickening of silica layers have been observed below any of the 'stalactites' at Creede. The layers that define the stratigraphic interval composing the silica 'stalactites' remain relatively uniform in thickness all around the vugs, even directly underneath a 'stalactite' (Fig. 2c). Only at the tips of a few silica 'stalactites' can thickened layers be observed. We have looked for, but not found, any example of the ponding of silica that might show horizontal stratification, such as is common in agate. This absence of accumulation of material beneath 'stalactites' contrasts strongly with the example of stalagmite formation at the epithermal Cirotan, West Java, gold deposit (Jébrak *et al.* 1996).

A typical silica 'stalactite' has an axis composed of concentric layers of microscopically lamellar silica forming tiny microspheres (100 to 300 μm in diameter), which may be individually linked like a pearl necklace (Fig. 2c) or grouped into a rod- or cone-shaped mass. The layers and microspheres of lamellar silica are enveloped by a thin (100 to 200 μm) white layer of very finely fibrous, radial crystallites of chalcedony. Dissolution of the lamellar silica is common, resulting in the creation of axial domains (with roundish, but generally not circular, cross sections) within the enclosing layer of fibrous silica. Dissolution down the center of the tubular structures has sculpted the layers of lamellar silica, creating, or perhaps merely widening, a central canal. Subsequent deposition of inward-pointing euhedral quartz partially or wholly fills the dissolution cavities.

The silica 'stalactites' have a "gelatinous"-looking outer layer that encases the finely fibrous layer. This "gelatinous"-looking layer also may form microspheres and has been observed to "hang" off the end of a "helictitic" cylindrical 'stalactite', an observation also made by Jébrak *et al.* (1996) at Cirotan, Indonesia. Nearly all of this material has been recrystallized, but remnants persist which indicate that the "gelatinous"-looking silica was also composed of radially oriented, finely fibrous chalcedony. Fibers are length-slow, and concentric lamellae mark stages of growth.

Encasing the layers that define the silica stalactites is more banded silica. The thickness of alternating layers of euhedral quartz and chalcedony in the banded silica is uniform when traced along the vein walls, down the side of the stalactites, and around their tips. The additional buildup of silica may total several centimeters, thereby completely burying and masking the presence of the 'stalactites'.

The dissolution, recrystallization, replacement, and overgrowth events in the silica 'stalactites' obscure the initial character of the stalactitic stage that is so critical to quantitative modeling. We have tried to determine the diameters of the initial stalactites, but we are uncertain of what to measure; we can find circular features from a millimeter or so up to 3 or 4 mm without decisive criteria to identify which, if any, are the original outer surfaces.

Description of sphalerite stalactites

Of all the stalactites observed at Creede, those composed of base-metal sulfides show the greatest compositional and morphological diversity (Fig. 3). The most abundant sulfide stalactites are composed mainly of sphalerite. Sphalerite stalactites were collected from the OH and the Bulldog Mountain vein systems, most of them by G.S. Plumlee, who clearly recognized their stalactitic character and verified their pendant orientation. Two of the best samples are of unknown orientation. One specimen (ER–121, noted on Fig. 1) is a cylinder 2.5 cm in diameter and >8 cm long, possessing a porous interior of stage-B sulfides, overgrown by stage-D sphalerite. It was collected by J. Jackson, who reported that the specimen was one of several similar 'stalactitic' features that lay "in all directions" in a vug near the 7 level on the west wall of the OH vein; we suspect that blasting had dislodged and disoriented originally attached stalactites. The second, from the Bulldog Mountain mine, is shown in Figures 3a and 3b.

Small amounts of galena and, occasionally, pyrite are intergrown or interlayered with sphalerite. Minor amounts of primary chalcopyrite are present in thin section as rod-shaped grains associated with similar, but larger, grains of galena. Both the galena and chalcopyrite rod-shaped grains grew with their long dimensions perpendicular to the growth banding of the sphalerite stalactites. Tiny euhedral crystals of quartz, usually with their *c* axes tangentially oriented, are commonly intergrown with the outermost layers, or decorate the surface of these stalactites. Euhedral blades of barite are occasionally observed within the sphalerite growth-bands. Aggregates of barite crystals, now leached out, also formed the substrate on which some of the sphalerite stalactites grew. Minor amounts of tetrahedrite and an unidentified silver-bearing sulfide associated with coarse-grained galena also are present. The ores of nearly all sphalerite stalactites have been altered by an episode of tetrahedrite disease (Plumlee 1989, p.49) or chalcopyrite disease (Barton &

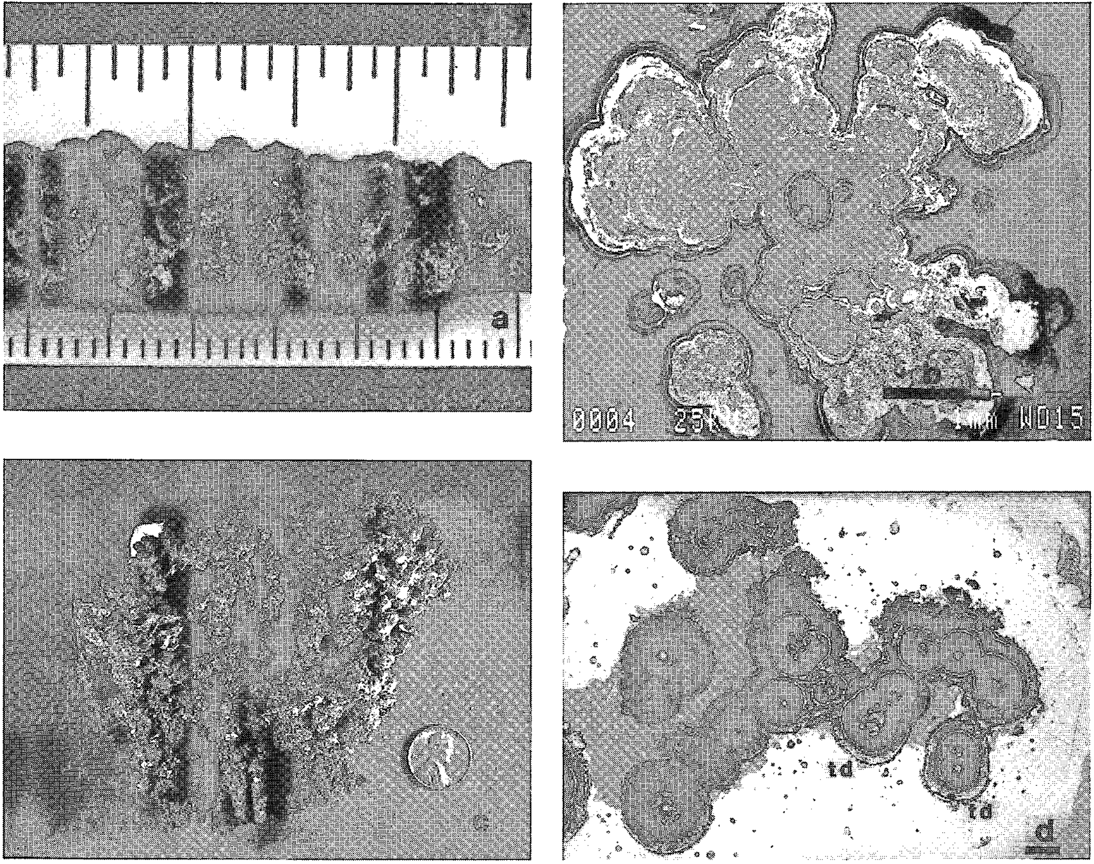


FIG. 3. Representative examples of stalactitic base-metal sulfides from the southern Bulldog vein system. a) Sulfide 'stalactite' complete with an axial canal. Intergrown, coarse-grained crystals of sphalerite and twinned galena encrust the surface of the 'stalactite'. Sample MR–1, collected by M. Roeber from an unknown locality within the Bulldog Mountain mine. Scale below 'stalactite' shows centimeters as the larger rulings; and above, the largest rulings are inches. b) SEM back-scattered electron image of colloform growth-bands and hollow axial canal of transverse section of sample MR–1. Black areas are holes, bright layers are galena, and medium gray area is sphalerite, both within the banded central region and extending outward beyond the limits of the figure. Note the euhedral crystal of late-stage sphalerite projecting into the axial canal. Bar = 1 mm. c) Sulfide stalactites with intergrown blades of barite. The stalactites grew on a substrate of large bladed crystals of barite. Sample GSP–AG collected by G. Plumlee from the Bulldog Mountain mine, elevation ~2853 m. The coin is 19 mm in diameter. d) Polished section through sample depicted in Figure 3c, viewed under transmitted, plane-polarized light. The stalactites have axial canals, some of which have coalesced, surrounded by growth-zoned, colloform sphalerite. These stalactites have been strongly altered by an episode of tetrahedrite (td) disease wherein dark (opaque in the photo), iron-rich sphalerite is replaced by clear sphalerite with finely intergrown tetrahedrite; it is seen in this photograph as a lightening of outer portions of the sphalerite layers. The "trashy" white area surrounding the stalactites and constituting half of the photo area is epoxy. Bar = 1 mm.

Bethke 1987) or both (Fig. 3d), which infected the sphalerite of stage B, but not that of stage D.

The morphologies of sphalerite stalactites include probable flowstone, narrow "strings", and more typical-looking stalactites, complete with axial tubes (Fig. 3). These stalactites have dimensions that range from 1 mm in diameter by 20 mm long to 2.5 cm diameter by >8 cm. Overall, the sphalerite stalactites are nearly cylindrical. Most of these stalactites have an axial tube, which may be hollow with tiny crystals (usually colorless sphalerite or galena lining the inner surface: Figs. 3b, d) or contain a system of interconnected pore-spaces.

Except for the flowstone, all of the sphalerite stalactites have colloform growth-bands composed predominantly of fine-grained, porous and, in some cases, friable layers of sphalerite. In sample MR–1, interlayered sphalerite and galena growth-bands form conspicuous bulbous colloform structures about the axial canal and along the entire length of the stalactite (Figs. 3a, b).

Also common to all of the sphalerite stalactites except the "flowstone" is a thick outer zone of coarsely crystalline (as much as 10 mm), yellow to brown sphalerite. Relatively large euhedral cubic crystals of galena also may be intergrown with the coarse sphalerite. Unlike the inner layers, which vary in thickness from place to place or even pinch out, this outer zone has a fairly uniform thickness (within a particular sample but not between samples) from base to tip of the stalactite. The outer zone was deposited after the episode(s) of tetrahedrite ± chalcopyrite disease mentioned above. This disease-type alteration wiped out almost all of the color banding within the sphalerite of the inner layers. The late sphalerite correlates well with the late "Stage D" sphalerite seen through much of the OH and P veins and locally in the Bulldog Mountain vein; it is known from thousands of fluid inclusion measurements to have been deposited in the 290 to 185°C range. No fluid inclusions from the flowstone-free parts of stalactites have been measured at this time; the fine grain-size and alteration probably preclude reliable measurements.

Delicate "strings" ($\leq$1 mm diameter by $\leq$20 mm long) form curtains that hang from small bulbous protuberances along the vein wall. Such stalactites have a central core of fine-grained light yellow sphalerite, which is surrounded by coarser-grained brown sphalerite. The coarser-grained sphalerite outer zone is formed by euhedral crystals of sphalerite (<1 mm diameter) that decorate the surface of the "strings".

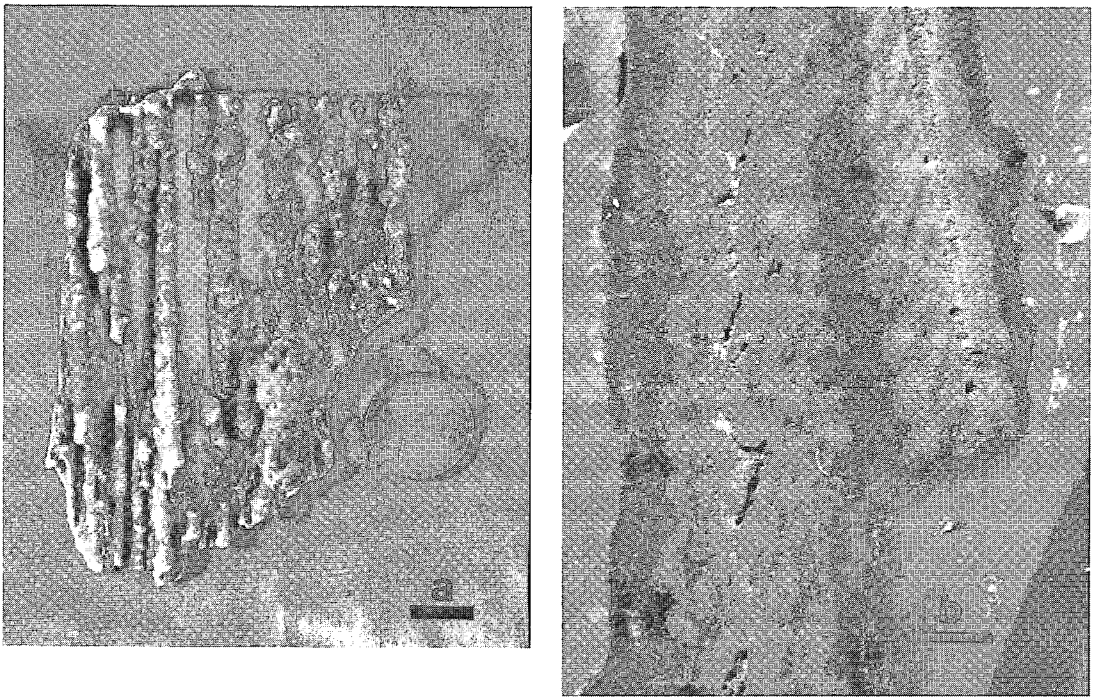
Plumlee (1989) described "flowstone", composed of a very fine-grained, porous, and light brown sphalerite (verified by X-ray diffraction), which forms ropy, icicle-like masses that were "oriented vertically within the vein" (Plumlee 1989; sample GSP–JT, his Fig. 1.6B, p. 41). The outside surface of these masses is covered with a dusting of fine crystals of galena. This feature has no evident internal structure except where thin layers of galena crystals mark the position of previous flowstone surfaces. In some cases, individual "ropes" form separate stalactites.

Description of pyrite stalactites

Pyrite stalactites in the Monon mine: Pyrite stalactites were collected by P.M. Bethke (sample PMB–AAM) from the Silver Horde level of the Monon mine, which is at a relatively low elevation (2710 m) at the southwestern end of the district. The Monon mine is unique in the Creede camp in that it yielded about 23 tonnes of silver (plus some lead and zinc) from orebodies in travertine and talus of the Creede Formation that buried a rhyolite knob. The stalactites are not coated by later ore or gangue minerals, as would be expected for very early material; thus the possibility must be considered that the pyrite was coeval with the "E" stage along the OH vein or the "V" stage along the Bulldog Mountain vein. However, it is not inconceivable that the stalactitic pyrite is associated with the travertine-forming event that occurred perhaps a million years prior to the silver mineralization. If such an early origin is accepted, the pressure – temperature – chemistry conditions deduced for the Creede mineralization would have nothing to do with the origin of this sample. Support for this latter alternative is provided by apparently similar stalactites of pyrite (described below) intercepted in drill core beneath the Mineral County airport, a little over 3.5 km south of the main Creede mining district and 3 km southeast of Monon Hill.

The Monon mine stalactites do not hang freely, but are ridges attached to the vein's nearly vertical footwall. The hanging wall of the vein has been removed by mining, but the stalactites seem to have been vertical columns connecting steeply dipping vein walls. The pyrite stalactites form pencil-size tubes that run parallel to each other down the wall (Fig. 4a). All pyrite stalactites have a porous central region (Fig. 4b).

In some stalactites, the individual tubes have coalesced to form a single stalactite. These pyrite stalactites have a diameter in the range 0.5 – 3.0 mm and a length greater than 10 cm. The Monon mine stalactites are composed of relatively thick layers of massive, fine-grained pyrite separated by thinner layers of euhedral, outward-radiating marcasite. Isolated crystals of marcasite are also observed "floating" in the layers of massive pyrite. A spongy, porous layer of pyrite makes up the walls of the stalactite's central canals, and in some cases, the outer surface as well (Fig. 4b). Polished sections of the pyrite stalactites etched with dilute nitric acid reveal a complex series of thin growth-bands within the pyrite layers. The degree of etching apparently correlates with compositional variations (mainly arsenic) within the pyrite (Plumlee 1989), although the recent observation by Dódony *et al.* (1996) of structural faults corresponding to marcasite structural layering in pyrite suggests that the anisotropism observed in this pyrite and its etching behavior may be related to structural defects. Etching also reveals that the spongy, porous layers are composed of framboidal pyrite. Each framboid is enclosed by a layer of radially oriented, bladed pyrite crystals. Minor, isolated framboids also occur within the radial layers of pyrite. The framboids are made up of rounded cubes of pyrite (1 to 3 μm on an edge) arranged into spheres (5 to 20 μm in diameter). The layers generally form a zone only 0.1 to 0.2 mm wide. According to the criteria of Kalliokoski & Cathles



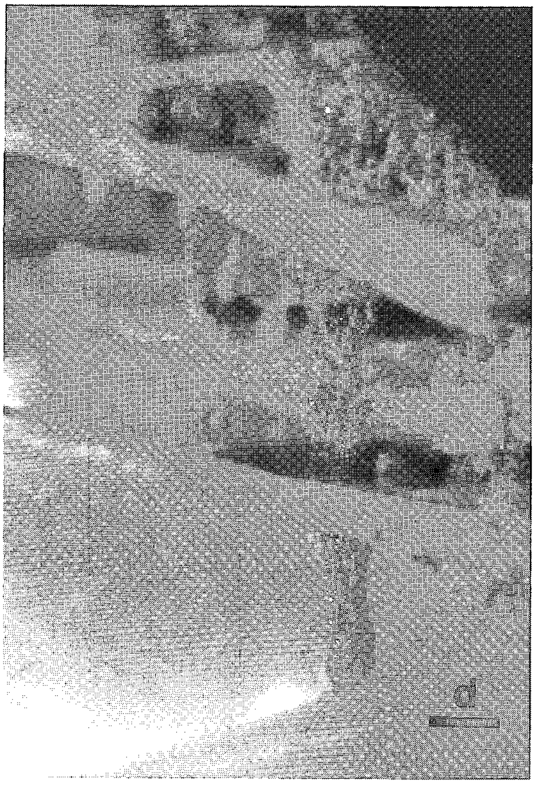


FIG. 4. Examples of the pyrite stalactites. The photos are oriented to agree with their geopetal orientation. a) Pyrite stalactites from the Monon Hill mine, sample PMB–AAM, elevation ~2710 m. The coin is 19 mm in diameter. b) Polished longitudinal section through pyrite stalactites seen in Figure 4a under reflected light. The central openings represent a discontinuous axial canal. The dull, spongy-looking layers around the axial canal and outer edge are composed of framboidal pyrite. The bar is equal to 1 mm. c) Slab through carbonate–pyrite veinlet in Snowshoe Mountain Tuff taken from core recovered in the U.S. Geological Survey's "Creede Caldera Moat Drilling Project". The drill hole was within 5° of vertical. The pyrite stalactites are suspended from the veinlet's hanging wall and the underside of the rock fragment in the middle of the veinlet. These stalactites are composed essentially of framboidal pyrite. Much of the white calcite filling the veinlet forms layers around the pyrite stalactites, which contrasts with the calcite plates in Figure 4d. The coin is 19 mm in diameter. d) Pyrite stalactite from a different vein, but the same core as noted in Figure 4c. Stalactites are suspended from vein's hanging wall into an open space within the vein. The gray, platy crystals partly surrounding the stalactites are a later stage of white calcite. The bar is equal to 1 mm.

(1969), the morphology of the framboidal pyrite grains indicates that the framboids have undergone post-depositional changes.

Pyrite stalactites in the moat, Creede caldera: Pyrite stalactites were recovered in November 1991 from drill core at an elevation of 1922 m, or a depth of 710 m (last core run from the bottom of the hole). The core resulted from the Creede Caldera Moat Drilling Project, which was part of the U.S. Geological Survey Continental Scientific Drilling Program. The stalactites in the core occur in pyrite–calcite veins that cut weakly to moderately welded Snowshoe Mountain Tuff. The stalactites are about 1 mm in diameter, as much as 15 mm long, and have a gently tapered morphology (Figs. 4c, d). Both the hanging wall and footwall of these veins are coated with a thin layer (1–2 mm thick) of pyrite. The stalactites hang from the pyrite layer coating the vein's hanging wall. No obvious stalagmitic mounds were observed beneath these stalactites, although the footwall layer is twice as thick as the hanging-wall layer. These stalactites are composed essentially of framboidal pyrite reminiscent of those from the Monon Hill sample.

Formation of these pyrite stalactites was followed by a stage of non-stalactitic, coarse, lamellar calcite. There is no visible base- or precious-metal mineralization in these samples, and we tentatively assign them to the roots of the travertine-forming system that was coeval with the filling of the structural moat of the Creede caldera, which preceded ore in the Creede district by more than a million years. It is conceivable that this part of the travertine deposition began so early that not even the present 710 m of cover was present. We do know that some of the latest travertine was deposited as knobs, terraces, and bedded sediments in the Creede Formation through a wide span of basin filling at elevations ranging from at least as low as 2400 m to at least as high as 2900 m. The early travertine may have had its own local, vapor-dominated system, an idea supported by the primary fluid inclusions in calcite examined by Nora Foley (pers. comm., 1995), which show low-salinity fluids that homogenize to the liquid at a maximum temperature of only 160°C, with no liquid CO_2 or clathrate; thus it appears that the pressure during boiling was too low for a deep, vapor-dominated regime.

Other gravitationally oriented textures in pyrite: Other textures influenced by gravity involving pyrite have been observed by Plumlee (1989, p. 226) from the Bulldog Mountain mine. Late, "Stage V" botryoidal pyrite forms vertically oriented surface striations (Plumlee's Fig. 3.4A) and downward "draped" and imbricated bulges (Plumlee's Fig. 3.4D) reminiscent of sagged paint.

Description of galena-cored stalactites

Galena, with minor sphalerite ± pyrite, forms the core of small, extremely lumpy stalactites collected from the Bulldog Mountain mine by G.S. Plumlee. They were found as pendant structures hanging from the tip of a "dagger"-shaped rock that projected from the back at the intersection of a subsidiary structure with the main vein. These stalactites are stubby, conical features, with outside dimensions ranging from 0.3 to 1 cm in diameter and from 1.2 to 3 cm long; however, the sulfide cores are only 1 to 2 mm in diameter. Rhodochrosite forms the outermost layer of these stalactites, covering euhedral, plate-like cavities that probably represent the molds of former crystals of barite 2 to 4 mm wide that had decorated the sulfide cores. The barite blades had been removed by hydrothermal leaching after the deposition of the rhodochrosite rind. No central canals have been observed in these stalactitic forms. Zhabin (1983) illustrated similar lumpy stalactites, from the Kvaisin deposit in the Caucasus, up to 54 cm long and composed of sphalerite with calcite, galena, and marcasite.

OTHER OCCURRENCES OF STALACTITES IN ORE DEPOSITS

A survey of the literature, and the recollections of our colleagues, reveal quite a few occurrences of stalactiform features from the hypogene stages of mineral deposits. The true stalactites among them serve to identify fossil vapor-dominated systems. Some occurrences of stalactiform silica, sulfides, and rhodochrosite are listed and briefly characterized in Table 1. Most examples come from epithermal and Mississippi-Valley-type deposits, where the literature supports both the conventional vapor-dominated stalactite scenario and, especially in the latter deposits, a mixing of two fluids to produce a "chimney" around a vent (see below). Presumably the epithermal examples grew in H_2O-rich vapors, probably also rich in CO_2. For Mississippi-Valley-type situations, the temperatures were too low for water vapor to have been the probable dominant gas, and we are left with CO_2, H_2S, and CH_4 as candidates. Barton (1967) proposed that H_2S and even CO_2 are probably very subordinate to CH_4 in the Mississippi-Valley-type setting, and it seemed likely that stalactite formation occurred in former, natural-gas-filled reservoirs. However, recent results of gas analyses from fluid inclusions in ore and gangue minerals from the Ozark region of the U.S. mid-continent [Landis & Hofstra (1991), discussed extensively by Plumlee *et al.* (1994)] show that CO_2 predominated over CH_4 during most of the mineralization. If the analyses also represent the vapor-dominated phases of mineralization, we must now conclude that the gas reservoirs contained principally CO_2.

STALACTIFORM FEATURES IN GENERAL

It is generally accepted that stalactites form as drip features in vapor-dominated environments, but even this may not always be correct. Figure 5 summarizes several modes of formation of stalactiform features, and the next few paragraphs explains them in some detail.

The common calcite stalactites in subaerial karsts form in two manners (Moore 1962), both of which share the critical chemistry wherein CO_2 escapes from slightly acid, lime-bearing, bicarbonate solutions, with concomitant increase in pH and precipitation of calcite as the residual bicarbonate hydrolyzes. The first type of stalactite forms as a downward-growing collar around an orifice through which water flows; these typically grow straight downward as "soda straws" (Fig. 5, point IIa). Their outside diameters are universally about 5.1 mm if the drip rate maintains a nearly complete droplet at the orifice (Curl 1972). Blockage of the tube can produce leakage at the sides and give rise to irregular forms.

The second mechanism of growth involves

movement of water as a surficial film downward to drip points, in the manner of formation of an icicle (Fig. 5, points I, IIb, and III). Because evaporation (or CO_2 loss) occurs all along the surface film, such stalactites tend to become conical. A soda straw may evolve into this second type of stalactite if an evaporating outer surface film is maintained. This second style of stalactite forms by the same process as does flowstone.

Several of the authors whose descriptions of stalactites are cited in Table 1 recognize that a vapor–liquid interface is required; but by analogy with modern karst, they automatically assume that the vapor is air and assign stalactite formation to supergene processes. We, also, consider that the presence of vapor is essential, but the presence of sulfides indicates a reducing environment that is incompatible with the circulating air needed to achieve evaporation [the example from the O'kiep district, Namaqualand, South Africa (Cornelissen 1958) may be a rare exception]. Furthermore, where known, the temperatures of mineralization, both before and after stalactite formation, are far too high for supergene processes.

Pseudostalactites

Although true stalactites, as we have defined them above, form as pendant features at a vapor–liquid interface, there can also be topologically similar structures having other origins; to distinguish these, we suggest the term "pseudostalactites".

Some of these pseudostalactites may form subaqueously in the presence of a single fluid phase. A possible example is given by Jébrak *et al.* (1996), who interpret silica stalactites from a mine at Cirotan, Indonesia to have formed by dripping of plastic colloidal silica into open space; such a mechanism may yield the sagged forms shown in Figure 5, point V and might evolve to the pendant forms shown in point VI. Jébrak *et al.* consider the open space to have been vapor-filled, but we offer the alternative that vapor may well not be an essential feature of such a process and that sagging might also be subaqueous. From Creede, the pyrite morphologies suggestive of sagging noted by Plumlee (1989) may also be formed by this process. Except for the lack of associated stalagmitic material, we lack proof that some of the silica 'stalactites', such as those shown in Figure 2c, do not also represent this phenomenon. The existence of tracks of pendant droplets presumably excludes most silica stalactites at Creede from this category; however, unrecognized selective dissolution of the original stalactite's amorphous-silica core might produce pseudotracks and thereby mimic true stalactites.

The injection of one fluid into another, from below, laterally, or even downward can result in localized mineral precipitation (Table 1, Fig. 5, points VII and VIII). The spectacular deep-sea vents and their deposits, known respectively as "smokers" and "chimneys", are excellent examples of this phenomenon; we suggest the term "chimney" for similar features in other settings. The chimneys differ from stalactites and flowstone in that chimneys do not require the receiving fluid to be a gas. Moreover, the mechanism of precipitation for stalactites and flowstone involves the partial or complete evaporation of the depositing fluid rather than a mixing of fluids leading to precipitation. Other examples include the crater-like deposits known as "geysermites" (Hill & Forti 1986), where upwelling waters enter a cave floor. Another is the subaqueous "stalactitic" feature described by DiColbertaldo (1947), where CO_2 and Ca–Mg salts from old workings entered the roof of a flooded mine at Raibl, Italy; dilution of the descending fluid precipitated arborescent carbonate stalactites (Fig. 5, point VIII).

The Mississippi-Valley-type (MVT) ores may well include numerous examples (Table 1) of both true stalactites and pseudostalactites. Peck (1978) and A.V. Heyl (written comm., 1990) carefully described and interpreted upward- and laterally growing sulfide "stalactites" from the Upper Mississippi Valley deposits; other MVT deposits exhibit similar features (Table 1). Some chimneys are marcasite, others are sphalerite and galena, and a few are elongated galena crystals with a central feeding hole. Peck's sphalerite "chimneys" have dark concentric bands of early-deposited ferroan sphalerite surrounded by coarse, banded light yellow-orange iron-poor sphalerite; thus they are typical representatives of the main sphalerite stratigraphy of the district. The marcasite chimneys have feeding central tubes up to 3 cm in diameter. Elongated cubic "chimneys" of pyrite were found in the floor of the Fletcher mine of the Viburnum trend, southeast Missouri district. "Inverse stalagmites", without central tubes, are reported hanging down above the "chimneys" on the floor. Most are vertical upward, a few are in columns or curved pencils, others (shown above the "inches" on the scale on Fig. 56 of Heyl *et al.* 1959, p. 88) may be horizontal, and still others may curve dramatically. Peck (1978, his Fig. 1.3) shows one making a sharp, 180° turn, suggesting the possible reversal in the relative densities of the incoming and receiving fluids during chimney growth. These MVT chimneys thus show a local hydrology involving extremely localized interfaces between two chemically distinctive liquids (Peck 1978); this situation contrasts strikingly with that which prevailed at Creede. The idea of a multiplicity of fluids for the MVT deposits received substantial support from the recent study of Goldhaber *et al.* (1995), who interpreted at least three chemically and isotopically distinct brines interacting to deposit the ores of the Viburnum trend, southeast Missouri.

The overgrowth of later layers of minerals on an acicular substratum is another process that can create

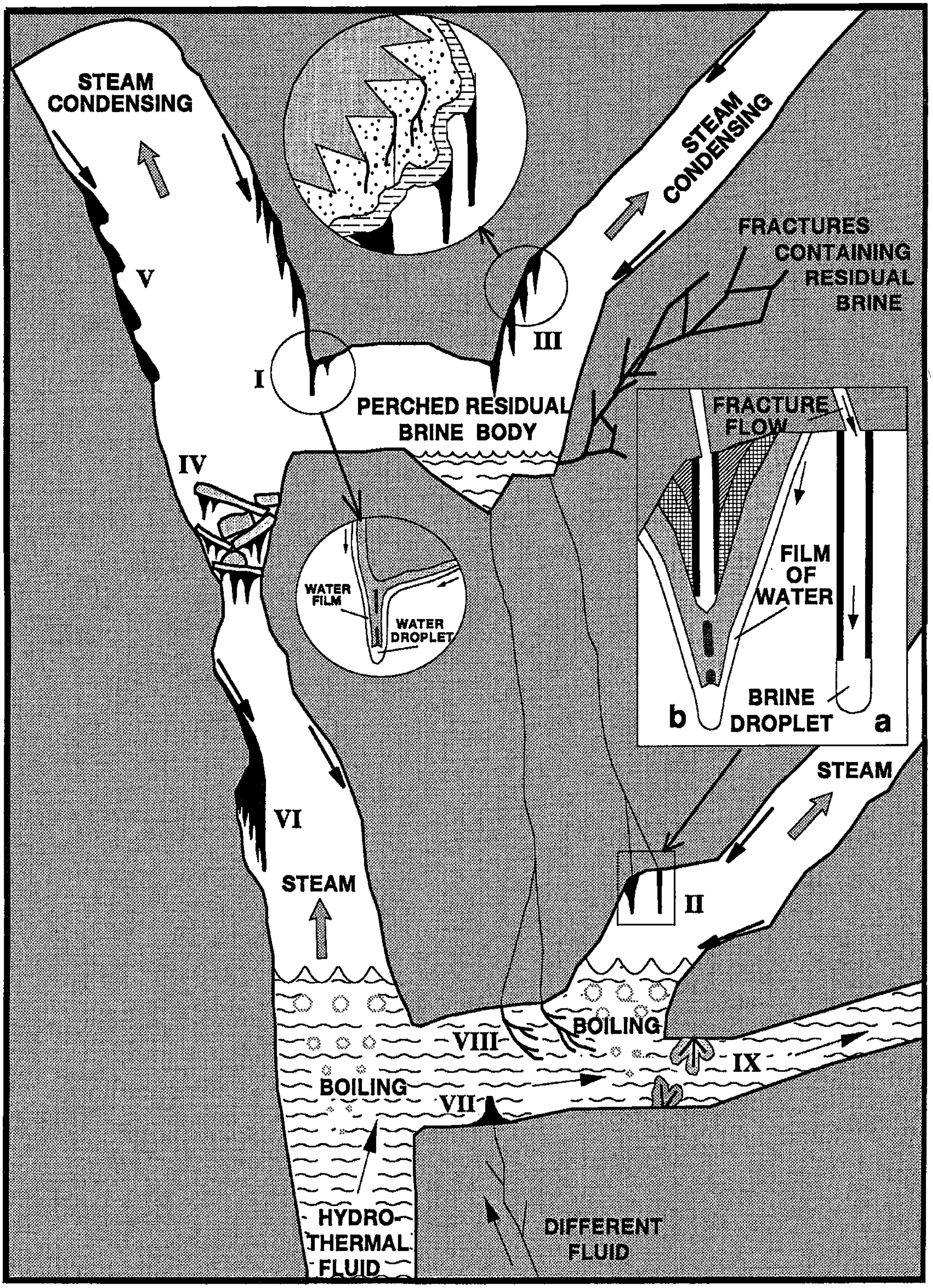

STEAM CONDENSING
STEAM CONDENSING
FRACTURES CONTAINING RESIDUAL BRINE
V
I
III
PERCHED RESIDUAL BRINE BODY
IV
FRACTURE FLOW
FILM OF WATER
WATER FILM
WATER DROPLET
BRINE DROPLET
b
a
STEAM
VI
STEAM
II
BOILING
VIII
IX
BOILING
VII
HYDRO-THERMAL FLUID
DIFFERENT FLUID

FIG. 5. Schematic diagram depicting the occurrence of speleothem-like morphologies within an active hydrothermal fracture system. Boiling of the hydrothermal vein fluid produces regions that are vapor dominated. Gray vein-walls underlying speleothems may be either previously deposited mineral layers, or surrounding rocks. The broad gray arrows are steam; the black arrows are liquid water, as only a film in the vapor-dominated part of the figure. I) Formation of icicle-like morphologies. In the magnified detail, the water droplet at the tip is fed by fluid flowing along the outside surface; there is no feeder fracture. Growth takes place as the water droplet evaporates and yields solid stalactites that may contain tracks of the pendant droplets. II) This feature shows fluid derived from remnants of a brine that occupied the vein system prior to the vapor-dominated stage, but that is not a requirement to develop soda straws. a: Formation of a soda straw by fluid flow down an axial canal localized by a fracture. Although soda straws are common in karst caverns, and their existence is suspected in mineral deposits, we have not proven their existence at Creede. b: Coeval or subsequent deposition (or both) from liquid surface-films converts cylindrical soda straw to a flowstone-covered cone that may contain tracks of the pendant droplet. Depending on the source, the fluid may be either condensate or residual brine. III) Flowstone precipitating from evaporating film of water, a process similar to that yielding I. Magnified detail shows stalactites hanging from colloform banded silica layers, which may surround slightly earlier 'helictites' that grew from large amethyst crystals that line the vein wall. IV) Stalactites dripping from the underside of breccia fragments within the vein as observed in Figure 2b. V) "Drape" features resulting from the arrested slumping of viscous, plastic precipitated material, as interpreted at Creede by Plumlee (1989). VI) "Drape" features that have become pendant. We have no evidence whether type V or VI features form in the liquid- or vapor-dominated region, or both. VII) Hydrothermal sulfide chimneys as within Mississippi-Valley-type deposits and at Ballynoe, Silvermines, Ireland, described by Heyl *et al.* (1959) & Larter *et al.* (1981), respectively. These represent a common type of pseudostalactite. VIII) Subaqueous inverted chimneys such as those from the lead–zinc Raibl mine (DiColbertaldo 1947). These represent a rare type of pseudostalactite. IX) "Nail hole" feature described by Coats & Blisset (1971) for the Mt. Painter mine. These represent a common type of pseudostalactite and are readily distinguished from other features.

←

---

forms superficially resembling stalactites (Fig. 5, point IX). An example of such a feature is the "nail hole" quartz from Mount Painter, South Australia (Table 1). Here, small fans of gypsum "swords" have been overgrown by quartz; then dissolution removed the gypsum, leaving radiating stalactiform silica clusters. The central tube of one "chimney" structure from Viburnum has the shape of a gypsum mold, but most tubes are round and partly filled with late-stage octahedra of galena, yellow sphalerite, and calcite (A.V. Heyl, written comm. 1990) We have not identified such stalactiform features from Creede, although molds of lamellar crystals of barite are abundant.

One more possibility for stalactitic morphologies should be kept in mind, although evidence to evaluate it is lacking. The common existence of framboidal textures in the pyrite stalactites suggests a possible association of biological activity with stalactitic growth. Went (1969) has identified fungi on modern stalactites, and one wonders whether meteoric waters entering a cool hydrothermal system might have sufficient nutritive matter to support a filamentous biota that could provide a stalactiform substratum for pyrite deposition. Walker (1919) described small, curving stalactites of barite from Madoc, Ontario, which he attributed to precipitation on rootlets. Such deposition would have no bearing on the existence of a vapor-dominated system, except, perhaps, to demonstrate that temperatures were too low to expect appreciable water vapor pressures.

THE FORMATION OF STALACTIFORM FEATURES AT CREEDE

The strongest indications that the Creede textures described above are stalactitic and formed from dripping fluid in a local, vapor-dominated environment are their distinctive dripstone-like morphology, complementary association with other geopetal features, presence of axial tubes in some, vertical orientation where observed in place, and parallel orientations where the depositional orientation has not been preserved. The fact that they formed as integral stages in the hypogene paragenetic sequence within an epithermal vein system below the paleo-water table demonstrates that parts of the Creede hydrothermal system at times became, at least locally, vapor-dominated.

Having already associated stalactite-forming processes with the presence of gas-filled cavities [one author who previously recognized this process in ore deposits is Zhabin (1983)], we now intend to explore further the conditions of stalactite formation in the Creede epithermal environment. There are at least two schools of thought concerning the hydrologic setting of vapor-dominated regimes at Creede. On one hand, Plumlee (1989) attributed boiling to pressure decrease as flow into the zone of mineralization waned and the system discharged toward lower elevations to the south; this interpretation followed the mechanism originally proposed by White *et al.* (1971). On the other hand, we suggest that vapor development may have resulted from increased focusing of gas (principally CO_2) flow and sealing under quasi-constant external hydrologic conditions, as described by Henley (1984). Inasmuch as we consider that the silica-depositing event was early, whereas Plumlee was discussing the late pyrite stage, both hypotheses may have merit.

The term "vapor-dominated" was introduced by White *et al.* (1971) to describe geothermal reservoirs in which the continuous, pressure-transmitting phase was gas rather than liquid. Although we do not have a good measure of temperature during stalactite formation at Creede, vapor-dominated conditions did interrupt the liquid-dominant hydrothermal mineralization, for which extensive fluid inclusion evidence (more than 2500 inclusions measured: Woods *et al.* 1982, Hayba 1992) shows temperature to have been in the 185–290°C range. No direct evidence is present for a high concentration of CO_2 at any stage; in fact, neither liquid CO_2 nor CO_2 clathrate has ever been identified from Creede. Nonetheless, as calculated by Barton & Chou (1993), CO_2 contents having up to several times the vapor pressure of pure water can be present without the appearance of either liquid CO_2 or the clathrate; thus appreciable CO_2 is clearly permissible. The vapor pressure must have at least equalled that of the water boiling curve (11 to 74 bars, respectively, for the 185–290°C range) and would have been considerably higher if gases such as carbon dioxide were present in quantity.

Any hydrothermal system that seals off and accumulates exsolved or entrained gases is a candidate to experience a hydrothermal "eruption" by a process described by Henley (1984, p. 52), who showed that as gas accumulates and the deep water table below the vapor-dominated region descends, "progressively greater aquifer pressures are transmitted to the seal by the gas-cap." If the vertical extent of the gas-cap becomes large enough, the top of the vapor-dominated zone can exceed lithostatic pressure; this can result in breaking the seal and explosively releasing the accumulated gas, flashing more liquid to steam, and subsequently allowing the vein system to return to liquid-dominated conditions.

A vapor-dominated reservoir is a very efficient engine to transfer heat from depth toward the surface because the low viscosity, large heat capacity, and large latent heat of condensation of steam effectively preclude thermal gradients within the chamber (unless the top is hotter, which is considered a very unlikely situation for an epithermal ore deposit). The vapor is very close to saturation in pure water, since water is boiling at the bottom and condensing at the top. Condensate will continually trickle back down, on the way redissolving small amounts of the earlier (pre-vapor-dominated) mineralization, and it is the evaporation of such a mineralized condensate to which we are appealing to form the stalactites (especially those of silica). Isolated, slowly draining pockets of earlier brine might also transport metals and deposit sulfides as stalactites on dilution by the trickling condensate (as well by evaporation, provided that the salinity of descending brine was less than that of the deep, boiling brine.)

One might well ask how a vapor that is boiling at the bottom and condensing at the top could have permitted any additional liquid to evaporate. The answer is that the liquid at the bottom of such a vapor chamber at Creede was a brine (from 6 to 12 wt.% NaCl, unusually saline for an epithermal deposit, and perhaps the reason why Creede has so many stalactites, whereas many other deposits apparently do not). Cirotan shares this attribute of high salinity (Jébrak *et al.* 1996). At the same temperature, the brine has a slightly lower vapor pressure than that of the far more dilute condensate. The rising steam can thus evaporate just a little of the trickling condensate, leaving behind stalactitic deposits.

The combination of a boiling hydrothermal fluid, particularly one that might be effervescing a gas such as carbon dioxide, with the existence of any upwardly closed pockets, might be expected to form gas accumulations. One might imagine small local traps or, alternatively, a major part (as much as hundreds of meters in dimensions) of the vein system filled with vapor. The difference between the local pockets and the pervasive vapor zone is mainly one of scale, not of process; but we shall discuss one consequence of the alternatives below.

Whereas portions of the system were vapor-dominated during the episodes of stalactite formation, they did not remain so for the lifetime of the hydrothermal system. The encapsulating "Stage IV" sphalerite layer in samples shown in Figure 3, and similar silica in many instances, illustrate such a return from vapor- to liquid-dominated conditions.

UNRESOLVED PUZZLES

Why is the mineralogy so simple?

If stalactites do form in the way described above, it is very difficult to understand how small, isolated pockets of vapor could generate individual boiling → recondensation → dissolution → evaporation → precipitation configurations, because the minimal difference in temperature between the floor and roof of a small cavity would be so trivial as to preclude a significant flux of fluid. In addition, the silica 'stalactites' (referring only to the cores that grew as stalactites, not the overgrowth on the stalactitic substrata) are constrained to two thin zones of chalcedony that are consistently correlatable within a thick and complex sequence of silica and are thus suggestive of pervasive, rather than local pockets of gas. Therefore, we favor a model with recurrent large regions of vapor rather than small ones; but because the sulfide and silica stalactites do not represent the same part of the paragenetic sequence, they cannot be associated with individual distinct, district-wide, vapor-rich intervals. We cautiously select the large-vapor-zone model, at least for the Last Chance Cave region.

Having reached this tentative conclusion, we are nonetheless puzzled by the overall great mineralogical diversity of the stalactites on one hand, and, on the other, by their simple mineralogy as individuals. One would think that materials exposed in the upper parts of a vapor-dominated chamber would permit simultaneous saturation of the condensate in several minerals (*e.g.*, silica, barite, rhodochrosite, sphalerite, hematite, galena, pyrite, *etc.*) and that evaporation would yield a mineralogically heterogeneous product. Neither a wide range of condensate compositions (that could dissolve and precipitate different minerals preferentially), nor selective prior mineralization events that provided differing selections of nutrients to the condensates, seems acceptable. A reasonable explanation has been suggested by C. Gammons (pers. comm., 1996), who proposed that perched bodies of earlier ore-forming brine may well drip into the vapor-filled fractures to form stalactites; such a process is indicated in Figure 5, point II. The concept involving residual brine also provides a mechanism to achieve sufficient solubility of sulfide to transport the sulfides; however, it does not explain the near-absence of silica in the sulfide stalactites.

What is the origin of the axial tubes in silica stalactites?

Our first response on seeing the axial cavities (in some cases filled by later crystals of quartz) in the Creede silica 'stalactites' is that they originated exactly like the soda straws in limestone caves. Indeed, some may have; however, we could not find any evidence of feeder channels in the supporting materials. Some silica 'stalactites' with axial tubes grow from solid-looking quartz, and commonly from individual crystals. How and where would the liquid get into the tubes? Where are the feeder channels? A second point is that their diameters seem not to fit a growth-from-a-pendant-drop genesis (see further discussion below). Thus we have sought an alternative processes, one of which is the already-discussed possibility of selective dissolution of a more soluble core material; but there is one more factor to consider.

P.M. Bethke has suggested that the slow evaporation of a suspended droplet might precipitate solids preferentially at its outer margin, where the evaporation is occurring. The droplet is continually fed by downward flow of the thin film constituting the wetted outer surface, as in an icicle; in fact, Makkonen (1988) showed that icicles may contain water-filled axial tubes, even though the axial tube does not participate in the water flow. Precipitation occurs around the margins of the pendant drop; and, if the rate of dripping is high relative to the rate of vapor loss (or freezing in the case of an icicle), a stalactite having a terminal diameter of 5.1 mm develops. There is no central feeding channel, but since deposition is along the margin of the pendant drop, an axial track may develop (Fig. 5, point I and the later stages of point VIb). In contrast to the soda-straw model, in which most of the volume of liquid drips from the stalactite and maintains the hemispherical morphology of the terminal droplet, we suggest that evaporation severely depleted the water from the tips of the Creede stalactites, and therefore the droplets were much smaller, and the tubes correspondingly more narrow.

Why does the "soda-straw" diameter of these ore-deposit-related stalactites differ from that expected for karst-related carbonate "soda straws"?

William White (pers. comm., 1990) has pointed out that the diameter of a soda straw stalactite is a function of temperature. This is because the interplay of surface tension and gravitational forces that creates a pendant drop constrains the diameter of the drop. The relation is described by Curl (1972) in terms of the equation:

$$d = \sqrt{\frac{B\alpha}{\rho g}}$$

in which d is the drop diameter (= outside diameter of the soda straw) in cm, B is the dimensionless Bond number, experimentally determined by Curl to be 3.5 for water [Ferguson (1923) found B to be about 3.8; see also the discussion by Andrieux (1965)], α is the surface tension in g/s^2, ρ is the density contrast in g/cm^3, and g is the gravitational constant, 980 cm/s^2. This gives a diameter of 5.1 mm for calcite-saturated water at low temperature. As temperature rises, the surface tension of water decreases (eventually reaching nil at the critical point, 374°C), leading to smaller droplets and smaller soda straws at higher temperature. Operating in the opposite direction (but to a less dominant degree) as temperature rises, the density of the steam increases, and that of the drop decreases, so that buoyant forces on the droplet increase with temperature, eventually negating the effect of gravity at the critical point [data for the properties of water are taken from Haar *et al.* (1984)]. Because the critical element in the growth model is that the tangent to the droplet at its contact with the stalactite is vertical and thereby parallel to the axis of the stalactite (as illustrated in the detail for point IIa in Fig. 5), the droplet size, and therefore the diameter of the soda straw, is independent of the mineralogical nature of the supporting stalactite (we make the reasonable assumption that the differences in chemistry responsible for different mineralogies cause insignificant changes in liquid density and surface tension). One then can derive the curve representing the diameter of a soda straw as a function of temperature, as shown in Figure 6.

We believe that the application of this analysis to the stalactites we describe must be erroneous for two reasons. First, as can be seen from Figure 6, the small (~1 mm) diameter of some of the stalactites would require temperatures of 330°C or higher; that temperature is far in excess of the 290°C maximum we have noted from numerous fluid inclusions (Woods *et al.* 1982, Hayba 1992), and also far too high to be compatible with the presence of poorly crystallized chalcedonic silica, which composes the silica stalactites and their underlying and overlying layers of silica.

Second, from Porco, Bolivia, Cunningham *et al.* (1994) described (and we have also examined the specimen) coeval sphalerite 'stalactites' that grew less than 10 mm apart, but the sizes of the stalactites differ from each other at each growth stage (see the right side of their Fig. 5). The probable original soda-straw-like tubes are 2.3 and 3.0 mm in outside diameter (the respective axial tubes are 2.0 and 2.3 mm in diameter), yielding "temperatures" of 285 and 330°C from Figure 6. Either the coeval tubes only 10 mm apart formed under drastically different thermal conditions, or the soda straw model does not apply. Since such a difference in temperature seems totally unreasonable, we conclude that stalactites in vapor-dominated ore deposits demonstrate an alternative pattern of growth to that for soda straw stalactites in caverns in limestone. A larger stalactite from a different part of the paragenesis is also illustrated by Cunningham *et al.* (1994); it has such a large axial tube (about 10 mm) that it cannot have originated *via* the soda straw model. It probably either had an earlier stalactitic core that has since been removed, or it is a chimney rather than a true stalactite.

Curl (1972) also showed that his analysis applies to icicles, even though they may not have a central tube, and they grow by freezing of a downward-flowing surface film that culminates in a pendant drop. When the dripping rate is rapid, the fastest growth is at the tip, where freezing is concentrated along the outer edge so that the droplet is encompassed by a downward-growing collar whose continued growth may trap fluid so as to leave an axial track. A soda-straw-like morphology develops; additional freezing of the surface film converts the shape from cylindrical to conical. This is a very good analog for the silica stalactites, except that the evaporation can force the pendant droplet to be much smaller than the incipiently dripping size that Curl's analysis treats. Thus the

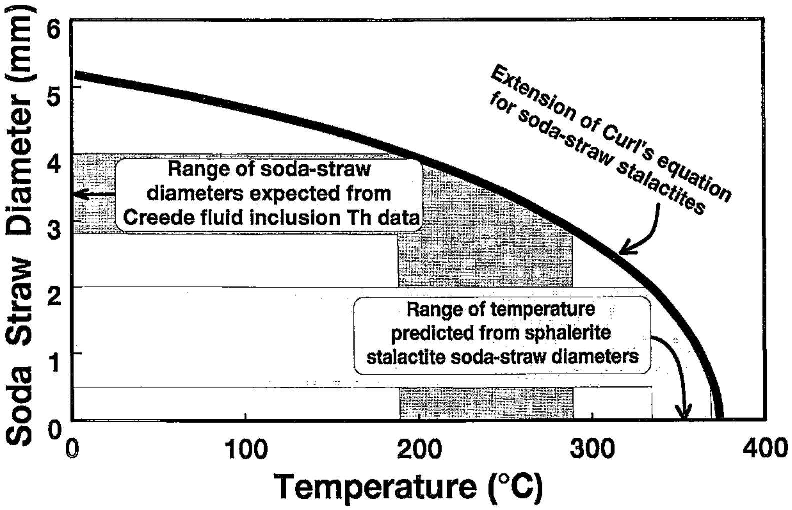


FIG. 6. Relationship between equilibrium diameter of soda straw and temperature of formation, based on the equation of Curl (1972), modified to accommodate the densities of steam and liquid and the surface tension of water as a function of temperature. The darkly shaded region indicates the expected diameters from measurements of homogenization temperatures of fluid inclusions. The lightly shaded region indicates the temperatures that might be erroneously interpreted from measurement of the axial canal diameters of Creede stalactites. We reject this relationship as a model for Creede stalactites (see text).

diameter of the stalactites provides a maximum possible temperature that is not appropriate for some Creede samples; that constraint may apply to other hydrothermal environments as well.

Why are the diameters of individual stalactites so constant?

Recognizing that although some stalactites are "lumpy" (*e.g.*, the galena stalactites noted above), most individuals are surprisingly uniform in diameter. We are puzzled as to how, under the evaporation model we propose, the stalactites maintained such a uniform diameter, implying that the terminal droplets maintain a relatively constant size despite the evaporation of fluid volumes that must have been on the order of a thousand times larger than the volumes of the stalactites [at 250°C the solubility of quartz is ~450 ppm, and that of amorphous silica, only ~1200 ppm: Truesdell (1984)]. Perhaps the terminal droplets contained a bit of salt (possibly residual from the brine formerly filling the vein), which would limit the amount of evaporation because the activity of water cannot go below that of the boiling brine at the base of the vapor-dominated region, and thus evaporation of the droplet would cease when the salt content built up to some critical concentration. The maintenance of such constant salinity would imply a surprisingly stable system wherein residual salts are rinsed down to stalactite tips and remain there for a long time.

Despite the Porco example noted above, in many cases there are rather uniform diameters among coeval stalactites. The suggestion made above seems inadequate, because the feed for the stalactite-building solutions could clearly have come from a range of drainage sites and thus from a range in amount of available salts.

CONCLUSIONS

Stalactitic structures involving minerals that form an integral part of the hypogene mineral deposition in the epithermal silver deposit at Creede, Colorado, show that brief vapor-dominated intervals occurred during mineralization below the paleo-water table. Most stalactites from Creede grew from evaporation of pendant droplets that were fed by downward-flowing surface films analogous to icicles, except that growth required bulk evaporation of fluid rather than simple bulk freezing (as in icicles) or CO_2 loss (as for calcite stalactites in karst caverns). Perhaps in some cases (mostly sphalerite), stalactite growth was similar to the axially nourished soda straws common in karst caverns in limestone, but proof of this is lacking. A variety of other processes create features that may resemble stalactites, but these may not demonstrate vapor-dominant conditions or even provide fossilized plumb lines.

Vapor-dominated conditions are known to have existed in other epithermal and geothermal systems (Henley 1984). However, few authors have described stalactites as part of the hypogene mineralization. The presence of stalactites within such deposits would indicate that portions of these systems had once been vapor-dominated. Such vapor-dominated conditions may lead to explosive eruptions and brecciation, and thereby serve to supplement tectonic activity as a mechanism to open structures for mineralization.

ACKNOWLEDGEMENTS

Various drafts of this manuscript have been reviewed by C. Gammons, C.G. Cunningham, R.O. Fournier, A.V. Heyl, J.S. Huebner, M. Jébrak, R.F. Martin, G.S. Plumlee, E. Roedder, D.E. White, and W.B. White. We are indebted to all of them for useful comments and suggestions, especially to W.B. White, who called our attention to Curl's theoretical discussion of stalactite growth. Informal comments and specimens have also been provided by M.D. Barton, P.M. Bethke, J.J. Jackson, W.C. Kelly, R.V. Kirkham, B. Lees, G.E. McKelvey, P. Magaw, G.S. Plumlee, M. Roeber, and E. Roedder. Translations of some references were provided by G. Vaggeli, M.A. Logan, A.F. Redkin, and M. Sato. For all of these contributions, we are most appreciative.

REFERENCES

ANDERSON, C.A. (1930): Opal stalactites and stalagmites from a lava tube in northern California. *Am. J. Sci.* **220**, 22-26.

ANDRIEUX, C. (1965): Étude des stalactites tubiformes monocristallines. Mécanisme de leur formation et conditionnement de leurs dimensions transversales. *Bull. Soc. franç. Minéral. Cristallogr.* **88**, 53-58.

BARTON, P.B., JR. (1967): Possible role of organic matter in the precipitation of the Mississippi Valley ores. *In* Genesis of Stratiform Lead – Zinc – Barite – Fluorite Deposits in Carbonate Rocks, A symposium (J.S. Brown, ed.). *Econ. Geol., Monogr.* **3**, 371-378.

________ & BETHKE, P.M. (1987): Chalcopyrite disease in sphalerite: pathology and epidemiology. *Am. Mineral.* **72**, 451-467.

________, ________ & ROEDDER, E. (1977): Environment of ore deposition in the Creede mining district, San Juan Mountains, Colorado. III. Progress toward interpretation of the chemistry of the ore-forming fluid for the OH vein. *Econ. Geol.* **72**, 1-24.

________ & CAMPBELL, W.R. (1994): Occurrence, origin, and significance of stalactites in ore deposits. *Eos, Trans. Am. Geophys. Union* **75**(16), 69 (abstr.).

________ & CHOU, I-MING (1993): Refinement of the role of CO_2 in modifying estimates of pressure of epithermal mineralization. *Econ. Geol.* **88**, 873-884.

BERNARD, A.J., LAGNY, P.H. & LELEU, M.G. (1972): A propos du rôle métallogénique du karst. *24th Int. Geol. Congress, Sect. 4, Mineral Deposits*, 411-422.

BETHKE, P.M., BARTON, P.B., JR., LANPHERE, M.A. & STEVEN, T.A. (1976): Environment of ore deposition in the Creede mining district, San Juan Mountains, Colorado. II. Age of mineralization. *Econ. Geol.* **71**, 1006-1011.

________ & LIPMAN, P.W. (1987): Deep environment of volcanogenic epithermal mineralization; proposed research drilling at Creede, Colorado. *Eos, Trans. Am. Geophys. Union* **68**(177), 187-189 (abstr.).

________ & RYE, R.O. (1979): Environment of ore deposition in the Creede mining district, San Juan Mountains, Colorado. IV. Source of fluids from oxygen, hydrogen and carbon isotope studies. *Econ. Geol.* **74**, 1832-1851.

BRODKORB, A. & BRODKORB, M. (1979): Rhodochrosit aus Argentinien. *Lapis* **4**(10), 19-22.

BROUGHTON, P.L. (1974): Silica deposits in eastern Wyoming caves. *Bull. Nat. Speleol. Soc.*, **36**(3), 9-11.

CALDCLEUGH, A. (1829): On the geology of Rio de Janeiro. *Trans. Geol. Soc. London* (second ser.) **2**, 69-72.

CANNADAY, F.X. (1950): *The OH Vein and its Relation to the Amethyst Fault.* M.S. thesis, Colorado School of Mines, Golden, Colorado.

COATS, R.P. & BLISSETT, A.H. (1971): Regional and economic geology of the Mount Painter Province. *Geol. Surv. South Australia, Bull.* **43**, 426 p.

CORNELISSEN, A.K. (1958): Note on botryoidal and stalactitic copper ores from Namaqualand. *Geol. Soc. S. Afr., Trans. and Proc.* **61**, 367-376.

CUNNINGHAM, C.G., APARICIO, N.H., MURILLO, S.F., JIMÉNEZ, C., N., LIZECA, B., J.L., MCKEE, E.H., ERICKSEN, G.E. & TAVERA, V., F, (1994): Relationship between the Porco, Bolivia, Ag–Zn–Pb–Sn deposit and the Porco caldera. *Econ. Geol.* **89**, 1833-1841.

CURL, L. (1972): Minimum diameter stalactites. *Bull. Nat. Speleol. Soc.* **34**(4) 129-136.

CURRIER, R.H. (1995): The Bolivian death switch. *Mineral. Rec.* **26**, 195-200.

DALHEIMER, M., WAUSCHKUHN, A. & AMSTUTZ, G.C. (1983): Tektonische, fazielle, und petrographisch-lagerstättenkundliche Untersuchungen an der Westflanke des Domo de Yauli, Zentral-Peru. *Zbl. Geol. Paläontol.* **3/4**, 526-535.

DEAL, D.E. (1964): Scintillites: a variety of quartz speleothems. *Bull. Nat. Speleol. Soc.* **26**(1), 29-31.

DICOLBERTALDO, D. (1947): Stalattiti e stalagmiti subacquee nella minera di Raibl. *L'Universo* **27**(5), 647-654.

DÓDONY, I., PÓSFAL, M. & BUSECK, P. (1996): Structural relationship between pyrite and marcasite. *Am. Mineral.* **81**, 119-125.

EMMONS, S.F., IRVING, J.D. & LOUGHLIN, G.F. (1927): Geology and ore deposits of the Leadville mining district, Colorado. *U.S. Geol. Surv., Prof. Pap.* **148**.

FERGUSON, A. (1923): Liquids and Gases. Chapter I in *The Mechanical Properties of Fluids.* Blackie & Son, Ltd., London, U.K. (1-49).

GAIT, R.I., ROBINSON, G.W., BAILEY, K. & DUMKA, D. (1990): Minerals of the Nanisivik mine, Baffin Island, Northwest Territories. *Mineral. Rec.* **21**, 515-534.

GOLDHABER, M.B., CHURCH, S.E., DOE, B.R., ALEINIKOFF, J.N., BRANNON, J.C., PODOSEK, F.A., MOSIER, E.L., TAYLOR, C.D. & GENT, C.A. (1995): Lead and sulfur isotope investigation of Paleozoic sedimentary rocks from the southern midcontinent of the United States: implications for paleohydrology and ore genesis of the Southeast Missouri lead belts. *Econ. Geol.* **90**, 1875-1910.

HAAR, L., GALLAGHER, J.S. & KELL, G.S. (1984): *NBS/NRC Steam Tables*. Hemisphere Publ. Co., Washington, D.C.

HAGNI, R.D. & TRANCYGNER, T.C. (1977): Sequence of deposition of the ore minerals at the Magmont mine, Viburnum Trend, southeast Missouri. *Econ. Geol.* **72**, 451-464.

HAYBA, D.O. (1992): *Numerical Hydrologic Modeling of the Creede Epithermal Ore-Forming System.* Ph.D. thesis, Univ. of Illinois, Urbana, Illinois.

HEALD, P., FOLEY, N.K. & HAYBA, D.O. (1987): Comparative anatomy of volcanic-hosted epithermal deposits: acid-sulfate and adularia–sericite types. *Econ. Geol.* **82**, 1-26.

HENLEY, R.W. (1984): Gaseous components in geothermal processes. *Rev. Econ. Geol.* **1**, 45-56.

HEYL, A.V., JR., AGNEW, A.F., LYONS, E.J. & BEHRE, C.H., JR. (1959): The geology of the Upper Mississippi Valley zinc–lead district. *U.S. Geol. Surv., Prof. Pap.* **309**.

HICKS, F.L. (1950): Formation and mineralogy of stalactites. *Bull Nat. Speleol. Soc.* **12**, 63-72.

HILL, C.A. & FORTI, P. (1986): *Cave Minerals of the World.* Nat. Speleol. Soc. Publ., 226 pages.

HOUSLEY, R. (1952): The occurrence of quartz stalactites in the Rock Creek district of Douglas County, Oregon. *Bull. Nat. Speleol. Soc.* **14**, 24-29.

HUDSON, J.D. (1982): Pyrite in ammonite-bearing shales from the Jurassic of England and Germany. *Sedimentology* **29**, 639-667.

JÉBRAK, M, MARCOUX, E. & FONTAINE, D. (1996): Hydrothermal silica–gold stalactites formed by colloidal deposition in the Cirotan epithermal deposit, Indonesia. *Can. Mineral.* **34**, 931-938.

KALLIOKOSKI, J. & CATHLES, L. (1969): Morphology, mode of formation, and diagenetic changes in framboids. *Bull. Geol. Soc. Finland* **41**, 125-133.

KOJIMA, S. & SUGAKI, A. (1983): On the rhodochrosite stalagmite from the Oe mine, Hokkaido, Japan. *J. Japanese Assoc. Mineral., Petrol. and Econ. Geol.* **78**, 491-496 (in Japanese).

KUCHA, K. & BARNES, H.L. (1995): Compounds with mixed and intermediate sulfur valences in pyrite from the Amelia mine, southwest Wisconsin. *Mineral. Deposita* **30**, 78-81.

KYLE, R.J. (1981): Geology of the Pine Point lead–zinc district. *In* Handbook of Strata-Bound and Stratiform Ore Deposits **9** (K.H. Wolf, ed.). Elsevier, Amsterdam, The Netherlands (643-741).

LABERGE, G.L. (1984): The geologic history of Wisconsin. *Rocks and Minerals* **59**(2), 61-73.

LACY, W.C. & HOSMER, H.L. (1956): Hydrothermal leaching in central Peru. *Econ. Geol.* **51**, 69-79.

LAGNY, P. (1971): Les minéralisations plombo-zincifères de la région d'Auronzo (province de Belluno, Italie): remplissages paléo-karstiques d'âge Anisien supérieur. *C.R. Acad. Sci. Paris* **273**, 1539-1542.

LANDIS, G.P. & HOFSTRA, A.H. (1991): Fluid gas chemistry as a potential minerals exploration tool: case studies from Creede, CO, Jerritt Canyon, NV, Coeur d'Alene, ID and MT, southern Alaska mesothermal veins, and mid-continent MVT's. *J. Geochem. Explor.* **42**, 25-59.

LARTER, R.C.L., BOYCE, A.J. & RUSSELL, M.J. (1981): Hydrothermal pyrite chimneys from the Ballynoe baryte deposit, Silvermines, County Tipperary, Ireland. *Mineral. Deposita* **16**, 309-318.

LEES, B. (1990): Recent mineral discoveries in Colorado, Ouray and Harris Park. *Friends of Mineralogy, Colorado chapter newsletter* (November issue).

LELEU, M. & MORIKIS, A. (1967): Sur des sulfures de basse température aux mines du Larium (Attique). *Bull. Soc. franç. Minéral. Cristallogr.* **90**, 241-245.

MAKKONEN, L. (1988): A model of icicle growth. *J. Glaciology* **34**, 64-69.

MARIKOS, M.A., LAUDON, R.C. & LEVENTHAL, J.S. (1986): Solid insoluble bitumen in the Magmont West orebody, southeast Missouri. *Econ. Geol.* **81**, 1983-1988.

MAVROGENES, J.A. & HAGNI, R.D. (1992): Mineralogy, paragenesis, and mineral zoning of the West Fork mine, Viburnum Trend, southeast Missouri. *Econ. Geol.* **87**, 113-124.

MOORE, G.W. (1962): The growth of stalactites. *Bull. Nat. Speleol. Soc.* **24**, 95-106.

MURATA, K.J. & NORMAN, M.B., II (1976): An index of crystallinity for quartz. *Am. J. Sci.* **276**, 1120-1130.

PECK, S.B. (1978): Stalactites and helictites of marcasite, galena, and sphalerite in Illinois and Wisconsin. *Bull. Nat. Speleol. Soc.* **41**, 27-30.

PLUMLEE, G.S. (1989): *Processes Controlling Epithermal Mineral Distribution in the Creede Mining District, Colorado*. Ph.D. dissertation, Harvard Univ., Cambridge, Massachusetts.

_______, LEACH, D.L., HOFSTRA, A.H., LANDIS, G.P., ROWAN, E.L. & VIETS, J.G. (1994): Chemical reaction path modeling of ore deposition in Mississippi Valley-type Pb–Zn deposits of the Ozark region, U.S. mid-continent. *Econ. Geol.* **89**, 1361-1383.

ROUVIER, H. (1971): Minéralisations plombo-zincifères et phénomène karstique. Exemple tunisien: le gisement du Djebel Hallouf. *Mineral. Deposita* **6**, 196-208.

SASS-GUSTKIEWICZ, M., DZULYNSKI, S. & RIDGE, J.D. (1982): The emplacement of zinc–lead sulfide ores in the Upper Silesian district – a contribution to the understanding of Mississippi Valley-Type deposits. *Econ. Geol.* **77**, 392-412.

SHAUB, B.M. (1972): Rhodochrosite: the ornamental banded material from Argentina. *Mineral Digest* **4**, 47-56.

SOBCZYNSKI, P. & SZUWARZYNSKI, M. (1975): Sphalerite dripstones from the Trzebionka mine, (Cracow-Silesian region). *Rocznik Polskiego Towarzystwa Geol. Annal. de la Société Géol. Pologne* **XLV**, 171-175.

STEVEN, T.A. & EATON, G.P. (1975): Environment of ore deposition in the Creede mining district, San Juan Mountains, Colorado. I. Geologic, hydrologic, and geophysical setting. *Econ. Geol.* **70**, 1023-1037.

_______ & RATTÉ, J.C. (1965): Geology and structural control of ore deposition in the Creede district, San Juan Mountains, Colorado. *U.S. Geol. Surv., Prof. Pap.* **487**.

TRUESDELL, A.H. (1984): Chemical geothermometers for geothermal exploration. *Rev. Econ. Geol.* **1**, 31-44.

VIKRE, P.G. (1989): Fluid–mineral relations in the Comstock Lode. *Econ. Geol.* **84**, 1574-1613.

VONSEN, M. (1941): Preliminary report on minerals of Geysers of Sonoma County, California. *The Mineralogist* **9**, 245-248.

WALKER, T.L. (1919): Stalactitic barite from Madoc, Ontario. *Am. Mineral.* **4**, 79-80.

WENT, F.W. (1969): Fungi associated with stalactite growth. *Science* **166**, 385-386.

WHITE, D.E., MUFFLER, L.J.P. & TRUESDELL, A.H. (1971): Vapor-dominated hydrothermal systems compared with hot-water systems. *Econ. Geol.* **66**, 75-97.

WOODS, T.L., ROEDDER, E. & BETHKE, P.M. (1982): Fluid inclusion data on samples from Creede, Colorado, in relation to mineral paragenesis. *U.S. Geol. Surv., Open-File Rep.* **82-313.**

ZHABIN, A.G. (1983): Sphaleritic stalactites in endogenous lead–zinc ores in the Kvaisin ore field, central Caucasus. *Geologiia Rudnykh Mestorozhdenii* **24**(4), 115-118 (in Russian).

ZUFFARDI, P. (1976): Karsts and economic mineral deposits. *In* Handbook of Strata-Bound and Stratiform Ore Deposits **3** (K.H. Wolf, ed.). Elsevier, The Netherlands (175-212).

________ & SALVADORI, I. (1964): Supergene sulfides and sulfates in the supergene zones of sulfide ore deposits. *In* Sedimentology and Ore Genesis **2** (C.G. Amstutz, ed.). Elsevier, Amsterdam, The Netherlands (91-99).

Received April 22, 1996, revised manuscript accepted July 23, 1996.