

SULFATE MINERALOGY FROM ACID-ALTERATION OF PYRITE: LEADVILLE, COLORADO. S. J. Chipera¹, D. L. Bish², P. Sarrazin³, L. Alcantar-Lopez¹, D. T. Vaniman⁴, & D. Blake⁵, ¹Chesapeake Energy Corporation, 6100 N. Western Ave, Oklahoma City, OK, 73118, SChipera@CHKenergy.com, ²Dept. of Geological Sciences, Indiana University, Bloomington, IN 47405, ³inXitu Inc., Mountain View, CA, ⁴Earth & Env. Sciences, Los Alamos National Laboratory, Los Alamos, NM 87545, ⁵NASA Ames Research Center, Moffett Field, CA.

Introduction: Terrestrial sulfide alteration localities hold considerable interest for Mars-analog mineralogy studies (e.g., [1,2]). Leadville, Colorado, located at 3094 m elevation, has been extensively mined since the late 1800's for lead, zinc, silver, and gold. Other mines in the vicinity include the massive Climax molybdenum mining operation. The mining areas of Leadville are situated above the town in alpine terrain and are dotted with old ruins and equipment (Fig. 1).

Extensive mine spoil piles contain pyrite that has been oxidizing for over a century. The resultant sulfates are highly soluble and were leached from the spoil piles to precipitate upon evaporation. In particular, sulfates are found thickly deposited on wooden structures where the wood helps to wick the sulfate solutions to exposed surfaces. Extensive deposits of sulfate minerals are also found under old mill structures where pyrite-containing rock was finely ground and oxidized to form sulfates. The wooden structures and buildings also provide protection from redissolution due to rain and snow.



Figure 1. One of many mining areas above the town of Leadville, CO. Old mill and mine spoils in the foreground, more contemporary gold mining operation in the back ground.

Two localities were chosen for more extensive study of the sulfate mineralogy at Leadville. The first centered on wooden structures helping to support mine-spoil piles (Figs. 2,3). The second consisted of sulfates formed from the oxidation of finely ground material, protected beneath an old mill (Fig. 4).



Figure 2. Wooden framework holding a spoil pile.



Figure 3. Sulfates precipitated from spoil pile.



Figure 4. Old mill structure that sits above and protects sulfate accumulations.

Sulfate mineralogy observed at Leadville: The sulfate samples analyzed are rarely mono-mineralic but tend to be complicated mixtures of sulfate minerals containing variable cations and hydration states. Presumably, the hydration states of some of the sulfates will depend on the variable ambient temperature and humidity during the changing seasons [3,4]. Colors of the sulfates are likewise quite variable with a full spectrum of white to yellow to green to pink (Fig. 3). Table 1 lists the minerals that have been identified. Minerals listed with a question mark are believed to be present but abundances were too low for definitive identification. Likewise, some of the phases have similar structures but different cation compositions making them difficult to distinguish. A sample taken from underneath the wooden mill structure (Fig. 4), dissolved in DI water and analyzed for cation content, was composed of mainly Mg (43%), Zn (32%), Mn (18.7%), and Fe (5.9%).

Table 1: Sulfates observed in the Leadville, CO mine spoils. Minerals with (?) are believed to be present but at an insufficient abundance to be certain.

Mineral	Chemical Formula
Epsomite	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$
Hexahydrate	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$
Pentahydrate(?)	$\text{MgSO}_4 \cdot 5\text{H}_2\text{O}$
Starkeyite	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$
Ferrihexahydrate	$\text{Fe}^{+2}\text{SO}_4 \cdot 6\text{H}_2\text{O}$
Rozenite	$\text{Fe}^{+2}\text{SO}_4 \cdot 4\text{H}_2\text{O}$
Fibroferrite	$\text{Fe}^{+3}(\text{SO}_4)(\text{OH}) \cdot 5\text{H}_2\text{O}$
Copiapite	$\text{Fe}^{+2}\text{Fe}^{+3}_4(\text{SO}_4)_6(\text{OH})_2 \cdot 20\text{H}_2\text{O}$
Magnesiocopiapite	$\text{MgFe}^{+3}_4(\text{SO}_4)_6(\text{OH})_2 \cdot 20\text{H}_2\text{O}$
Slavikite	$\text{NaMg}_2\text{Fe}_5(\text{SO}_4)_7\text{O}_3(\text{OH})_6 \cdot 33\text{H}_2\text{O}$
Apjonite	$\text{MnAl}_2(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}$
Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
Konyaite	$\text{Na}_2\text{Mg}(\text{SO}_4)_2 \cdot 5\text{H}_2\text{O}$
Gunningite	$\text{ZnSO}_4 \cdot 4\text{H}_2\text{O}$
Mirabilite (?)	$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$

On one trip after an early fall snow storm, a green ooze was observed migrating through the snow on the side of a spoil pile above the mill shown in Figure 4. Unfortunately, by the time the sample was returned to the lab and analyzed, it had separated into a brownish colored sediment and a bright red liquid. The bright red liquid was predominantly ferric-sulfate and possessed the same interesting properties described in an earlier study of ferric-sulfate solutions [5]. The brown sediment was composed of relatively pure fibroferrite (Fig. 5). It would have been interesting to see what the origi-

nal sample might have been before it separated into aqueous and solid components. Meridianiite ($\text{MgSO}_4 \cdot 11\text{H}_2\text{O}$) is a recently described mineral that is stable only at temperatures below 2°C [6]. Above this temperature, meridianiite decomposes to epsomite and water. A similar situation could account for the “green ooze” phase which decomposed to fibroferrite and solution (the liquid phase presumably dissolved some of the fibroferrite to form the bright red ferric-sulfate solution). Sampling the next summer in early August and at the exact location where the fibroferrite was found produced copiapite with minor fibroferrite (Fig. 5).

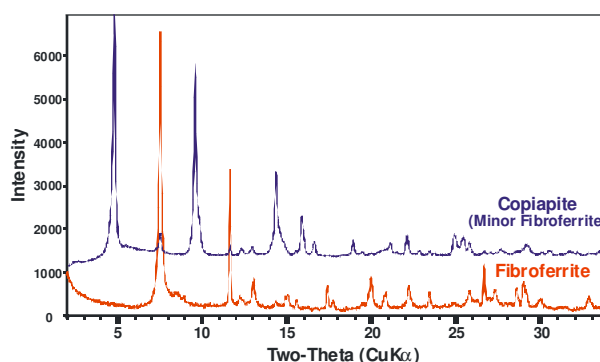


Figure 5. X-ray diffraction patterns of the fibroferrite found oozing through the snow and the copiapite collected later from the same location.

Summary: Acid sulfate alteration occurring at mining operations such as those at Leadville, Colorado, can provide analog sites for study of Martian mineralogy. The mining areas above Leadville have a wide variety of sulfate minerals and are accessible during much of the year. Of particular interest would be studies of the sulfate mineralogy during the colder months as it would have direct relevance to the cold temperatures encountered on Mars.

References: [1] Fernández-Remolar D. C. et al. (2005) *Earth Planet. Sci. Lett.* 240, 149-167. [2] Alpers C. H. (2006) In *Martian Sulfates as Recorders of Atmospheric-Fluid-Rock Interactions*, LPI #7064. [3] Chou I.-M. and Seal R. R. II (2003) *Astrobiology* 3, 619-630. [4] Chipera S. J. and Vaniman D. T. (2007) *Geoch. Cosmoch. Acta.* 71, 241-250. [5] Chipera S. J. et al.. (2007) *LPSC XXXVIII*, #1409. [6] Peterson R. C. et al. (2007) *Amer. Mineral.* 92, 1756-1759.