Subsidence Impacts at the Molycorp Molybdenum Mine
Questa, New Mexico

Prepared for
Amigos Bravos

By
Steve Blodgett, M.S.
Center for Science in Public Participation

Surface subsidence scarp (white area) formed along fault plane on Goat Hill. Scarp is caused by underground block-cave mining at the Molycorp mine (October 2001).

February 2002

Executive Summary

Underground mining using the block-caving technique has created approximately 72 acres of subsidence at the Molycorp molybdenum mine east of Questa, New Mexico. Future mining could create an additional 200 acres of surface subsidence. Block-caving began in 1983 and could continue until 2015. Impacts to the ground surface and the adjacent Red River have not been studied in any detail.

The Molycorp mine has created a groundwater sump 1800 feet below the surface. This sump collects 600 gallons per minute from the mine area. The mine sump also de-waters a one-mile stretch of the Red River from Spring Gulch to Goat Hill Gulch. Consequently, the alluvial aquifer underlying the Red River is de-watered and the concentrations of metals and sulfate in the river are not diluted by influent water from the alluvium. Over the long-term, the subsidence area is likely to cause increased infiltration of poor quality water to the mine sump. This water will require treatment in perpetuity.

No mitigation measures have been proposed for subsidence at the Molycorp mine. Block-caving is designed to create surface subsidence and the underground workings cannot be backfilled after caving begins. A comprehensive literature review revealed that no historic or existing underground hardrock mines have ever reclaimed and/or revegetated subsidence areas. Molycorp must complete a study of the subsidence area and propose a reclamation plan by April 2004. If this study indicates that reclamation is infeasible for the subsidence area, Molycorp will request a waiver from the requirement to reclaim the area to support a Self-Sustaining Ecosystem as required by the New Mexico Mining Act.

Several case histories of block-cave mines are presented to illustrate the mechanisms and effects of block caving on surface and hydrologic features. Experience from these mines indicates that predicting and controlling hardrock mining subsidence has not been successful and that unintended impacts can occur for many years after the completion of mining. No evidence was found that subsidence effects at underground hardrock mines using block caving can be managed or mitigated short of not mining. Under the New Mexico Mining Act, any additional mining proposed by Molycorp would be considered a “new unit” and would be subject to more stringent requirements.

Table of Contents

1.0 Introduction

This report describes the environmental impacts of subsidence caused by underground mining at the Molycorp molybdenum mine near Questa, New Mexico. The Questa mine employs block caving as the principal mining method, and the current and projected subsidence area at the mine is projected to cover more than 200 acres when mining is done. The Questa mine subsidence is likely to have long-term impacts on reclamation activities at the mine and on water quality and quantity in the Red River, which is immediately south of the mine and subsidence area.

This study was commissioned by Amigos Bravos, a citizens' group based in Taos, New Mexico working on environmental issues which affect the Rio Grande watershed in New Mexico. Amigos Bravos also provided support for a larger study on the effects of hardrock mine subsidence on the environment, particularly on water resources (Blodgett and Kuipers, 2002).

This report provides a brief description of the mining history; the geology and hydrology of the mine area; current and projected subsidence effects at the mine; and recommended mitigation and closure measures to address the long-term impacts of subsidence. Molycorp, Inc. is required under its current mining permit to complete a study on the subsidence at the mine by April 30, 2004. While this study is underway, the mine has requested, and has been granted, a variance from the requirement to reclaim the subsidence area to achieve a Self-Sustaining Ecosystem as specified in the New Mexico Mining Act.

2.0 Site Description and Background

Mining for molybdenum near Questa began in the early 1900s when prospecting for gold and silver revealed ore that contained molybdenum. In 1919 the Molybdenum Corporation of America was incorporated and acquired many of the properties in the area 5 miles east of Questa, New Mexico on the north side of the Red River. Initially, high-grade veins were worked through adits in Sulphur Gulch. By 1923, a mill was treating 40 tons of ore per day (Schilling, 1952). Over the period from 1919 to 1958, more than 35 miles of underground workings that extended up to 1200 feet below the surface were developed. In 1941 the Moly tunnel was constructed to allow for more efficient development of the historic underground workings (URS, 2001).

In 1975 exploration drilling identified another economic orebody extending west-southwest beneath an open pit that had been developed in 1965. Development work from 1977 to 1983 sunk vertical shafts and built a 1.25-mile-long decline. In 1983 block caving began and continues to the present.

3.0 Mine Geology and Hydrology

The ore deposit at Questa is located along the southern margin of the Questa caldera, a large-scale volcanic structure that extends from the village of Questa, east to the town of Red River, and north into the Latir Range, part of the Sangre de Cristo Mountains. The caldera is oblate and extends approximately 9.3 miles east-west and 7.5 miles north-south. On the mine, basement rock consists of Proterozoic quartzites, granites, and volcanic rocks. In the early Tertiary, conglomerates were deposited over the granites. About 27 million years ago a sequence of andesitic lava flows was deposited. Approximately 25.7 million years ago, quartz latite and rhyolite lava flows mapped as the Amalia tuff were deposited to a depth of 3,700 feet (Lipman, 1988). These flows comprise the Questa caldera. Later (22 to 25 million years ago), mineralizing intrusions of porphyritic stocks, sills, and dikes of granitic composition were emplaced along the southern margins of the caldera.

Geothermal scars are prominent features in the mine area. These areas consist of poorly consolidated, mixed sediments, mostly unvegetated, that contribute low pH water and sediment to the Red River. Large debris fans drain south off the mine and from drainages east and west of the mine into the river. The valley of the Red River, which forms the southern margin of the Questa caldera, is filled with alluvium that has eroded from the volcanic and granitic rocks on either side of the river.

Groundwater flow on the mine is approximately 3 cfs (600 gpm) [Ralph Vail, personal communication, November 2001]. All groundwater on the mine is captured by a sump at the 1800-foot level of the mine. Because of this pumping, a one-mile reach of the Red River alluvial aquifer between Spring Gulch and Goat Hill Gulch is de-watered, thereby removing water from the river that would otherwise dilute the acid drainage from the mine and low pH water draining into the river from geothermal scar areas. This water is pumped to the mill where it is mixed with tailing and sent by pipeline to the tailing ponds west of Questa. Some of this water then drains from the tailing pile into the Red River and, ultimately, the Rio Grande. Several springs and seeps discharge minor flows on the mine and along the Red River. In Goat Hill Gulch, surface water flow of 60 gallons per minute (gpm) drains into the subsidence zone and ultimately to the underground sump. Proposed mining of the D orebody will disturb a surface subsidence area of 86 acres with an infiltration rate of 3 inches/year, for a potential total infiltration of 16 gpm (URS, 2001a, p. 3).

4.0 Subsidence History at Questa mine

Evidence of surface subsidence appeared in Goat Hill Gulch soon after block caving began in 1983. The method of block caving at the Questa mine is to form an undercut level 20-50 feet above the draw points. The roof of this undercut level is drilled and blasted to induce the collapse of the roof to form a cave. The caving action causes the breaking rock to fragment and funnel into the draw points. The breaking ore then propagates upward as ore is drawn from the draw points (URS, 2001a).

By 2002, the subsidence area at the Questa mine covered approximately 72 acres in Goat Hill Gulch. Molycorp depicts a 20 acre “subsidence zone area” and a 72 acre “outer extent of surface influence” area in a letter report submitted to NMED in June 2001 (URS, 2001a, Fig. 2). No explanation is provided for the difference between the inner and outer subsidence areas, but one can assume that the inner area is still actively subsiding and the outer area shows surficial tension cracks. The proposed D orebody subsidence zone would have an inner area of 26 acres and an outer area of 86 acres (URS, 2001a, Fig. 2). An additional subsidence area that would occur in the open pit is not depicted on the map. A large scarp has formed on Goat Hill itself (cover photo) and appears to have reached the plane of a fault that strikes north-south through the east side of Goat Hill to the south side of the Red River. The surface topography in Goat Hill Gulch is extremely steep, with 30-40º slopes and a vegetative cover of spruce-fir-pine forest, shrubs, and grasses and a significant upstream area of unvegetated ground resulting from a geothermal scar. A large, bowl-shaped depression has formed in the drainage of the gulch (**Figure 1**). This depression acts as a *de facto* catch basin for sediment moving down the gulch and sloughing from the rubbleized and over-steepened slopes. The hummocky, rough terrain along the sides of the gulch, and numerous trees tilted at odd angles are further evidence of surface subsidence.

Mining in the area of Goat Hill Gulch was within 250 feet of the surface (URS, 2001b, Fig. 2-8). The underlying zone of extraction was 620 feet high and the draw angle was 82º22’44,”with the outer extent of surface subsidence forming a subsidence angle of 67º20’11” (URS, 2001b, Fig. 2-8). By 2002, the maximum depth of surface subsidence in Goat Hill Gulch was ~200 feet. The underground area has caved completely and Molycorp believes that most of the surface subsidence has already occurred in Goat Hill Gulch. Mine personnel inspect the Goat Hill Gulch area on a regular basis, but do not measure or monitor the existing subsidence quantitatively. A road built along the east side of the gulch by the mine in 2000 does not yet show any subsidence features.

Figure 1—“Glory hole” sediment basin formed in Goat Hill Gulch by surface subsidence at Molycorp mine. Note acid mine drainage in bottom of basin, rubbleized surface, and tilted trees.

The entire subsidence area is considered to be unstable and will pose serious reclamation problems. The mine has requested a variance from the state to allow time to develop a reclamation plan for the existing subsidence zone and must submit the plan by April 30, 2004.

5.0 Future Subsidence Predictions

Molycorp is proposing to create 150-200 acres of additional surface subsidence as they mine deeper orebodies over the next 15 years. Future underground mining is scheduled to include both the Southwest and Northeast orebodies (URS, 2001b, p. 3-1). Subsidence from underground mining of the Southwest orebody is expected to extend to the ridge on the southern edge of Goat Hill and into the open pit at the east end of the orebody. Underground mining of the Northeast orebody will extend from Goat Hill on the west to beneath the bottom of the open pit on the east (URS, 2001b. p. 3-2). For a mean draw height of 500 feet, subsidence depth is expected to range from 200-400 feet (URS, 2001b, p. 3-2). Subsidence at the east end of the orebodies will begin to encroach on top of the past movement area in the west wall of the open pit.

Cross-sectional figures in the Questa mine Closeout Plan (URS, 2001b, Figs. 2-6—2-12) show the projected areas of future underground mining and surface subsidence. Thicknesses of extraction zones range from 300 feet (Deep “D” orebody, Fig. 2-6) to 700 feet (“D” orebody, Fig. 2-10) and overburden thickness ranges from a low of zero feet ("daylighting" into the bottom of the open pit by the F2 orebody, Fig. 2-7) to 1250 feet over the Deep "D" orebody (Fig. 2-9).

The projected draw angles for all of the orebodies is from 83-85º, and the projected subsidence angles range from 67º ("D" orebody) to 78º (all other orebodies) [URS, 2001b, Figs. 2-6—2-12)]. Using these projections, Molycorp estimates that the additional area of surface subsidence likely to be created if all orebodies are mined out will be ~160 acres. None of the data presented in the Closeout Plan regarding the future subsidence areas have been generated through a model. The projected data are based upon field mapping and the best engineering judgment of the Molycorp mine staff and its consultants.

The only measured subsidence angle on the mine is 67º20'11" in Goat Hill Gulch. Consequently, if this angle were to be created from the bottom of the draw zone to the surface for each orebody, the total projected area of surface subsidence could end up closer to 200 acres than to the expected 160 acres. Although future mining will be much deeper than under Goat Hill Gulch and the extraction zones are thinner (except for the "D" orebody, which is planned to be a 700-foot thick extraction zone), surface subsidence is expected to occur above each of the orebodies.

6.0 Environmental Issues Related to Future Subsidence at Questa mine

The question is whether the current and projected subsidence at the Questa mine can ever be reclaimed. Subsidence has occurred along very steep slopes and across drainages. In some areas of Goat Hill Gulch, scarps of 50 feet form sheer cliffs within the subsidence zone. The surface rock and soil is rubbleized and it is not safe to move men and equipment across the existing subsidence zone. Given the experience at other mines, the subsidence areas at the Questa mine may remain unstable and unsafe for many decades. The mine has tentatively proposed to examine the idea of backfilling the surface subsidence area with tailings and revegetating that material. However, no significant work has been done to see how de-watered tailings (which would still contain 50% water) or paste tailings could be applied to the subsidence areas; how much material would be required to fill the areas; or how stable the tailings would be on top of rubbleized rock. A thorough review of the scientific literature reveals that no such plan has yet been tried, let alone proven to be successful.

Another concern with the projected subsidence zone is the impact on the existing open pit. Figures 2-6 and 2-7 (URS, 2001b) show the "vein zone" and F2 orebodies creating subsidence in the west pit highwall and under the bottom of the pit. This subsidence is projected to undermine the entire west pit highwall and pit bottom by lowering the surface from 100-200 feet. The northeast pit highwall is already extremely unstable and the north highwall suffered a catastrophic failure in 1982 when a large slab slid into the pit bottom. Although no more mining is planned for the open pit and Molycorp has applied for waiver to avoid reclaiming most of the pit, mining the "vein zone" and F2 orebodies will rubbleize the west pit highwall and pit bottom and almost certainly create landslides and chronic instability on top of an already unstable 45º slope.

Previous experience at Jerome, Arizona and Rio Tinto, Spain is instructive. At Jerome, a slab of muck 100 feet thick, 300 feet long, and 500 feet wide slid into the open pit at the United Verde mine in 1931 as a result of subsidence caused by mining 1200 feet below the surface (Mills, 1934, Figs. 1 & 2). At the San Dionisio lode mine in the Rio Tinto district, the highwall of an open pit developed deep cracks and became unstable as a result of mining ~640 feet under the highwall (Palmer, 1930, Figs. 1-21). These cracks were first noted in 1908, developed over a 20-year period, and continued to open as far as ½ mile from the pit by 1928.

A third related issue is the quality of water draining through the subsidence zones. Most of the rock on the Molycorp mine is acid generating. Because the surface will be rubbleized and the transmissivity of groundwater will be increased by orders of magnitude, additional water of poor quality will drain into the underground mine sump. Molycorp believes that this scenario is allowable because the water will likely be captured in the sump and treated in perpetuity with all other contaminated water collected in the sump. Molycorp also believes that the upward draft of air from the underground mine through the subsidence zone will evaporate a significant portion of infiltrating surface water (URS, 2001a, p. 3). However, no studies have been done to confirm that water draining through the subsidence areas will be evaporated by updrafts or captured by the mine sump after mine ventilation ceases.

If water draining through the subsidence areas were to discharge into a surface water drainage or create seeps under the existing waste rock dumps, poor quality surface water draining off the mine could further impair the Red River and undermine the stability of the waste rock dumps. Molycorp must complete detailed studies addressing all of the issues above over the next 3 years as they develop the final Closeout Plan for the Questa mine.

7.0 Mitigating Future Subsidence Affects at the Questa mine

The current plan to create another 150-200 acres of subsidence at Questa does not include any mitigation measures. One possible outcome is that Molycorp would request a waiver for the subsidence area to not reclaim the area to a Self-Sustaining Ecosystem as required under the New Mexico Mining Act. Other possibilities include partially backfilling the existing and proposed subsidence areas; covering the tailing with Non-Acid Generating material, and re-vegetating (as discussed by Molycorp); or the No Action alternative. Under both the waiver and reclamation scenarios, the subsidence area would most likely have to be fenced for safety reasons. Otherwise, there is nothing that can be done to prevent subsidence if mining occurs. Because it is not possible to backfill a block-caving mine, the underground extraction zone will remain open until it is eventually filled as overlying rock caves into the void. The mine will act as a perpetual sump to collect water that must be pumped and treated until it meets New Mexico water quality standards for discharge.

No subsidence mitigation measures were proposed when Molycorp first began block caving in 1983. The final landscape at the Questa mine could include ~200 acres of surface subsidence. There is no current plan to reclaim the current and proposed subsidence area, although Molycorp must conduct studies over the next 3 years to identify a reclamation strategy. If those studies conclude that reclamation is infeasible, Molycorp could apply for a waiver from the requirement to create a Self-Sustaining Ecosystem. Future underground mining being proposed is considered part of an existing unit and was not reviewed under the New Mexico Mining Act that was passed into law in 1993. Any additional underground mining that would create subsidence would be subject to a thorough review as a “new unit” that would be regulated under the provisions of the New Mexico Mining Act. Molycorp would have to meet the Act’s more stringent requirements to control unwanted effects from subsidence at any “new units.”

8.0 Conclusions

It is too late to mitigate the effects of current subsidence at the Questa mine. A common impact of block caving is surface subsidence. Subsidence effects at the Questa mine will make reclamation of the surface difficult, if not impossible. The perpetual water treatment plant to be built at the mine may have to be designed to accommodate a larger quantity of low pH water as a result of increased infiltration through the rubbleized material in the subsidence area. Subsidence will continue to occur even if the mine stops operating today. How long it will continue and to what extent is unknown. If the mine fully exploits the permitted orebody, within 15 years another 200 acres of surface subsidence will occur. Perpetual water treatment and fencing the unstable subsidence area will be the final mitigation measures at the Questa mine.

9.0 Case Histories of Block-Caving Mines

The following subsidence case histories of block-caving mines illustrate the wide range of geologic and hydrologic conditions that can occur at underground hardrock mines. It is significant that none of the mines discussed below was able to predict the timing, extent, and hydrologic impacts of subsidence as mining progressed. Also significant is the fact that none of these mines was as close to a major river as the Questa mine is to the Red River.

9.1 Background

The systematic study of environmental impacts from subsidence did not begin until the late 1970s, although studies on subsidence engineering in the United States did begin in the early 1900s when engineers in the Appalachian and Midwest coalfields documented the same causes and effects of subsidence. In a similar manner, there is only limited information that documents the causes and effects of mine drainage and even less documentation on the impacts to groundwater aquifers and surface waters.

Several different terms have been employed by authors to describe the mining techniques used and the resulting subsidence features. "Draw" or "zone of draw" is a term used originally in coal mining to describe the distance on the surface to which the subsidence or creep extends beyond the underground workings (Thrush and others, 1968, p. 347). It is defined by a line drawn from the margin of the area caved underground to the most distant fracture at the surface. A line thus drawn is a "cave line," and its angle with respect to the horizontal is the "cave angle" or "angle of draw" (Vanderwilt, 1945, p. 360). This angle is also referred to as the "angle of subsidence" by some authors. The "subsidence area" refers to the area above underground mining and is synonymous with "zone of draw." The "angle of break" is the angle at which the ore being mined breaks with respect to the vertical plane that extends above the orebody. Thus, a 90º break angle is straight up from the block of ore toward the ground surface. As the subsidence propagates upward from the caved block, this break angle generally flattens and becomes the "angle of draw" or "angle of subsidence" by the time it reaches the surface.

9.2 San Manuel Copper Mine, Arizona

9.2.1 Site Description and Background

The San Manuel mine is a low-grade porphyry copper deposit located about 50 miles northeast of Tucson, Arizona. Large-scale underground mining began in 1953, and during the early development work mine operators recognized that ground movement, subsidence, and rock mechanic problems would occur. Consequently, the San Manuel Copper Corporation and the U.S. Bureau of Mines agreed to conduct a cooperative investigation to study the subsidence effects of block caving, the mining method chosen at San Manuel (Wilson, 1956; Johnson and Soule, 1963, p. 2). These studies were able to measure subsidence as it occurred in an area undisturbed by previous mining. Other subsidence studies at San Manuel have included two master's theses (Griswold, 1957; Hatheway, 1966). San Manuel presents a unique case where subsidence was measured and analyzed from the beginning of mining in 1953 until the present when the mine (now owned and operated by BHP) is leaching low-grade oxide ore and underground operations have ceased.

9.2.2 Mine Geology and Hydrology

The San Manuel geologic terrane is relatively simple, consisting primarily of Precambrian quartz monzonite basement rocks that have been intruded by early Tertiary monzonite porphyry. Both the monzonite units have been intruded by irregular diabase bodies and later by a few Tertiary rhyolite dikes. Overlying the basement rocks are the Cloudburst, San Manuel, and Quiburis formations, a series of tuffs and flows of early Tertiary to Pliocene age. These rocks are covered by as much as 1000 feet of Gila conglomerate of Quaternary age (Johnson and Soule, 1963, pp. 6-7; Hatheway, 1968, p. 113). This conglomerate, which forms a wedge-shaped caprock over the orebody, figures most prominently in the surface expression of subsidence at San Manuel.

The orebody at San Manuel consists of quartz monzonite and granodiorite porphyry. One key factor in deciding to mine an orebody by block caving is the ease with which rocks break into relatively small, uniform fragments. At San Manuel the structural weakness of the ore is due to widespread fracturing and pervasive alteration that has produced varying amounts of clay minerals, sericite, chlorite, calcite, and epidote (Hatheway, 1968, p. 115). Clays and sericite are well known as agents destructive of rock strength. Fracture spacing in the orebody at San Manuel ranges from about 3 inches to six feet. Extensive fracturing combined with intensive hydrothermal alteration have created an orebody at San Manuel that is highly amenable to mining by block caving.

Water in the underground workings at San Manuel is commonly found in association with the rhyolite dikes and persistent fracture zones (Wilson, 1956, p. 78). None of the studies of subsidence at San Manuel mention mine flooding or major pumping of water, so it is assumed that the underground workings are relatively dry and that a fluctuating or persistently high water table is not a factor in subsidence.

Surface subsidence at San Manuel occurs in the Gila conglomerate, a highly variable rock unit consisting of bedded pebbles, cobbles, boulders, ash flow tuffs, and layers of sand, silt, and clay. The Gila conglomerate forms a wedge-shaped caprock over the orebody that thickens from 150 feet on the northeast edge of the deposit to more than 1000 feet on the southwest margin (Johnson and Soule, 1963, p. 8). The structural integrity of the conglomerates has been weakened by faulting and poorly bonded contacts at bedding planes separating the intercalated tuff beds and the surrounding rock.

Faults at San Manuel are important factors in causing and forming boundaries to surficial subsidence. The largest in the mine area, the San Manuel fault, is a low-angle reverse fault that varies in both strike and dip, with an average dip of 26º SW (Wilson, 1956, p. 77). Other low-angle faults roughly parallel the San Manuel fault and create conditions favorable to mining by block caving. In addition to these low-angle faults, two sets of high-angle faults that are younger than the San Manuel fault extend from the surface downward through the conglomerate. These younger high-angle faults do not appear to reach the orebody, where zones of breccia, gouge, and intense shearing appear to be caused by numerous low-angle faults. Some of the E-W fractures that dip 60º – 80º N occur in the footwall of the San Manuel fault and are possibly complementary to it (Wilson, 1956, p. 76). The combination of younger, high-angle faults intersecting older low-angle faults creates ideal conditions for both block caving and large-scale surface subsidence.

9.2.3 Subsidence History

After three years of development work, block caving began at San Manuel in 1956. Surface subsidence began to occur immediately in the form of “pipes” (not to be confused with soil “pipes,” a feature caused by erosion) which were visible on the ground surface within 100 days of the initial draws by block caving (Hatheway, 1968, p. 115). Pipes are upward extensions of caved areas that provide a path for transport of broken fragments of conglomerate into the mined area below. The surface expression of these pipes resembles crater-like depressions similar to those caused by chemical explosives in soil (Hatheway, 1968, p. 115).

By 1965 approximately 100 million tons of copper ore had been removed from underground workings at San Manuel. Two large subsidence areas had formed over the North and South orebodies, respectively. In 1965 the subsidence pit over the South orebody was more than 500 feet deep, 3000 feet long, and 2000 feet wide (Hatheway, 1968, p. 113). Each subsidence pit was surrounded by a series of near vertical tension fractures. The South orebody, largest of the three orebodies at San Manuel, was developed on the 1475-foot level underground. The area mined was approximately 3600 feet long and 900 feet wide, with a caprock of Gila conglomerate more than 750 feet thick over the southwestern part of the orebody (Johnson and Soule, 1963, p. 7). Subsidence has continued to occur over both the North and South orebodies to the present, although no published measurements of the subsidence areas have been issued since 1968. Dr. John Spencer of the Arizona Geological Survey (personal communication, August 2001) reported that during a field trip by the Arizona Geological Society in 1996 the subsidence areas were extensive, still active, and the mine did not allow access or photos of the subsidence pits which cover tens of acres.

Subsidence over the South orebody began about 3 months after the draw was begun. The effects of subsidence first extended into the area of thinnest caprock (Gila conglomerate) [Hatheway, 1968, p. 119]. There is no indication of a linear relationship existing between the depth of the mined area and the horizontal influence of subsidence at the surface. There does appear to be some connection between known fault locations and positions of boundary escarpments in the subsidence pit.

Conditions in the intermediate pit (North orebody, west pit) have been substantially different from those of the other two pits (South orebody and North orebody, east pit). Caprock thicknesses in the vicinity of this pit range from 350 to nearly 1100 feet. A total time lapse of 560 days occurred between initiation of draw and measurable ground settlement (Hatheway, 1968, p. 119). When settlement reached a critical point, the ensuing subsidence was rapid and large amounts of conglomerate broke and caved into the subsidence pit. The density of faulting is greater in this area than over any other mined area at San Manuel.

Conditions at the smallest pit (North orebody, east pit) may be taken to represent subsidence in its earliest growth stages. The Gila Conglomerate is thinnest at this pit and the area covered by pipes is abnormally large (Hatheway, 1968, p. 119). Peripheral tension cracks have extended laterally to a greater distance than in the other two pit areas. Similar to the other two pits, the faults planes here have formed the end escarpments to the subsidence area. The angle of subsidence is largest when measured in a plane parallel to faulting (Hatheway, 1968, p. 121). The case of preferential breakage has permitted the pits to grow faster in their long dimensions and has enlarged the angle of subsidence along these sides.

Results of a quantitative survey conducted by the U.S. Bureau of Mines (Johnson and Soule, 1963, p. 1) produced the following data on subsidence at San Manuel:

1. Angles of break range from 53º to about 95º (beyond vertical, which is 90º).
2. Angles of subsidence range from 64º to 95º.
3. Ratio of the volume of material mined to the volume of surface subsidence is approximately 1.44/1, which results in a swell factor of ~30%.

9.2.4 Environmental Impacts of Subsidence at San Manuel

Johnson and Soule (1963, p. 32) recommended that mine shafts and permanent surface installations be located 1200 feet from the nearest edge of a block caving stope situated on the 1475-foot haulage level.

From 1963 to 1995 mining at San Manuel continued to the 2700-foot level and the recommended distance for locating surface features was then increased to a minimum of 2100 feet from the edge of a block caving stope on the 2700-foot level. A general recommendation was made to assume 765 feet of lateral distance on the surface for each 1000 feet of depth mined in order to protect structures and ensure safety (Johnson and Soule, 1963, p. 32).

At present the San Manuel mine is owned and operated by BHP and minor leaching of low-grade oxide ore is done. However, surface subsidence continues to occur and the 2 large subsidence pits have been fenced off and posted with no trespassing signs (Nyal Niemuth, Arizona Dept. of Mines & Mineral Resources, personal communication, October, 2001). The subsidence areas, which now cover tens of acres, continue to be unstable and will pose safety risks for many years into the future. Both subsidence pits at San Manuel now act as highly transmissive pathways for precipitation to reach the underground workings.

9.3 Henderson Molybdenum Mine, Colorado

9.3.1 Site Description and Background

The Henderson mine is located approximately 50 miles west of Denver in the Front Range part of the Colorado Mineral Belt. The molybdenum deposit is located beneath Red Mountain (12,300 feet msl) and the mine surface facilities are in a valley north of Red Mountain at 10,400 feet msl. The mill site is linked to the mine by a 9.6 mile long railroad tunnel and an additional 4 miles of surface rail. Ore is extracted from the Henderson orebody using a large-scale, mobile, panel-caving system. Production was from the 8100-foot level, with undercutting from the 8155-foot level. Rail haulage was from the 7500-foot level. Production mining at Henderson ended in 1989, but ore production occurs for 3 months every 3 years in order to maintain the permit in standby status under Colorado law.

9.3.2 Mine Geology and Hydrology

The Henderson orebody is a stockwork molybdenite deposit located within multiple rhyolitic-granitic intrusions of the Red Mountain igneous complex (Stewart and others, 1984, p. 205). This Tertiary complex intruded the Precambrian Silver Plume granite and formed an irregular composite system of stocks approximately 2400 feet long and 1000 feet wide. Stocks exposed at the surface are modified by a subvolcanic pipe, concentric and radial dikes, and a shallow breccia pipe. The subvolcanic plug is a steeply dipping cylinder that probably grades into the Urad porphyry, the volumetrically major intrusive hosting the Henderson orebody. The Urad stock has been intruded by at least 12 stocks, 4 of which are the source of most of the molybdenite mineralization (Ranta and others, 1976, p. 477-481).

The Henderson orebody has the shape of an inverted cup that is slightly elongated to the northeast. Its dimensions are 3000 feet by 2000 feet, with an average thickness of 600 feet. The Red Mountain igneous center was emplaced in the acute angle between two regional faults, the Berthoud Pass fault to the east and the Vasquez Pass fault to the west of Red Mountain. Both faults form large, stranded, broken zones which pass within one mile and one-half mile, respectively, of the Tertiary igneous complex. No data were included on the hydrology of the Henderson and Urad orebodies so it is assumed that a high water table or mine flooding are not significant factors in the subsidence on Red Mountain.

9.3.3 Subsidence History at the Henderson Mine

Panel caving of the Henderson orebody began in August 1976. Fifty months later, on September 10, 1980, the cave zone appeared on the surface as a steep-walled cavity positioned directly above the caved area underground. Although surface survey data revealed the development of a slight depression over the production area, a surface inspection by geologists 3 days before breaching resulted in no evidence of impending glory-hole development. Geologic factors such as rock contacts and alteration-zone boundaries had little influence on the location of the initial glory hole. Another glory hole had formed several years earlier (1969-1974) on the southwest side of Red Mountain from underground mining being done 2100 feet higher at the adjacent Urad mine (Stewart and others, 1984, p. 206, Figure 6).

The caved zone at the mine crosscut Henderson orebody-related rocks and alteration zones at high angles, and growth progressed primarily within the Silver Plume granite (Precambrian). No major faults are known to exist in the region of the original surface disturbance, and the Silver Plume granite is actually less fractured than the Tertiary orebody rocks (Stewart and others, 1984, p. 209).

The actual shape of the cave zone when the surface was breached remains unknown. Brumleve and Maier (1981) speculated that two shapes could have formed:

1. A circular chimney centered over the area of high extraction (ore columns drawn in excess of 400 feet); or
2. A full-base model corresponding to ore column heights greater than 100 feet.

The shape was probably a combination of the two because the caved area is cantilevered on the southern and eastern boundaries and connected to a chimney over the initial production area. The volume of the glory hole calculated from September 30, 1980 aerial photos was 50,611,295 cubic feet compared with the volume of ore drawn of 338,280,129 cubic feet. Initial angles of draw (from vertical) range from –12º (102º) to 1º(89º). Little is known about the development and significance of tension cracks proximal to the glory hole. These cracks were not noted until the surface caved and the mine did not use the development of cracks as long-term, cave-growth predictors.

From 1981 to 1983 the growth of the glory hole was surveyed by the mine staff.. Although underground mining advanced north along a north-south axis, the glory hole grew larger in an east-west direction (which is up and downslope on Red Mountain). Local faulting influenced the shape of the glory hole once it formed. Intersecting faults defined the western and southern boundaries in 1981 and have influenced perimeter shapes and growth directions since then.

To summarize, the Henderson glory hole grew vertically through 3500 feet of igneous rock at an average rate of 2.3 feet/day. The ratio of ore drawn to the volume of the caved area was calculated in October 1980 to be 6.68:1. By October 1983 this ratio had been reduced to 2.37:1 (Stewart and others, 1984, p. 212).

9.3.4 Environmental Impacts of Subsidence at Henderson mine

The glory hole created on Red Mountain by mining at Henderson was approximately 1500 feet in diameter by October 1983. Another glory hole created by underground mining at Urad on the southwest side of Red Mountain is much larger and extends almost to the summit (Stewart and others, 1984, p. 209, Figure 6). Together these two subsidence areas have created dangerous, unstable conditions on Red Mountain that pose hazards to humans and wildlife.

Extremely heavy snowfalls (30-40 feet/year) in this part of the Colorado Rockies cause frequent avalanches at the elevations of both glory holes (10,000-12,000 feet msl). Both subsidence areas provide highly transmissive zones for precipitation to drain into underground workings more than 3000 feet below the ground surface. Steep slopes, avalanches, and frost heaving create surface conditions on Red Mountain that will cause unstable ground for many years as the caved material settles.
Although mine facilities at both Henderson and Urad were located at the base of Red Mountain and were not directly affected by subsidence, Red Mountain itself has been devastated by mining subsidence. Because both glory holes have expanded by moving up and down slope, it can be assumed that the upper limit for each subsidence area is the summit of Red Mountain. By the fall of 2001, the Henderson and Urad glory holes had expanded such that surface fractures from each caved area had merged to form one massive subsidence zone along the southwest flank of Red Mountain.

9.4 Miami (Inspiration) Copper Mine, Arizona

9.4.1 Site Description and History

The Miami (Inspiration) mine is located approximately 6 miles west-northwest of Globe, Arizona. Beginning in 1896 when the Black Warrior Copper Co. began mining a large outcrop of siliceous oxidized copper ore, the Inspiration Consolidated Copper Co. produced 7.5% of Arizona copper and 3.7% of U.S. copper (through 1968)[Olmstead and Johnson, 1968, p. 143].

The Inspiration mine began operations in 1910. From 1910 to 1925, 24.4 million tons of high-grade ore was mined by top slicing and sublevel caving. From 1926 to 1954, 102 million tons of low-grade ore was mined by block caving. From 1936 to 1943, 9.8 million tons of ore was mined by block caving. From 1955 forward 23 million tons of additional low-grade ore was scheduled for mining by block caving (Fletcher, 1959, pp. 413-414). As of 2001, the current owner BHP is conducting leaching operations on oxide ore at Miami in the area of subsidence. The Inspiration mine represents one of the earliest successful block caving operations that allowed the efficient and economical recovery of low-grade ore that previously would have been considered waste rock (Maclennan, 1929, p. 177).

9.4.2 Mine Geology and Hydrology

The geology at Inspiration is relatively simple. The orebody is in the highly faulted and shattered Pinal schist (Precambrian) which has been intruded by the Schultze granite porphyry (Tertiary), diabase dikes, the Willow Springs granodiorite, and partially covered by the Whitetail conglomerate, a dacite cap, and Gila Conglomerate (Quaternary)[Olmstead and Johnson, 1968, pp. 144-146]. The Miami fault to the east truncates the orebody, and the Pinto fault to the southwest of the orebody causes reoxidation of enriched sulfides producing mixed ore. Ore minerals at Miami consist of chalcocite, chalcopyrite, bornite, covellite, malachite, azurite, chrysocolla, cuprite, native copper and molybdenite. Both the orebody and caprocks have been strongly altered by extensive fracturing, silicification, and kaolinization along the numerous fault planes and slip surfaces.

There is very little groundwater and all water is drained off or evaporated during development preparatory to stoping (Maclennan, 1929, p. 174). The orebody can be divided into 3 classes: strong rock requiring no timbering; medium-strength rock requiring timbering; and weak rock requiring close timbering and repairs.

9.4.3 Subsidence History

F.W. Maclennan (1929, pp. 167-178) published the first major report on subsidence at Inspiration. His research found that by 1929 the maximum subsidence was 79.4% of the ore drawn in the East 250 section of the mine. This report showed that the subsidence had lowered the ground surface from 50-300 feet, and that a "daylight" glory hole had formed over the 256 stope that extended from the surface into the underground workings (Fletcher, 1959, p. 415).

The angle of draw ranged from 46º to 83º over the East 250 orebody, from 42º to 73º over the West orebody, and from 44º to 75º over the EO orebody (Fletcher, 1959, op. cit.). From 1929 to 1959 the subsidence angles had flattened considerably over each orebody. The cave angle at Inspiration averaged 45º in both the Pinal schist and Gila conglomerate. Original mining by block caving occurred at the 875-foot level and subsidence was noted at the surface during 1926, the first year of block caving (Fletcher, 1959, p. 413).

Assuming for purposes of discussion that the first surface subsidence was noted exactly one year after the initiation of block caving on January 1, 1926, the average daily rate of subsidence was at least 2.4 feet. By 1959 the volume of subsidence averaged about 67% of the volume of ore mined (Fletcher, 1959, p. 419). Neither the Miami fault nor the Pinto fault formed boundaries to the subsidence at Inspiration. The subsidence area extended from 500 to 1500 feet beyond the trace of these faults (Olmstead and Johnson, 1968, Fig. 1, p. 149). The swell factor for subsided material ranges from 1.0 (same density as in-place ore) to 1.6 (Fletcher, 1959, p. 420). By 1968 the subsidence area was depicted in plan view on a map by Olmstead and Johnson (Fig. 1, p. 149) as being approximately 4000 feet (NE-SW) by 3000 feet (NW-SE) and less than 250 feet from the Miami copper concentrator. As of 1968 this area was approximately 275 acres.

The combination of a relatively weak caprock (Gila conglomerate) and a highly fractured and altered orebody (Pinal schist) created favorable conditions for subsidence at Inspiration. During the earlier stages of caving, with a smaller diameter pit, horizontal arching tended to resist slippage of the pit walls. As the subsidence pit grew larger, the arching effect was weaker with resultant greater tendency to slip (Fletcher, 1959, p. 421). This is the same mechanism observed at the San Manuel mine, which also has Gila conglomerate caprock. Because the Pinal schist is both highly fractured and altered by sericitization and kaolinization, numerous slip planes and schistosity created weak, unstable rock which caused ideal conditions for both block caving and subsidence.

Piping was observed in the earliest stages of block caving over each of the major orebodies at Inspiration. Piping can be caused by an uneven draw or too wide a spacing of the draw point (Fletcher, 1959, p. 421). Tension cracks formed on the surface above the caved block and continued to radiate outward until the tensile stresses in the caved ground had been released. These tension cracks do not represent shear planes extending from the surface to the mining level, but are near surface features.

9.4.4 Environmental Impacts of Subsidence at Inspiration Mine

The impacts of subsidence at Inspiration are similar to those found at San Manuel and Henderson. Some roads were re-located as the main subsidence pit expanded; the stability of the Miami concentrator (less than 250 feet from the east edge of the subsidence area in 1968) was threatened; and additional precipitation entered the underground workings due to the increased transmissivity of caved rocks in the 275-acre subsidence area. In 2001, the caved ground at Inspiration was still unstable and will remain in this condition for many years to come.

9.5 Climax Molybdenum Mine, Colorado

9.5.1 Site Description and History

The Climax molybdenum mine is located on Fremont Pass at the head of Tenmile Creek about 100 miles west of Denver and 10 miles north of Leadville, Colorado. Elevations at the mine range from 11,400 feet msl to 12,800 feet msl.

The deposit was explored for gold in the 1890s and in 1900 the Colorado School of Mines identified molybdenite (MoS_2) from Bartlett Mountain that had previously been identified as graphite. Production began in 1914, ceased from 1919 to 1924, and resumed in August 1924. In 1933 the Climax deposit was being developed as the largest single metal-mining operation in the history of Colorado (Butler and Vanderwilt, 1933, p. 195). Major production continued throughout World War II, and the mine operated intermittently thereafter, finally being shut down in 1989.

Because of the high elevation and steep slopes, avalanches are common winter occurrences at Climax, where the snow depth often reaches 40 feet. The entire mine operation is above timberline, except for the tailing disposal area in the headwaters of Tenmile Creek.

9.5.2 Mine Geology and Hydrology

The ore deposit at Climax is in Precambrian granite, which contains schist inclusions and Tertiary dikes. The mineralized area is conspicuous because of limonite-stained outcrops of altered granite and schist. The central core of the mineralized area is largely composed of quartz cut by veinlets of orthoclase, molybdenite, fluorite, pyrite, chalcopyrite, sphalerite, and other minerals (Butler and Vanderwilt, 1933, p. 195).

The Mosquito fault, the most pronounced structural feature in the region, is a normal fault with a steep westerly dip and a northerly strike. There are many other faults in the area. Most of them are in Precambrian rocks and are unmineralized. Strong shear zones at Climax that are associated with Tertiary dikes are often mineralized. Many fissures also occur on the mine. Of 24 fissures mapped at Climax in 1932, 21 had strikes from N10º-80Eº and dips mostly 50º-60ºSE, although a few were vertical (Butler and Vanderwilt, 1933, p. 219).

None of the studies consulted for Climax mention the depth to groundwater at the mine. However, water is shown in concreted slusher drifts on Figure 4 in a report done on the chute and grizzly and slusher systems at Climax (Henderson, 1945, pp. 206). Henderson (1945) also mentions on page 200 that, "A great amount of water comes through the cave[d area] during spring runoff and spills from the chute are fairly common."

9.5.3 Subsidence History at Climax Mine

By 1920 surface subsidence had begun on Bartlett Mountain at Climax. In 1931 mining at Climax was done through the Phillipson tunnel at an elevation of 11,463 feet msl. By 1944 approximately 45 million tons of ore had been extracted. The caved area on the west side of Bartlett Mountain was roughly in the shape of a horseshoe open to the east. In 1933 the circumference of the caved area was 6000 feet, with an average width of 400-600 feet. The open end of the horseshoe (which caved after later mining) was 2800 feet long (Vanderwilt, 1945, pp. 363-364). The initial break angle was about 85º and by September 1933 the draw angle had flattened to about 65º. In 1927 the mining had been done on the 600-foot level; by 1933 mining had progressed to the 900-foot level.

The northern part of the caved area is on the slope of Bartlett Mountain above 12,500 feet msl. The southern part of the caved area extends into the drainage of Tenmile Creek at an elevation of 11,400 feet msl. The thickness of overburden in the caved area ranged from 900 feet in the northern area to from 10-40 feet in the southern area. Vertical escarpments in the caved area were from 50 to 100 feet high (Vanderwilt, 1945, p. p. 364).

Ground movement and subsidence at Climax have followed the patterns described in other mines. Vertical tension fractures at the surface are common at distances of several hundred feet outside the limits of caving on mining levels 400 to 800 feet below. Lines drawn in the conventional manner at the surface make conventional cave angles as low as 60º (Vanderwilt, 1945, p. 365).

By 2001 the subsidence area on Bartlett Mountain covered approximately 100 acres. The glory hole had intersected an open pit which was partially filled with waste rock that had sloughed into the pit around the perimeter. The combination of caved ground, unstable pit highwalls, and frequent winter avalanches makes the west side of Bartlett Mountain in the area of the pit extremely dangerous.

Vanderwilt (1945) described the process of caving at Climax through the period from 1940 through 1945. One caved block was 500 feet long x 500 feet wide x 600 feet high. Mining of the block began in 1940 and the block was completely undercut and caved by January 1943. By April 1943 tension cracks were expressed through several feet of snow. Two months later the surface over the entire caved block had subsided 25-50 feet, and vertical tension cracks roughly parallel to the subsided area could be seen on the 30º slope at distances of 150-200 feet from the margins of the main area of subsidence. By midsummer 1943 the entire area from the edge of the cave to the most distant crack was intersected by several fractures, and it was evident that the surface over an area of about 400 feet by 500 feet was slowly moving down the 30º slope and into the main area of subsidence (Vanderwilt, 1945, p. 365). The tension cracks formed a series of blocks 50-100 feet wide, 100-150 feet high, and 100-500 feet long. Survey stakes were placed on the top of a block and within 30 days those stakes had moved 3-5 feet parallel to the 30º slope. Some blocks tipped over from the top as the tension cracks widened. The blocks then moved downslope as rock-slumps or rock-slides. In a rock-slump the surface of the block is reversed as the mass rotates backward at the top and forward at the base. In a rock-slide the broken material moves in a mass or the individual blocks roll on fracture planes parallel to the surface.

Cracks from the caving of the block described above were visible in three of the underground workings at Climax at depths from 150-225 feet below the surface. These cracks were spaced relatively far apart and the rock between cracks was not fractured, indicating a movement of large units or blocks. Cracks in the Denver drift ranged from 1-10 inches wide and were spaced at 20, 30, and 80 feet. It was not possible to project fractures found on one level of mine workings to any other level. Nor was it possible to correlate fractures found underground with fractures observed at the surface.

9.5.4 Environmental Impacts of Subsidence at Climax Mine

Subsidence caused by block caving at Climax has created an area of chronic instability. Because the walls of the glory hole are nearly vertical and the natural slopes on Bartlett Mountain are very steep (30-60º), the area around the open pit is hazardous. Frequent winter avalanches aggravate the instability of the subsided area. As with other subsidence areas, the increased transmissivity of caved rocks above the original mining area allows for more infiltration of groundwater into underground workings.

9.6 Athens Iron Mine, Negaunee, Michigan

9.6.1 Site Description and History

The Athens iron mine was one of the largest producers of soft hematite ore in the Marquette iron range of the Upper Peninsula of Michigan. This area south of Lake Superior is one of the oldest hard rock mining districts in the United States, with numerous underground iron and copper mines that date to the early 1800s and Native American workings of native copper deposits that are several hundred years old.

Some of the earliest examples of hard rock mining subsidence in the United States are found on the upper Michigan peninsula. The Athens mine was opened in 1913 and began shipping ore in 1918, with a total production of 3,063,711 tons by January 1, 1932 (Allen, 1933, p. 195). A special system of mining was developed for the Athens mine that combined top slicing and sublevel caving of an orebody that was 500 feet wide, 300 feet thick, and 2000 feet long.

9.6.2 Mine Geology and Hydrology

The geology of the Athens mine consists of 150 feet of Pleistocene sand and gravel that overlies 1900 feet of jasper (iron oxide or "gossans cap"). This gossans cap overlies the 300-foot-thick orebody of soft hematite, which in turn overlies a footwall of slate (Allen, 1933, p. 197). A vertical diorite dike forms the north boundary to the orebody, while a near-vertical (95°) fault bounds the orebody on the south.

A large amount of water (~225 gpm) was encountered at the lowest part of the orebody (Allen, 1933, p. 197). This water was pumped out of the working area before the cave occurred and was considered to be manageable. However, once caving began in the gossans cap, the flow increased to ~300 gpm, and during the month in which the complete subsidence developed, the flow into the mine increased to ~600 gpm. The water table in an idle mine 1000 feet to the southwest dropped 6 feet during the development of the caved area at the Athens mine (Allen, 1933, p. 199).

9.6.3 Subsidence History at Athens Mine

The main shaft at the Athens mine was sunk north of the orebody to a depth of 2489 feet. A connection was made to the Negaunee mine by a drift 1100 feet below the surface and development work was started on the two bottom levels at 2200 feet [eighth level] and 2400 feet [tenth level] (Allen, 1933, p. 197). Production started at the western and lowest end of the mine in 1918 and a considerable amount of water was encountered. Mining proceeded through the method of top slicing and sublevel caving over the next ten years with efficient recovery of the orebody. After initial problems with water in the deeper parts of the mine, little additional water was encountered and the dry weight iron content of the soft hematite ore increased each year.

Finally, at 5 AM on June 19, 1932, block 2, which was 250 feet thick, 350 feet wide, and 600 feet long, caved to the surface through 1900 feet of jasper (gossans cap) [Allen, 1933, p. 199]. The mined-out area that collapsed was only 1/10th the thickness of the jasper cap. The cave-in occurred during a shift change and no injuries were reported. Immediate inspection revealed no evidence of inundation by water or sand, no crushing of drifts or workings, and no signs of an air blast. From June 19th the pumping log showed an increase from about 300 gpm to ~600 gpm by early July. This maximum pumping rate, which remained steady for one month, lowered the water level in an adjacent mine ~6 feet. By August, the pumping rate had been reduced to 540 gpm and by October 1932 the rate had decreased to 431 gpm (Allen, 1933, p. 199). Apparently, the cave opened a new water course above the orebody through the fault dike to the impervious footwall of slate (Allen, 1933, p. 200).

Two dikes, the "north" dike and "fault" dike, bounded the orebody on north and south. The outer portions of both dikes were composed of fault gouge and were planes of shearing weakness. This left little or no support for the jasper capping on its north and south borders over the mined area. A study of surface caves resulting from the Maas-Negaunee mines about ½ mile north of the Athens mine revealed similar conditions that created surface subsidence there. The caved areas at Maas-Negaunee appeared along the line of east-west dikes, all of which are fault planes (Allen, 1933, p. 201).

The Maas-Negaunee properties were mined at only half the depth of the Athens mine. The mining sequence at Maas-Negaunee was the reverse of that at the Athens, progressing downward from east to west. A predictable sequence of cracks formed at the Maas-Negaunee properties before subsidence. The western end of the caved area advanced by a series of breaks, forming terraces or steps, while the north and south borders followed the line of dikes. The cracks were 1-6 inches wide and appeared 100-400 feet in advance of the actual subsidence (Allen, 1933, p. 201).

Local geologic factors were responsible for the unexpected caving at the Athens mine. A fault (dip~ 95°) and a dike (dip~ 91°) bounded the orebody on the south and north, respectively. Instead of the expected draw angle of 60-85°, the near-vertical caved block did not widen at the surface and the resulting cross-sectional area of the deepest part of the surface cave was about one-third of the area mined underground (Allen, 1933, p. 202).

In a discussion section appended to the Allen report, W.R. Crane, a mining engineer with the US Bureau of Mines, noted that in his extended investigation of the iron mines at Ishpeming and Negaunee (Bulletin 295, USBM), the angles of draw were found to be 80° (Ishpeming) and 85° (Negaunee) and that he had noted draw angles as flat as 35° in glacial drift of sand and gravel and 45° in sand, gravel, and clay.

9.6.4 Environmental Effects of Subsidence at Athens Mine

As a result of the surface subsidence at the Athens mine, a railroad line was re-routed to avoid the area of instability. The lowest part of the mine was flooded and required pumping as an aquifer above the orebody was breached by the cave-in. Water levels in two adjacent mines were lowered by 6 feet as a result of the draining of the aquifer into the deeper Athens mine.

10.0 Other Case Studies

The following case studies include examples of hydrologic impacts to surface water from underground mining operations or tunnels under lakes.

10.1 Sunnyside Mine, Colorado

One of the most dramatic mining impacts on surface hydrology was observed at the Sunnyside silver mine just east of Silverton, Colorado in May 1978. A stope was being opened directly under Lake Emma when the last shift finished work on a Friday afternoon. Geologists had mapped the mine roof as being 30 meters below Lake Emma, which was thought to be shallow (2 meters deep), with a relatively flat bottom that was lined with several meters of sediments. Instead, the bottom of Lake Emma was V-shaped and located only 5 meters above the top of the stope. The bedrock was highly weathered and was overlain with ~25 meters of saturated sediments and 2-4 meters of water in the lake. On Sunday morning water and mud broke through and flooded the workings in a matter of minutes. Fortunately, the 200 workers normally in the mine were not underground or there would have been a huge loss of life from the mine flooding (Andrew Marcus, personal communication, December 2001). The mine was destroyed by the draining of Lake Emma and the lake remains dry today as it continues to drain water into the abandoned workings of the Sunnyside mine.

10.2 Kentucky-Utah Tunnel, Utah

The 2.7–km-long Kentucky-Utah Tunnel was constructed in the 1940s to drain excess groundwater from overlying hardrock mining activities located in the Wasatch Mountains. The tunnel was constructed through fractured limestone and dolomite with bulk permeability ranging from 10^{-7} to 10^{-4} cm/s. Heavy inflows of water occurred when the tunnel entered a high permeability fracture zone. This caused the water level to fall in a small surface water feature, Lake Solitude, located 900 ft above the tunnel and 1700 feet distant along the fracture zone. Reportedly, the lake was not drained entirely, possibly due to the high precipitation rate (>60 in. per year) (Gurrieri, 2001, p. 51).

10.3 Stillwater Mine, Montana

The Stillwater Mine is a platinum-group metal mine located in Montana. The underground mine began operation in 1986 and drove an adit to access ore serves. At 4,000 ft the adit encountered a large inflow of water that peaked at 884 gpm and within a few months decreased to a steady-state of approximately 200 gpm where it has remained. A small watershed containing a several springs and a perennial stream was located a vertical distance of 830 ft above the adit. The springs and stream both dried up and have remained dry ever since. In 1994 the ongoing mining operations resulted in the drying of three additional springs in another basin.

Other workings at Stillwater exhibited particular behaviors. When a tunnel below the Stillwater River connecting the east and west side workings was constructed water began draining at a peak of 350 gpm from the above lying groundwater aquifer. Above lying strata consists of 790 ft of fractured bedrock overlain by 310 ft of unconsolidated glacial and alluvial sediments. Despite grouting efforts, heads in the above lying bedrock zone dropped over 120 ft. and a large downward gradient was produced between the alluvial aquifer and the bedrock aquifer. However, water levels in the sediments representing the alluvial aquifer were not affected due to the low permeability of the sediments near the bedrock contact and the large permeability contrast between the sediments and underlying bedrock (Gurrieri, 2001, p. 52).

10.4 Northshore Tunnel, Wisconsin

A large tunnel of up to 26 ft diameter was driven under the city of Milwaukee in a layered, fractured dolomite aquifer more than one mile from and 230 ft below Lake Michigan, resulting in inflows averaging 770 gpm. Up to 165 ft drawdowns of the aquifer were observed dropping the potentiometric surface below the lake, and it was determined that 295 gpm was flowing from the lake into the tunnel. A 65 ft thick clay-rich lake bottom layer of sediment in the lake bottom did not isolate the aquifer systems (Gurrieri, 2001, p. 54).

10.5 Final Conclusions

The case studies cited here provide ample proof of the impacts mines can have on local hydrologic features. There is no reliable way to predict how soon or how long any mine might impact a stream, lake, or wetland. Subsidence can have unforeseen impacts on the volume and quality of contaminated mine water. The Molycorp mine has done extensive block caving immediately adjacent to the Red River and has created a mine sump that de-waters the alluvium of the river for a mile. This condition will be required as part of closure, when the water from the mine will be pumped and treated until it meets standards, which may take hundreds of years.

De-watering the alluvium and reducing the dilution from the alluvial aquifer will continue to damage the health of the Red River. Unfortunately, pumping and treating contaminated mine water will have impacts on the Red River for a long time.

11.0 References

Allen, Charles W. *Subsidence Resulting from the Athens System of Mining at Negaunee, Michigan*. Transactions of AIME, New York meeting, January, 1933.

Brumleve, C., and Maier, M., 1981, Applied investigation of rock mass response to panel caving, Henderson mine, Colorado: in *Design and operation of caving and sublevel caving mines*, D. Stewart, ed. SME of AIME, pp. 223-249.

Butler, B. S., and Vanderwilt, J.W., 1933, *The Climax molybdenum deposit*: USGS Bulletin 846C.

Fletcher, James Bishop. *Ground Movement and Subsidence from Block Caving at Miami Mine*. Manuscript, Nov. 10, 1958. AIME Trans., Vol. 217, 1960. San Francisco Meeting, February 1959.

Griswold, G.B., 1957, A study of the subsidence at the San Manuel mine, Tiger, Arizona: M.S. thesis, University of Arizona, Tucson, 86 pp.

Gurrieri, J., 2001, *Hydrology and Chemistry of Wilderness Lakes and Evaluation of Impacts from Proposed Underground Mining, Cabinet Mountains Wilderness, Montana*: Montana Dept. of Environmental Quality, 58 pp.

Hatheway, A.W., 1966, Engineering geology of subsidence at San Manuel mine, Pinal County, Arizona: M.S. thesis, University of Arizona, Tucson, 110 pp.

_____________, 1968, Subsidence at San Manuel copper mine, Arizona: *in* Titley, S.R., ed., Southern Arizona Guidebook III, Arizona Geological Society, pp. 113-124.

Henderson, R, 1945, A comparison between the chute and grizzly system and the slusher system at the Climax mine: AIME Transactions, pp. 198-214.

Johnson, George H., and Soule, John H. *Measurements of Surface Subsidence, San Manuel Mine, Pinal County, Ariz.* BuMines Report of Investigations 6204.

Lipman, P.W., 1981, Evolution of silicic magma in the upper crust: the Mid-Tertiary Latir Volcanic Field and it's Cogenetic Batholith, Northern New Mexico, USA: Transactions of the Royal Society of Edinburgh: Earth Sciences, vol. 79, pp. 265-288.

Maclennan, F. W. *Subsidence from Block Caving at Miami Mine, Arizona*. New York Meeting, February, 1929.

Mills, C. E., 1934, Ground movement and subsidence at the United Verde mine: Transactions of the AIME, pp. 153-171.

Olmstead, H.W., and Johnson, D.W., 1968: Inspiration geology: *in* Titley, S.R., and Hicks, C.L., eds., Geology of the porphyry copper deposits—southwestern North America, pp. 143-150.

Palmer, Robert E., London, England. *Observation on Ground Movement and Subsidences at Rio Tinto Mines, Spain. Trans. AIME,* New York Meeting, February, 1930.

Peng, Syd S. *Surface Subsidence Engineering*. Society of Mining, Metallurgy, and Exploration, Inc. 1992. AIME pp1-23, pp115-125, pp135-150, pp155-158.

Ranta, D., White, W., Ward, A., Graichen, R., Ganster, M., and Stewart, D., 1976, Geology of the Urad and Henderson molybdenite deposits—a review: *in* Epis, R.C., and Weimer, R.J., eds., Studies in Colorado Field Geology, No. 8, pp. 477-485.

Schilling, J.H., 1952, The Questa molybdenum mine: M.S. thesis, New Mexico Institute of Mining & Technology, Socorro, 73 pp.

Stewart, Daniel; Rein, Richard; and Firewick, David. *Surface Subsidence at Henderson Mine*. AMAX Inc. Empire, Colorado.

URS, 2001a, Questa Mine Closeout Plan: submitted to New Mexico Mining & Minerals Division on October 23, 2001.

______, 2001b, Alternatives Evaluation: Mine Rock Piles, Open Pit, and Subsidence Zone: submitted to MMD on March 20, 2001

Vanderwilt, John W. *Ground Movement Adjacent to a caving Block in the Climax Molybdenum Mine*. Manuscript, Dec. 1, 1944. Issued as TP 2000 in Mining Technology. May 1946.

Wilson, E.D. *Geologic Factors Related to Block Caving at San Manuel Copper Mine, Pinal County, Ariz*. Progress Report, April 1956-1958. BuMines Rept. of Inv. 5336.