Technical Report on

Underground Hard-Rock Mining: Subsidence and Hydrologic Environmental Impacts

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Abstract: *Subsidence and hydrology impacts occur at every underground mining operation bringing about changes to surface landforms, ground water and surface water. Although the same impacts to mining operations, man-made surface structures and other features are relatively well known and studied, the environmental impacts related to subsidence and hydrology at underground mines are not well known and have not been extensively described. This report examines the occurrence and environmental impacts of subsidence and effects on hydrology at underground hard-rock metal mines in the U.S. and abroad. Technical and scientific literature is cited on the cause and effect of underground mining on surface landforms and water resources. Existing laws and recommended regulatory provisions to address these impacts are discussed. Conclusions about subsidence and hydrologic impacts at underground hard-rock metal mines are provided along with recommendations for addressing those impacts. Case studies are provided from copper, molybdenum, silver and other hard-rock mines where significant subsidence and hydrology-related environmental impacts have occurred.*

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Executive Summary

Subsidence is an inevitable consequence of underground mining – it may be small and localized or extend over large areas, it may be immediate or delayed for many years. Underground mining causes impacts to hydrologic features like lakes, streams, wetlands, and underground aquifers. Modern hard-rock metals mining, using large-scale methods like block caving and room-and-pillar mining creates large areas of hydrologic and subsidence related impacts. Most studies of subsidence and hydrology impacts and their associated environmental effects have been done on underground coal mines. However, the fundamental engineering principles of hydrology and subsidence are the same for coal and metals mines.

Some underground mining methods like block caving by their very design affect subsidence to the surface almost immediately, along with associated hydrologic impacts. Other underground mining methods, like room and pillar mining, result in short-term impacts to aquifers and longer-term subsidence impacts. The effects on the environment may develop slowly over years in the form of degraded water quality, lowering of the water table, and chronically unstable ground. Methods used to predict subsidence and hydrologic impacts are not reliable when applied to the more complex geologic and hydrologic conditions found at most hard-rock metals mines. Hard-rock mines often contain faults and folds and hydrothermally altered rocks, which complicate and exacerbate subsidence and hydrologic impacts. Once mining begins, it is very difficult to mitigate the effects on the environment. There is little evidence in the scientific literature demonstrating effective mitigation of subsidence or hydrologic impacts at hard-rock metal mines. Consequently, the environmental impacts from mining may worsen over time as the ground continues to settle and aquifers are de-watered or degraded.

A review of federal and state regulations on subsidence and hydrologic impacts reveals that there is no federal statute or regulation within the Bureau of Land management or United States Forest Service regulations to address the impacts of hard-rock mining subsidence and that few states have laws that attempt to mitigate the impacts of subsidence. The Bureau of Land Management Revised 3809 Rules do contain requirements for financial assurance to address long-term impacts to water resources from mining; however, the Forest Service does not have similar rules.

Under the federal Surface Mining Control and Reclamation Act of 1977 (SMCRA) a mine is required to identify and develop subsidence and hydrologic impact plans before mining begins to deal with potentially negative environmental impacts. This report recommends that regulations similar to SMCRA be promulgated for underground metals mines to prevent and/or mitigate negative environmental and economic impacts. This report also concludes that because subsidence and hydrology impacts cannot be avoided as a consequence of underground mining, such activities should be considered inappropriate in National Parks, Wilderness Areas, and adjoining localities that might affect those areas.

Several case histories are presented to illustrate the mechanisms and impacts of hard-rock mining subsidence and hydrologic impacts. In some cases, subsidence and hydrologic impacts continue to affect the surface environment more than 100 years after mining occurred. These cases illustrate the wide variability of conditions at hard-rock mines and emphasize the basic fact that opening a void underground to conduct mining operations inevitably results in some impacts to surface and hydrologic features.

1.0 Introduction

The extraction of base and precious metals from hard-rock mines by underground mining can create environmental problems and safety hazards. Underground mining impacts water quality and flow and, as a result of subsidence, can also affect geologic structures overlying the mining areas resulting in surface impacts on the natural geomorphology and land use. Owing primarily to their size, open pit mines are typically thought to create more significant impacts, and thus underground mining is generally viewed as resulting in less damage to the environment. However, as this report demonstrates, the impacts from underground mining are not trivial. The methods and size of major underground mining operations and the extent to which hydrologic and subsidence impacts from those operations can impact the environment make appropriateness of underground mines in certain settings questionable.

The purpose of this report is to provide technical documentation of environmental impacts related to underground mining, to discuss that information as it pertains to existing and proposed regulation, and to assess existing and proposed underground mining projects that may significantly impact the environment and land use. This report draws upon extensive research into existing scientific information on hydrologic and subsidence impacts due to underground mining activities. This effort has revealed that subsidence impacts from coal mines are well documented, but are less well documented for hard-rock mines. However, information about hydrologic impacts at coal mines, and in particular underground hard-rock mines is less well documented. Although subsidence and hydrologic information from underground coal mines is applicable to underground hard-rock mining, empirical observations are necessary to validate similarities and fundamental differences as well as site-specific circumstances.

The study of the impacts of mining subsidence and hydrology has been directed towards the repercussions on mining efficiency/economics, mine dewatering, ground control, and safety. Most studies have not directly focused on, or in many cases recognized, the associated environmental impacts. By focusing on environmental impacts, this report is intended to serve environmental scientists, mining regulators, and others interested in and/or concerned about mining issues. One goal of this report is to identify the degree of uncertainty surrounding present methods that predict potential environmental impacts from underground mining and to suggest additional research needed to provide a sound basis for scientific, regulatory, industry and public opinion.

This report is based on the scientific method and information cited within this report was collected to test the null hypothesis that "Underground hard-rock mining causes surface subsidence and hydrologic impacts that affect the environment." This report contains six sections. The introduction is followed by sections on subsidence and hydrological impacts, including principles, environmental effects, and control and prevention. The fourth section discusses existing regulation of underground hard-rock mining subsidence and hydrological impacts and provides a model for their regulation. The fifth section provides conclusions and recommendations. The final section contains case studies of hard-rock underground mines that employ various mining methods and the resulting subsidence and hydrological impacts and environmental repercussions.

2.0 Mine Subsidence

Subsidence is a natural and man-made phenomena associated with a variety of processes including compaction of natural sediments, ground water dewatering, wetting, melting of permafrost, liquefaction and crustal deformation, withdrawal of petroleum and geothermal fluids, and mining of coal, limestone, salt, sulfur and metallic ores (Soliman, 1998). Most subsidence is either created or accelerated by humans (Environmental, 1972). Singh reports that, "Subsidence is an inevitable consequence of underground mining – it may be small and localized or extend over large areas, it may be immediate or delayed for many years" (SME, 1992). Fejes calls subsidence "a natural result of underground mining," and goes on to state that, "When a void is created nature will eventually seek the most stable geologic configuration, which is a collapse of the void and consolidation of the overburden material" (Mining, 1997). Central to all these opinions is the underlying fact that subsidence will occur and will result in impacts to the overlying strata.

Subsidence has always been a consequence of underground mining to at least some extent, beginning when the first rock fell on top of a person working underground for the purpose of extracting a mineral resource. Historical evidence of subsidence, beginning more than 5,000 years ago, has been reported on by Hoover (Agricola, 1950), Gregory (1982), Kratzsch (1983), Whittaker and Reddish (1989) and numerous others. In 1556 Georgius Agricola noted in *De Re Metallica*, his classic work on mining and metallurgy that the Italians had forbidden any mining in or around the extensive vineyards and fields of the prime agricultural regions because of the negative impacts of subsidence and degraded water quality caused by mining (Agricola, 1950).

People engaged in underground mining operations have always been concerned about the collapse of the overlying strata for safety reasons as well as mining logistics reasons. The formal study of subsidence engineering began in the 19th century and was focused on European coal mines in Belgium, France and Germany. The studies were initiated by damage to overlying mine facilities and railways (Kratzsch, 1983)(Whittaker and Reddish, 1989). These early reports established a scientific foundation for future subsidence studies and identified the mechanisms of subsidence (Whittaker and Reddish, 1989).

The study of surface movements led to the development of theoretical concepts that gradually evolved into the subject of *mine subsidence engineering*. Specific areas of study in this field include ground movement, structural geology, geomechanics, surveying, mining and property law, and mining methods and techniques. To study the environmental consequences, a complete understanding of the subject of mine subsidence engineering also requires the study of construction procedures, communications technology, agricultural science, hydrology and hydrogeology, urban planning, and socioeconomic considerations (SME, 1986).

Most studies to date have concentrated on the coal mining industry. As a result, much of the basis of subsidence engineering is based on experience from underground coal mines, and the information presented here is at least partly drawn from those examples. According to Singh, "Information … pertinent to coal mining … generally applies to other bedded deposits" (SME, 1986). Although principles developed for coal mining can be extrapolated to hard-rock mining, conclusions need to be verified by actual experience. For that reason, available information that demonstrates actual conditions at hard-rock mines has been included in the case studies provided at the conclusion of this report.

The creation of a cavity as a result of mining results in subsidence. But another mining-related phenomenon that also creates subsidence is the withdrawal of water to facilitate underground mining. Water withdrawal also causes the formation of cavities (which were once filled with water) and, like cavities directly created by mining, may result in subsidence as the hydro-geological properties of the associated strata are changed. The principles of water withdrawal as they relate to subsidence are discussed in this section and are also addressed in broader scope in the section on hydrologic impacts.

2.1 Principles of Subsidence

To be fully analyzed from an environmental as well as mining standpoint, all surface effects of subsidence associated with mining must be recognized. The narrow analysis of vertical displacement that will impact mining operations has often been the primary focus of subsidence investigations. This report is intended to provide primary focus on the impact mining operations have on the environment and is directed towards identifying all surface effects as well as secondary effects on hydrology, land use and other similar factors.

Although the principles of subsidence are similar regardless of the mining methods used, it is important to note that significant differences exist between coal and hard-rock mining subsidence. Most of the research worldwide has been done on subsidence caused by coal mining. While mathematical formulae that predict and manage coal mining subsidence have been developed and tested, similar efforts have not been undertaken to address subsidence at hard-rock metals mines.

Coal mining is almost always done in flat-lying or gently dipping sedimentary rocks comprising sandstone, shale, claystone, siltstone, marls, and similar rocks. Hard-rock metals mining more often involves igneous or metamorphic rocks that may or may not occur in stratified layers. Although some hard-rock mining involves sedimentary rocks (e.g., bedded copper deposits, limestone replacement deposits, roll-front uranium deposits), the majority disturbs rocks that have significantly greater strength than sedimentary strata. However, one feature common to most hard-rock mineral deposits is extensive faulting and intrusions by dikes, stocks, and sills. Another common feature in hard-rock mineral deposits is hydrothermal alteration of rocks caused by ore-bearing solutions. Argillic, kaolinitic, or sericitic alteration forms clays and clay-like minerals, with a subsequent reduction in rock strength. Sulfide ore bodies are often strongly weathered by acid generation, resulting in reduced rock strength. The effects of faults, intrusions, weathering, and alterations are discussed in the case histories analyzed in this report.

2.1.1 Development

Singh (SME, 1986) defines mine subsidence as "ground movements that occur due to the collapse of overlying strata into mine voids" which expresses itself in three major ways:

1. Cracks, fissures, or step fractures.
2. Pits or sinkholes.
3. Troughs or sags.

Mining activities that create relatively small voids may create pits or sinkholes, which are commonly associated with historic underground hard-rock mining activities. When mine voids are larger, like those at some of the largest historic hard-rock mines (see Butte, MT case study), or are created by modern highly mechanized, large-scale underground mines, the surface impacts are typically much greater, both in extent and relief. Factors that affect the manifestation of surface subsidence includes bulking (the swell of broken material versus that of in-situ material); water (which may transport material, change material properties, or result in cyclical wetting and drying); and the geology of the surrounding strata.

There are several common misconceptions about subsidence. For example, depth of the mine (as measured by the thickness of overlying strata) is often suggested as a prevention or mitigation measure.

Similarly, the extraction area is often correlated with the size of the subsidence area. However, according to Singh, mining at any depth can result in subsidence, and the affected surface area is generally larger than the extraction area (SME, 1986).

2.1.2 Components

Subsidence manifests itself upon the overlying strata in a variety of ways. The major components of subsidence that influence its environmental impacts are vertical displacement, horizontal displacement, slope, horizontal strain, and vertical curvature (SME, 1986).

Settlement, sinking, or lowering of the surface typically manifests vertical displacement. Horizontal displacement causes lateral movement at the surface. Both these phenomena may cause some damage (typically minor) to surface structures and can result in inundation of areas with a shallow water table. Slope dictates vertical displacement with respect to the horizontal, allowing in some cases for displacement that may be more pronounced and result in a greater degree of surface movement and increased environmental impact. Horizontal strain relates to horizontal displacement, with tensile or shear forces resulting in cracking and buckling of the surface, and is responsible for most of the damage to structures and other surface features located above mining areas. Vertical curvature is related to the slope and vertical displacement, which results in both shear strain and flexure or bending of the overlying strata (SMC, 1986; Mining, 1997).

The mining method is the other major component of subsidence that influences its environmental impact. The following mining techniques produce associated surface subsidence (Whittaker and Reddish, 1989):

1. Longwall mining
2. Top slicing
3. Sub-level caving
4. Room-and-pillar mining
5. Block caving
6. Stope mining
7. Solution mining

The first four methods listed are commonly used in the coal mining industry. Methods four through six are commonly used in the hard-rock mining industry. Method seven, solution mining, is not typical of hard-rock metals mining. The three common methods of hard-rock mining are further discussed in the following sections.

<u>Room-and-Pillar Mining</u>

This is a common mining method and many old room-and-pillar mine workings are in existence. It is generally only applicable to flat-lying deposits on a larger scale, although the same technique can be used on a smaller scale to mine dipping deposits. In room and pillar mining, some portion of the ore is mined while some ore is left in place to support the overlying strata. The portion of ore remaining in place is typically a function of the required support necessary to prevent the overlying strata from immediately caving or falling in while mining is being performed. In many cases, the pillars are removed or "robbed" at the end of mining when long-term support is no longer necessary.

The two most common forms of surface subsidence from room-and-pillar mining are sink-hole collapse and a saucer-shaped depression following pillar failure. In the case of room-and-pillar mining, surface subsidence can occur many years after mining is done (Whittaker and Reddish, 1989). The use of room and pillar techniques in hard-rock metals mining on a large scale is a relatively new and untested method, although it has been carried out as a part of some stope mining areas where larger ore deposits were encountered with varied success.

Block-Cave Mining

Block caving is used where underground access can be made through competent rock to access overlying ore deposits. The deposits are mined by removing underlying rock to the point where a controlled cave-in of overlying rock occurs and is taken advantage of as a mining method. The controlled caving of a block of weakened ore requires breakdown into sizes that permit discharge through cones at the base of the block and through finger raises into underlying transport drifts. Block caving is amenable to ore bodies that are structurally weak (e.g., fractured or hydrothermally altered) and will collapse under their own weight with a minimum of blasting.

The subsidence crater generated by block caving usually forms concentric lines of surface fractures. The subsidence crater has its major effects immediately over the mined-out block, although subsidence usually occurs outside of this area and is subject to the angle of draw, which depends on, the nature and thickness of overburden (Whittaker and Reddish, 1989). If ore withdrawal occurs in an uncontrolled manner from just one draw-point, then a draw ellipsoid can form and allow the overburden to be penetrated locally and possibly allow water to gain access to the mine (Whittaker and Reddish, 1989). In large block-caving operations, vertical scarps often form in a step-like manner radially from the center of the subsidence zone. The surface above large block-caving operations usually becomes rubbleized and highly unstable. Depth of surface subsidence over block-caving operations has been measured up to 500 feet (see San Manuel and Henderson case studies).

Stope Mining

Stope mining, combined with the development of adits, drifts and shafts, has historically been the most prolific form of hard-rock metals mining and has been done at both large and small scales. Stope mining is applicable to most vein-type ore bodies typical of base and precious metals deposits. The subsidence created by stope mining is usually the result of unintended cave-ins, inadequate support, pillar robbing, mining too close to the surface, and eventual collapse of the workings over time as the inevitable consolidation of the strata takes place. Most often subsidence is limited to the hanging wall side of underlying stopes. In many cases, the degree of surface subsidence that occurs from stope mining is both isolated and relatively minor. However, in some cases, particularly where extensive mining by this technique has been employed (see Butte, MT case study), the resulting subsidence can result in significant surface impacts.

2.1.3 Factors

A number of geologic and mining parameters can affect the magnitude and extent of subsidence. These include the thickness of extracted materials; overlying mining areas; depth of mining; dip of mining zone; competence and nature of mined and surrounding strata; near surface geology; geologic discontinuities; fractures and lineaments; in-situ stresses; degree of extraction; surface topography; ground water (including water elevation and fluctuation); mine area; method of mining; rate of advance; backfilling; time; and structural characteristics (SME, 1986). These factors have been recognized and examined in detail in the literature. Included below is a brief discussion of some of those factors, with particular emphasis on those that are more typical of hard-rock mining-related subsidence and its environmental impacts.

Ore Thickness: There is a direct relationship between the thickness of the extracted materials and the amount of surface subsidence that may result, making it an important factor in subsidence predictions. A greater thickness results in a greater amount of surface subsidence (SME, 1986).

Multiple Ore Zones: Where multiple mining horizons exist, subsidence which occurs in one area increases the likelihood of similar events in other areas, because the strata have been disturbed (SME, 1986).

Ore Zone Depth: Singh and others have determined that "Subsidence is independent of depth" and refute the notion that surface subsidence is prevented by leaving greater thicknesses of overburden. While this may prolong the time period before subsidence effects are observed at the surface, the total amount of subsidence is not changed (SME, 1986).

Dip of Ore Zone: Where the mining horizon is inclined, subsidence becomes skewed and mitigation measures such as pillars become less effective (SME, 1986).

Competence of Mine Floor and Roof: The mine roof and floor are critical factors in the initiation of subsidence events, since they propagate from these areas. Weak roof materials permit the fall of overlying strata, and compact more easily, resulting in a greater likelihood and severity of subsidence (SME, 1986).

Nature of Overburden: The strength of the overlying strata above the mining horizon is a factor in the timing and extent of subsidence (SME, 1986).

Surface and Near-Surface Geology: Surface and near-surface soils and unconsolidated materials tend to emphasize subsidence effects, because they behave in an inconsistent manner. They are an important factor relative to hydrologic impacts because they affect the exchange of surface water and ground water (SME, 1986).

Geologic Discontinuities: Faults, folds, and other inconsistencies in the overlying and surrounding strata may increase subsidence potential. The disturbance of equilibrium forces by mining can trigger movement along a fault plane. Faults may also weaken the overlying strata and trigger subsidence in materials that may otherwise show desirable properties (see Athens iron mine case study). Joints and fissures in the strata also affect subsidence but on a smaller scale (SME, 1986).

Degree of Extraction: The amount of pillar support is directly related to the timing and extent of subsidence. Lower extraction ratios result in greater thicknesses of pillars, which tends to delay and decrease subsidence. As the amount of pillar support is decreased, either by mine design or as a result of pillar extraction, subsidence occurs more rapidly and extensively. Complete removal of pillars is almost always followed by subsidence, with surface manifestations being a function of upward propagation to the surface (SME, 1986).

Surface Topography: Sloping ground like hillsides tends to emphasize the surface manifestation of subsidence, while it is less accentuated on flatter ground and in valleys (SME, 1986).

Ground water: Drainage gradients may be altered by disturbance of the strata around mine areas. Rocks may become weakened by saturation and erosion patterns could change. Where surface water is present, it may migrate more easily to fractures and fissures in the strata and into the mine area (see hydrology case studies) and may induce subsidence (SME, 1986). The creation of a cavity as a result of mining results in subsidence. But another mining-related phenomenon that also creates subsidence is the withdrawal of water to facilitate underground mining. Water withdrawal also causes the formation of cavities (which were once filled with water) and, like cavities directly created by mining, may result in subsidence as the hydro geological properties of the associated strata are changed. The principles of water withdrawal as they relate to subsidence are discussed in this section and are also addressed in broader scope in the section on hydrologic impacts.

Water Level and Fluctuations: The strength and stiffness of the overlying and surrounding rock strata, and any pillars left in the mining area, are significantly reduced by the effects of water (SME, 1986).

Mining Method: The extent and magnitude of subsidence is limited by techniques such as room-and-pillar mining, which limits the extent of extraction (Mining, 1997). The timing and extent of subsidence in room-and-pillar mines is not predictable, and eventual collapse of pillars in room-and-pillar mining may lead to trenching or sagging of the surface, with considerable displacement and strain over short distances (SME, 1986; Mining, 1997).

Backfilling: Partial or complete mine backfilling reduces subsidence and is dependent upon the type and extent of backfilling. However, it is important to note that backfilling does not eliminate subsidence (SME, 1986; Mining, 1997).

Time: The amount of subsidence has been observed as a direct function of time. Surface effects are delayed in room-and-pillar mining for some time, unless the pillars are removed. In block caving surface effects typically are immediately noticeable (SME, 1986) [see San Manuel and Climax case studies].

2.1.4 Measurement

Subsidence measurements are based upon a survey of the vertical and horizontal displacements that take place on the ground. A variety of specific methods may be used depending on the objectives, site, spacing and number, duration and cost. Automatic data acquisition systems have been utilized and are gaining acceptance (SME, 1986). The actual range of subsidence varies between a few feet to as much as several hundred feet vertically, and horizontal displacement may occur as well. It is important in monitoring subsidence that full coordinates (x, y, z) are measured in order to track the progress of ground movements.

2.1.5 Prediction

There are two basic methods of subsidence prediction: empirical and phenomenological. However, as many as five principal methods of predicting mining subsidence has been developed: empirical relationships; profile functions; influence functions; analytical models; and physical models (Whittaker and Reddish, 1989). All of these methods fall into the basic categories of empirical and phenomenological.

Empirical methods are based on field observation and experience and are generally applied to regions where adequate empirical data are available. Empirical methods for prediction of subsidence consist of graphical, profile function and influence functions that are constrained by the availability of observed data (SME, 1986). Empirical methods are quick, simple to use, and relatively accurate. These methods provide satisfactory results and are widely used in coal mining. However, the methods are site-specific and are only applicable to areas having identical geological and mining conditions (Bahugana, 1991).

Phenomenological methods are based on modeling principles, which use mathematical representation of idealized materials with the application of continuum mechanics. According to Singh (SME, 1986), "the (phenomenological) procedures … have not achieved much success to date, mainly due to the difficulty of representing complex geologic properties of the strata in simple mathematical terms."

Methods based on modeling principles have been made possible by advances in technology, and recent computerized models that take into account overburden, rock mass, and simulated mine geometry include Finite Element, Boundary Element and Distinct Element methods. However, simple analytical models cannot simulate the complex forces that strata undergo in the process of subsidence. In general, methods based on computerized mathematical models have been employed with limited success for subsidence prediction (Bahugana, 1991).

Bahugana presents a simple yet important general prediction relative to large-scale underground mines: "With the increase in mining activities, there will be a further corresponding increase in mine subsidence problems and the possibility of more damage unless proper subsidence control measures are taken." He goes on to state that, "…the effectiveness of preventive and protective measures greatly depends upon the accuracy of prediction of subsidence and associated parameters…" (1991).

Very little information is available concerning subsidence prediction for hard-rock mines, particularly in the United States, and the existing information is not applicable to a wide variety of circumstances.

2.1.6 Time Effects

The period during which mine subsidence occurs consists of distinct active and residual phases. Active subsidence occurs simultaneously with mining, whereas residual subsidence occurs after mining. The duration of residual subsidence is important from the standpoint of gauging the duration and extent of environmental impacts, including the extent of liability for post-mining subsidence (SME, 1986). Some coal mining methods and some hard-rock methods (including block caving) may induce subsidence concurrent with mining. Other methods employed in both coal and hard-rock (such as room-and-pillar mining) may result in delays of decades or until the support pillars have substantially deteriorated and collapsed. The actual time involved depends on a number of factors including strengths of ore zone; overlying and surrounding strata; extent of faulting and fracturing; depth of workings; pillar size and percent extraction. According to Singh, "prediction of when or how much damage may occur becomes difficult" (SME, 1986). There are documented cases of mine subsidence occurring 100 years after mines were abandoned (Soliman, 1998; Whittaker and Reddish, 1989).

2.2 Environmental Impacts

The following section discusses the environmental impacts caused by subsidence to surface structures and facilities; mine facilities; surface land use; and hydrologic impacts to streams, lakes, springs, and wetlands. Means of controlling and preventing impacts and reclamation and closure of surface subsidence are also discussed.

Mining's aftermath in terms of subsidence is impossible to ignore given increased concern for the environment (SME, 1986). It is a subject common to almost any environmental geology or hydrology textbook. Beyond the affects of subsidence to the land use and water, it may mar landscapes and diminish the aesthetic value of the natural landforms (Gill, 1971).

2.2.1 Surface Structures and Facilities

Because they are typically a part of the mining or ancillary operations, or because towns and other industries were built close to mining activities, damage to surface structures and facilities is the most commonly recognized and discussed environmental impact resulting from subsidence. Singh notes that the earliest motivation for the study of subsidence was severe damage to structures and other surface facilities and impacts to agricultural lands, which prompted landowners to demand compensation and restitution from mine operators (SME, 1986). Subsidence may well have been justification for the first use of the judicial system to address mining environmental issues.

The impacts to structures are based on tensile stresses, compressive damage, angular distortion and differential tilting or bending. These may act in a single deformation mode, but typically several of these forces are present and working together to produce complex impacts on buildings and other structures including bridges, railways lines, roads, communication and power systems. Most observations in the literature are based on coal-mining subsidence impacts to surface structures and facilities. These impacts have also been noted where hard-rock mines have been located in close proximity to dwellings and other structures.

According to Fejes, subsidence from hard-rock mines does not usually impact man-made structures because:

1. Hard-rock mines are frequently located in remote areas;
2. Block caving and other large-volume mining methods are known to cause “catastrophic” impacts to overlying strata, and as a result, the only solutions would be to purchase the overlying surface rights or limit mining; and
3. Even in cases where low-volume vein deposit mining methods are employed in competent rock at great depths with low extraction ratios, the surface expression of subsidence is not eliminated but will not appear “in the near future and possibly not for hundreds of years” (Mining, 1997).

2.2.2 Mine Facilities

Mine subsidence can impact both surface structures and structures or facilities located underground. Because mining practice tends to maximize the amount of material mined versus that necessary to provide adequate support during operations (and generally does not address the support needed post-mining), it is generally considered impractical not to mine within what is termed the “safety zone” (SME, 1986). Because this is an area of importance to mining companies that are primarily driven by cost implications (and by safety concerns), the subject has been thoroughly covered in the literature by Singh (SME, 1986) and others.

2.2.3 Surface Land Use

According to Soliman (1998), “Collapse of surficial materials into underground voids is the most dramatic kind of subsidence. Buildings and other engineered structures may be damaged or destroyed, and land may be removed from productive use by such ground failure.”

Surface land uses that may be affected by mining subsidence include crop production and grazing; areas which serve as aquifers and areas of recharge for underground waters; and areas with surface waters that support aquatic life or supply water for public use. Mining subsidence also affects the use of lands by wildlife or for human recreation. Additional consideration is required where lands are intended to support threatened or endangered wildlife species or in wilderness areas that are intended to retain certain undisturbed or natural characteristics.

Subsidence impacts agricultural lands in ways that include formation of surface fissures, change in ground slope, changes to surface drainage, disruption of ground water hydrology, deterioration of surface and ground water quality, and occurrence of subsidence areas (SME, 1986).

Subsidence-caused damage to surface land use is generally characterized by either a diminishment or loss of use or productivity. The amount of impact is site-specific and may be based on perception as well as measurable quantification. At a "moderate" level of damage, a particular surface land use may decrease the benefits or suitability of that use. At a "high" level of damage, a particular surface land use may become uneconomic, impractical, or in some cases may be lost.

Mining-subsidence impacts related to wildlife and human recreational use are generally characterized by either a diminishment of the actual or perceived value for such use or, in some cases, by the total loss of such use. Direct impacts on a particular aquatic species or for a particular recreational use might be measurable, whereas indirect impacts on a particular species or recreational use for an area is more difficult to evaluate and to some extent may be subjective. For example, one species of aquatic insect may be unique to a particular hydrological system that is threatened by mining. In an indirect manner, any mammalian wildlife, which depends on that species of insect for food would also be impacted. Similarly, recreational activities like fishing or hiking could be impacted by mining subsidence.

2.2.4 Hydrologic Impacts

Subsidence can cause both surface water and ground water impacts. The degree to which those impacts change the land use typically depends on the unaltered (pre-mining) surface water and ground water characteristics. Mining subsidence influences hydrologic systems in ways that cause changes to both water quality and quantity.

Subsidence can cause the formation of open cracks, fissures or pits, which, if connected either directly or indirectly to surface water (streams, lakes, ponds), may lead to partial or complete loss of water that is drained to lower strata or mine workings. Depletion of water resources in this manner can impact their suitability (quality and quantity) as well as impact aquatic life forms (SME, 1986) and other life which may depend on surface water systems.

Ground water can be affected by mine subsidence in various ways, including lowering of ground water levels, changes in flow rates, and impacts to water quality. Lowering of ground water levels may decrease the ground water supply and result in the decrease or loss of well water, and decreased surface transmission to springs, seeps and other surface water sources (streams, lakes and ponds). Changes to flow include increases brought on by faster movement through fractured strata, accumulation of water, and reduced evapo-transpiration. Decreases in flow may be brought about by water diversion caused by mining and mine subsidence. Alteration of water quality is caused by changes in the chemical reactions and reaction rates with the minerals or surrounding strata (SME, 1986). The high rate of occurrence of acid drainage and associated metals contamination associated with mining operations is well documented and is recognized as a major adverse consequence of many hard-rock metals mining operations.

According to Singh, "The prevailing hydro-geologic environment is significantly affected by subsidence-induced fissuring. Cessation of mining could bring about re-consolidation of the strata, but this may or may not result in the rebound of ground water to pre-mining levels. Water-table depression is generally localized near the mine workings, but the effects on the hydrologic regime could be highly variable and complex" (SME, 1986).

2.3 Control and Prevention

Four types of measures may control subsidence damage: alteration in mining techniques; post-mining stabilization; architectural and structural design; and comprehensive planning (SME, 1986; Mining, 1997). None of these measures entirely prevents subsidence, and most of the measures address only impacts to man-made structures and facilities and not impacts to land use, including aquatic species, wildlife habitat and human recreation, or water quality and flow.

Alteration in mining techniques can be accomplished through a variety of methods including partial mining, backfilling, mine layout or configuration, and extraction rate. Partial mining involves leaving protective features such as pillars. It should be noted that in areas supported by protective zones, water might become perched at a higher level than the surrounding ground that has subsided. If a water table was high, the area intended for protection may become an island or experience a lowered water table (SME, 1986). This may be an important limitation with respect to establishment of protective zones to protect surface water such as lakes or wetlands.

Backfilling may be done by hydraulic or pneumatic techniques, using a variety of materials including run-of-mine waste rock, milled tailings, or other materials, and may include the use of cement or other modifiers to increase strength. It may also have a beneficial effect on the environment by addressing water quality impacts (such as from acid drainage), reducing waste rock disposal requirements, reducing ground fissuring, and increasing long-term strata stability and providing roof support. Backfilling does not eliminate subsidence entirely, but only reduces the amount of subsidence (Mining, 1997; SME, 1986).

Post-mining stabilization techniques include backfilling, grouting, excavation and fill placement, and blasting (SME, 1986). The extent to which post-mining stabilization techniques can be relied on to mitigate subsidence damage is uncertain, as they require assessment of long-term stability. But analytical methods to predict the long-term stability of overburden in room-and-pillar (Mine, 1986) and other mining methods need significant improvement.

2.4 Reclamation

The scientific and engineering literature concerning subsidence does not mention reclamation and closure of subsidence areas. Previous studies have focused on the causes and effects of mine subsidence, with some discussion of mitigation techniques to reduce or minimize surface effects. There is no evidence that subsided areas can be effectively reclaimed. This may be in part because they are inherently unstable and unsafe for access by human-operated equipment. Upon closure, the only efforts generally undertaken to address hard-rock mine-related subsidence are to provide fencing and other measures to prevent public access. No known documented effort has been made to re-vegetate these areas, stabilize rubble, or prevent surface drainage from entering underground workings once mining is done. The reality is that these areas may remain unstable and unreclaimed for decades or centuries.

3.0 Hydrologic Impacts

Almost all human activities result in impacts to aquifers and their associated water aquifers, and some, including dam projects for irrigation and hydroelectric purposes, agricultural and domestic water use, oil and gas extraction, and mining have impacts that are significant and result in significant alteration and in some cases degradation of those water resources. The impacts by mining on water resources are well documented and the impacts to surface and ground water from underground mining operations have been reported on by Simons (Mining, 1997), Norton (1996), Park (1987), and others.

Major impacts to surface waters include subsidence, effects to springs, changes in wetlands, and water quality impacts, most particularly those from discharges. Stream channels have been shown to contribute the greater part of inflows to underground workings, so de-watering activities often reduce stream flows. Both surface features and underlying geologic structures and fracture systems which control surface water can be impacted by underground mining and subsidence. Pumping of aquifers associated with underground mining areas can interrupt flow to surface water. The hydrologic regime of alluvial systems and wetlands can be affected by underground mine dewatering, which may impact productivity, wildlife habitat, and other functions. Underground mining effects to surface water vary in form and severity (Mining, 1997).

Underground mining can change ground water flow paths and the geochemical environment. Mining may increase the permeability of rock units, create fresh rock surfaces, and allow water flow between previously unconnected units or between surface and ground water. This may disturb natural geochemical systems causing dissolution/precipitation reactions and result in impacts to ground water quality (Mining, 1997).

3.1 Principles

Underground mines impact ground water in much the same manner as open pit mines by draining water from the surrounding aquifer into the cavity (Thunvik, 1978). However, their impact on ground water elevations may be more pronounced as underground mines are frequently deeper and of larger areal extent than open pits. Ground water depletion as a result of underground mining can occur over miles and impact larger aquifers particularly in major mining operations.

The effects of surface subsidence on ground water are governed by the rate, direction and general pattern of water movement in an aquifer. Aquifer structure, lithology, permeability, water levels, topographic elevation and withdrawal characteristics control the movement of ground water in an aquifer. Ground water flow systems are classified as shallow, intermediate, and deep. Shallow flow systems occur just beneath the land surface and the surface drainage system. Intermediate flow systems occur some distance away from the surface. The ground water in deep flow systems travels from thousands of feet to miles, and moves water between surface basins. Wetlands and springs typify shallow flow systems, whereas intermediate flow systems may occur some distance from their source. Deep flow systems recharge over a large area such as major mountain ranges and they discharge into surface water (Peng, 1992).

Surface flow patterns can be affected by surface flow and water table changes caused by surface subsidence; formation of sink holes, pits and troughs; and by inflow into mines (Singh, 1982). The inflow into mines also impacts surface flow patterns and frequently water quality at its point of discharge into surface water as a result of mine dewatering.

Often, lakes and springs high in mountains have only an intermittent connection with deep ground water. The alluvium or colluvium in a high cirque, for example, is recharged annually by snowmelt. The discharge is often to shallow lakes, wetlands, springs, and small streams. Some water may flow vertically to recharge the underlying intermediate or deep ground water systems. The amount of this recharge as a function of the precipitation in the basin depends on the aquifer properties between the surface aquifer and the deep aquifer. In bedrock, this usually depends on the fractures.

3.1.1 Development

Underground mining creates a channel for water and air that did not previously exist. Ground water seeping into the mine can contact fresh rock surfaces that may contain reactive and soluble minerals. The chemistry of the entering ground water itself may be unstable, resulting in dissolution/precipitation reactions that change ground water quality. When ground water passes through highly mineralized rock in a mined area it can pick up large metals concentrations. The resulting effect on ground water quality depends upon treatment and the point of discharge (Mining, 1997).

Ground water quantity is affected by depletion of the aquifer when dewatering from underground mining acts as a drain and lowers the water table. When underground mines extend into saturated ground, the seeping water creates a hydraulic gradient and induces flow to the mine, which results in depressed water levels. There is usually a direct relationship between the depth of mining and the resulting static water level. In general, water levels will decline more as the mine goes deeper. Water levels will also decline relative to the location of the mine both aerially and vertically relative to recharge/discharge sources (Mining, 1997). Subsidence-caused fracturing of overlying strata can enhance vertical flow, which could lead to drainage of overlying aquifers. Permeability increases when fractures reach the ground surface, which may lead to increased ground water recharge and surface water depletion.

3.1.2 Components

The major influences of underground mining on hydrology are to reduce the protective layer of the aeration zone; raise or lower the water level above the surface in flooded areas such as wetlands; alter the hydraulic gradients causing changes in flow direction and speed; alter the natural retention features; and create turbid ground water due to rock bursts (Gremela, 1997).

3.1.3 Factors

Factors that affect ground water quality at underground mines include flow paths that result in movement of surface water to ground water, geochemistry, and geochemical barriers (Mining, 1997). By creating voids, mining creates new water flow paths or alters old flow paths. For example, an underground mine may cross geologic units, increasing the ability of water within one aquifer unit to mix with water in other units. Impacts typically depend on flow chemistry – if water chemistry entering is similar to existing water chemistry, impacts will be minimal. Underground mine subsidence creates an area of ingress of surface water to ground water and may expose or conduct ground water to the surface. When water containing more oxygen enters the ground, its equilibrium with surrounding rock units is disturbed, and rocks will achieve equilibrium by dissolving or precipitating minerals. A similar reaction may be caused by changing the flow of water from one area into another as a result of underground mining (Mining, 1997).

Surface subsidence and mine de-watering can cause compaction of an aquifer unit as water is removed from pore spaces and the weight of overlying rocks causes fissures and cracks in the aquifer unit too close (Whittaker and Reddish, 1989). As flow paths are altered, the direction of water flow may be shifted, resulting in new springs or wetlands. If an adit is to be plugged and the mine floods, pressure around the sealed adit can also create new discharge points.

Factors that affect the impact of underground mines on surface water include: size of water body; nature and thickness of strata between water body and mine workings; geological features and structural discontinuities; stress distribution mode; and water pressure. The size of water body is generally directly related to the amount of water entering a mine working and is particularly important where catastrophic circumstances may occur. For example, draining a small pond might result in relatively little water into the mine, but drainage from a large reservoir such as an ocean or large lake or major river can result in mine flooding. Lithology of the intervening strata has a significant influence on the impact of mine subsidence on surface water features. Structural discontinuities and structural features such as faults, dikes and fractures or joints can compromise strata thought to be otherwise protective. Stress modes influence strata deformation, which can dictate subsidence characteristics (Singh, 1986).

Underground mining water quality may be adversely affected by the increased exposure of fresh rock that provides a larger surface area for interaction of water and the rock geochemistry. By exposing fresh rock surfaces to contact with ground water, underground adits have the potential for impacting water quality. Mining also exposes fresh surface areas to oxygen, and if reactive materials such as pyrite are present, acid drainage can result in decreased pH and increased soluble metals loading (Mining, 1997). Protective pillars left in a mine filling with acid water can weaken and lose structural integrity as acid reactions create clays and clay-like minerals that have less strength than unweathered rock.

3.1.4 Measurement

Measuring water level and water quality changes are the basic means by which impacts to hydrologic systems from underground mining are determined. Where confined aquifers are present, piezometric level can be used to determine the pressure in a specific aquifer. Numerous investigations into the effect of underground mining on ground water flow have been performed (Peng, 1992), and although coal mining examples are numerous, only a few hard-rock examples have been documented. This is due more to a lack of impetus for study and the relative scarcity of major hard-rock mines.

3.1.5 Prediction

Water table lowering, or drawdown, predictions are generally based on the assumption that geologic materials transmit water equally in all directions (isotropic) and that they are the same over a great distance (homogenous). However, hard-rock mining usually occurs in anisotropic and inhomogeneous formations where structural features like faults and fractures may control, magnify and extend drawdown in selected directions (Mining, 1997). Furthermore, all models are simplified representations of the real world, and only a part of the natural systems are known or understood (Dodds, 1999).

A buffer zone or protective layer is sometimes "predicted" to stop or otherwise mitigate impacts to hydrologic systems. According to Singh, "At present it is not possible to incorporate all the factors in the design of a protective layer." (1982). Buffer zones assume that there is a practical areal limit to the extent that hydrologic impacts occur, however the available information suggests that the limits extend to the entire aquifer system (or watershed) in and around the mining activity and the only practical and effective mitigation is to exclude mining from an aquifer system if protection is intended.

3.1.6 Time Effects

The permeability, porosity, transmissivity, and other factors affecting a particular flow system largely dictate time effects. The time effect on springs and streams controlled by shallow flow systems has been shown to range from literally hours to days, whereas it may range from months to years on intermediate flow systems. The time effects on deep flow systems generally runs from decades to hundreds of years. The presence and effects of fracture flow systems may alter flow rates significantly in any of these flow systems.

3.2 Environmental Impacts

3.2.1 Springs and Seeps

Spring and seep flows may be reduced as a result of ground water depletion in an adjacent unmined aquifer due to depressurization by dewatering of the mined area. Ground water flow is induced to the mined aquifer resulting in the reduction of ground water levels in the unmined aquifer. Stream flow depletion may similarly occur, but may be difficult to detect (Mining, 1997).

3.2.2 Surface Lakes and Streams

Underground mine dewatering, by affecting ground water, can play a key role in the chemical regulation of lakes. For example, changes in the volume of ground water inflow to surface water can have an effect on the chemical balance and, consequently, on the biology of lakes and streams (Gurrieri, 2001). Gurrieri (2001) also confirms that there are few studies for non-steady ground water-lake or stream systems (such as where mining-related impacts to hydrology have occurred).

The dewatering of underground mine workings can contribute large quantities of flow to surface runoff, which may significantly exceed natural base flow conditions, with adit flows at some large operations on the order of several hundred cubic feet per second. These operations may discharge into streams or watersheds with average flows of less than a few cubic feet per second (Mining, 1997).

Underground mining impacts that alter flow regimes can affect the timing and amount of surface runoff. Upstream, local flows and downstream flows, both on and off the mine site, can be affected by underground mining-caused hydrologic impacts. Changes in surface water quantity and timing can change the frequency, magnitude, and duration of flood events and natural baseline flow conditions. It may also lead to downstream impacts including stream channel scour and sedimentation, disruption of aquatic habitats, and changes in both quantity and quality of water resources (Mining, 1997).

3.2.3 Ground water

A number of undesirable effects occur to the environment as a result of sustained withdrawal of ground water at a rate significantly greater than the natural recharge rate. Because these effects are slow to be recognized, by the time they are detected, mitigation measures are usually ineffective in stopping environmental damage. Such impacts may happen over a large area and over many years (Strahler, 1973).

Ponds, lakes and wetlands or bogs represent areas where the ground water table intersects the land surface. When the water table is lowered, such as by underground mine dewatering, these water bodies and the ecosystems that depend on them will be impacted, along with loss of aesthetic value. Water table decline also affects stream flow with similar impacts.

3.3 Control and Prevention

Two stages of water recovery occur in underground mines. In the first stage, because mine voids are being filled, the relative rate of water level recovery is slow. In the second stage, the relative rate of recovery increases as the natural pore spaces in the rock are filled (Mining, 1997).

The final stabilization level of ground water, once underground mining-related pumping ceases, usually occurs at a daylight point, such as an adit or access tunnel, and a new equilibrium level is established. This may result in ground water levels that remain depressed in the mine vicinity relative to regional levels, and mining discharge may be of poor quality relative to receiving waters (Mining, 1997).

Mine tunnel or adit sealing is sometimes employed as a mitigation measure. It is generally done to raise the ground water level in the mine, sometimes to the point of approximately pre-mining equilibrium. However, this may also result in the rise of water into zones of naturally fractured rock or rock disturbed by mining operations. This may result in more diffuse flows or new springs and seeps. The integrity of the mine seal is often an issue due to the hydraulic pressures which may develop (Mining, 1997). Since regulatory seal designs are rarely based on performance requirements, and industry guidelines similarly do not provide sufficient information about performance, assessment or prediction of seal effectiveness is highly speculative. In order to be effective, seal designs should be site-specific; performance-based, and address geomechanical and geohydrological considerations (Fuenkajorn and Stormont, 1997).

Another form of prevention is to restrict mining activities. This may be done by restricting the area of mining (via the establishment of "protection zones") or by not allowing mining to take place. It is common practice in Europe to consider such measures based on an appreciation that irreplaceable ground water and surface water resources must be protected from mining impacts even if it results in "the loss of a part of the mineral deposit" (Gremela, 1997). The use of "buffer zones" to protect surface structures or hydrologic features is unproven as a preventative technique in hard-rock mining. Buffer zones are not true mitigation measures because subsidence will still occur. Monitoring the effects of subsidence is also not mitigation. Buffer zones and monitoring will not prevent subsidence.

4.0 Regulatory Overview

Various federal, state and other regulations have been promulgated to address development, operation, and reclamation and closure of mining operations. At the federal level, mining regulations are contained in the Code of Federal Regulations for mining on public lands administered by the U.S. Forest Service in 36 CFR 228 and by BLM in 43 CFR 3809. Most states with significant mining activities have promulgated regulations in the form of Mining Acts and Mine Reclamation and Closure Acts, which may be applicable to state and private lands, as well as federal lands within each state.

The recognition of extensive and potentially dangerous pollution from coal mines led to the creation of the comprehensive federal Surface Mining Control and Reclamation Act (SMCRA) of 1977. However, despite the pervasive evidence of similar pollution from metal mines, no comprehensive federal law has been promulgated to address the operation, reclamation and closure of hard-rock mines. The General Mining Law of 1872 is silent on environmental issues, including such matters as reclamation, subsidence, water management, and bonding. As a result, each federal agency has been left to deal with the issue on its own, and in a similar manner each state has had to devise its own independent means to address environmental issues from abandoned, currently operating, and proposed mines.

A variety of programs have been developed to deal with these issues. To address the issue of historic mining, many states have developed Abandoned Mine Lands (AML) programs. However, these programs are generally intended to address public safety problems rather than broader environmental issues. Ironically, in many states the hard-rock AML programs are primarily funded by taxes on coal mining, and the metals mining industry pays no royalties or taxes to the federal government that are earmarked for reclamation of hard-rock mines. In more extreme cases abandoned mines are addressed by the U.S. Environmental Protection Agency as part of the Superfund program under CERCLA (Comprehensive Environmental Remediation and Cleanup Liability Act). In all cases, there has been a realization over the past 10 years that the actual liability associated with the cleanup of abandoned hard-rock metal mines, including those more recently abandoned by companies experiencing bankruptcy, is far more than was previously appreciated and could cost state and federal taxpayers billions of dollars to address (Kuipers, 2000).

With respect to modern mining operations, a variety of reclamation and closure regulations exist under the authority of different state and federal agencies. Those regulations are more generally intended to ensure that environmental issues are identified and addressed before and during mining operations. Mine reclamation and closure activities are required to address air and water quality and other issues both during and after mining. Because there is no comprehensive set of federal regulations that ensures consistency or thoroughness at the federal and state level with respect to hard-rock metals mining operations, the specific issues of subsidence and hydrologic impacts, particularly those concerning water quantity, have gone largely unaddressed.

4.1 Subsidence Regulations

A comprehensive analysis of state and federal regulations pertaining to reclamation and closure of hard-rock metal mines in the Western U.S. was conducted by Kuipers (2000). The study also found that although the state and federal relations in all cases have provisions for land stability, subsidence is specifically mentioned only in a few state regulations.

Alaska’s statutes allow for subsidence features to be exempt from reclamation requirements if the steepness of the subsidence feature makes reclamation impractical or impossible to accomplish (Alaska Reclamation Act).

Arizona's statutes allow for subsidence to be excluded from a reclamation plan or allowed to remain following reclamation (Arizona Revised Statutes §11-2-601).

Colorado's statutes require that, "Reclamation shall be required on all the affected land" (Colorado Mined Land Reclamation Act). However, despite the presence of extensive surface subsidence at several underground metal mines in Colorado (see Henderson and Climax case studies, Section 6), there are no present plans or bonding to address surface subsidence at those mines.

Montana's Metal Mine Reclamation Act requires that "The reclamation plan must provide for the reclamation of all disturbed land … to comparable utility and stability as that of adjacent areas" (Montana Code Annotated § 82-4-336) and the State's constitution requires "reclamation of all mined lands."

Although New Mexico's Mining Act is silent on subsidence with respect to existing mines, new mines are required, to the extent technologically and economically feasible, to prevent subsidence which may cause material damage to structures or property not owned by the operator (New Mexico Mining Act Rules § 507.C). New Mexico's mining act also requires that new mining operations specifically address hydrologic impacts caused by subsidence.

South Dakota regulations specifically address subsidence and requires that, "The operator must prevent or minimize subsidence that may result from mining activities. Where subsidence cannot be prevented, measures must be taken to minimize damage to and loss of value of property and to minimize hazards to livestock, wildlife, and humans" (South Dakota Administrative Regulations §74:29:01).

4.2 Hydrologic Impact Regulations

Although the federal and state regulations in nearly all cases address hydrology (with the exception of Idaho and Nevada, which do not contain any requirements specific to hydrology), only the states of California, New Mexico, South Dakota and Wyoming have specific requirements pertaining to hydrologic impacts, including water quantity. In addition, many of the state acts pertain to surface mining only, and are not applicable to underground hard-rock mines.

California's surface mining statutes do not allow the diminishment, except as allowed in the reclamation plan, of water quality, recharge potential, and storage capacity of ground water aquifers (California Surface Mining and Reclamation Act), but the state does not similarly regulate underground mines.

Colorado's statutes require that disturbances to the prevailing hydrologic balance in surface and ground water systems both during and after mining shall be minimized (Colorado Mined Land Reclamation Act).

Although New Mexico's Mining Act is silent on hydrologic issues with respect to existing mines, new mines would be required to be planned and operated to minimize negative impacts to the hydrologic balance in the mine and other potentially affected areas. Subsidence-caused hydrologic impacts are specifically dealt with for new mining operations that must be conducted "to avoid disruption of the aquifer and consequent exchange of ground water between the aquifer and other strata." New mines must ensure that "mining activities conducted beneath or adjacent to any perennial stream must be performed in a manner so that subsidence is not likely to cause material damage to streams, water bodies and associated structures" (New Mexico Mining Act Rules § 507.C).

South Dakota's statutes address hydrologic balance by referring to state laws dealing with water rights, and otherwise require compliance with state and federal water quality laws.

4.3 Reclamation and Bonding Examples

This study researched the published literature for coal and hard-rock mining, as well as other types of mining. A few examples can be found for reclamation and remediation of coal mine subsidence and hydrologic impacts other than water quality. However, no single mention of reclamation and closure that involved subsidence or hydrologic impacts (other than water quality) was found in searches conducted from sources at the U.S. Bureau of Mines, libraries at Montana College of Mineral Science and Technology and the New Mexico Institute of Mining & Technology, mining databases, metallurgy and metal industry periodicals, the Internet, and other sources, including oral accounts.

Kuipers (2000) reviewed many of the reclamation plans and bond requirements for hard-rock metal mines in the western United States. The study did not identify any reclamation and closure plans that specifically addressed subsidence or hydrology impacts other than water quality. The study also examined existing bonding for hard-rock metal mines and did not identify any financial assurance in place at any mines specifically to address subsidence, or hydrology impacts other than water quality. At one proposed mine which was recently denied a permit (Crown Jewel, WA), the proposed reclamation plan did contain extensive requirements addressing hydrologic balance of both ground water and surface water and required bonding to ensure the restoration of the hydrologic balance after mining (Kuipers, 2000).

The U.S. insurance industry considers mine and other subsidence uninsurable, based on its "devastation" and uncertainty with respect to risk, consequences, and cost. This makes financial assurance requirements for subsidence areas problematic. To address subsidence impacts to surface-structures caused by coal mining, some states have developed their own insurance programs (Ingram, 1993).

The paucity of cases for the underground hard-rock mining industry with respect to subsidence and hydrologic issues is due more to a lack of recognition of the issues than any other factor. In every case where underground mining has encountered ground water, some drawdown of the overlying and surrounding aquifer has occurred. There are several examples of surface impacts that have been noted and probably additional examples for which no information has been published. With respect to hydrologic impacts, state water rights laws have typically been viewed as the legal remedy, although such laws were never intended to address environmental impacts from mining. Lands removed from the public domain by the 1872 Mining Law or otherwise situated on private land have conducted most underground mining on a major scale. Consequently, no overwhelming public requirement has existed, except in a few cases, to address environmental impacts. In the few cases where the public has been impacted, like in towns and cities above or surrounding underground hard-rock metal mines, the responsible mining companies either already owned the land, bought out the affected parties, or used their underlying mineral ownership to allow for such impacts to occur.

According to Singh, future mine operators might be expected to provide information "that depicts predicted subsidence locations, extent, maximum subsidence locations, values and direction of tilt, compression and extension zones, and other pertinent data" (SME, 1986). He goes on to suggest that, "In extreme cases, construction may be barred from particularly risky areas, and those lands used for parks, forest preserves, and open spaces." In the same manner, future mine operators might also be expected to provide information that predicts impacts to ground water and surface water quantity and quality. In those lands used for parks and other public purposes, mining could be banned.

4.4 Regulatory Recommendations

Regulations to address subsidence and hydrologic impacts should be promulgated specifically for the hard-rock metals mining industry and underground mines. Such regulations need to address the requirements for prediction, measurement, mitigation, reclamation, and closure related to the environmental impacts, and to address where those impacts are deemed appropriate and where they may be deemed inappropriate and not allowed. It seems clear that if activities like mining are banned from National Parks in the United States, then lands and water resources which are highly valued as a public resource (designated wilderness areas and state parks for example) should also be protected. The information evaluated in this study makes it clear that any significant amount of underground mining can have detrimental effects on the hydrologic balance and potentially water quality, and that some extent of surface subsidence will occur. If the intent is to retain the naturally clean and healthy characteristics of lands like designated wilderness areas, then it is imperative that no mining activities be allowed, on the surface or underground, in or near such lands.

To regulate future underground hard-rock mining activities in areas where such impacts are deemed acceptable, state and federal mining laws should be either added to or modified to include specific provisions to address both subsidence and hydrologic impacts. The comprehensive federal Surface Mining Control and Reclamation Act (SMCRA) of 1977 could serve as a good template for similar regulations pertaining to the underground hard-rock metals mining industry. However, it is important to note that regulations, no matter how strong, are protective only if they are fully and consistently enforced by a regulatory agency. The history of enforcement under SMCRA is inconsistent, and Congress has never adequately funded mine inspector positions in OSMRE (Office of Surface Mining Reclamation and Enforcement) to allow for full enforcement of SMCRA regulations. Consequently, promulgating strong regulations to address the surface and hydrologic impacts of underground hard-rock mining is only the first step in managing the negative impacts of subsidence. Adequate funding and staffing of regulatory agencies is essential to ensure that laws and regulations are fully and consistently enforced.

4.4.1 Subsidence

SMCRA requires a subsidence control plan and has subsidence performance standards for surface and underground coal mines on federal and Indian land. Two different sections in SMCRA deal with subsidence caused by underground coal mining. The first, §784.20, requires a permit applicant to submit a subsidence control plan. The subsidence control plan must be submitted as part of the permit application package well in advance of any actual mining. If the permit is granted and subsidence is part of the mining plan, another section of SMCRA specifies the performance standards regulating subsidence. Note that any subsidence control plan must be submitted before mining begins. Monitoring the effects of subsidence is not mitigation, and mining under SMCRA is not allowed to proceed until the full environmental effects of possible subsidence have been evaluated. Only after a subsidence control plan has been developed, discussed, and approved is mining allowed to proceed.

If the permit is granted and subsidence is part of the mining plan, another section of SMCRA specifies the performance standards regulating subsidence. Those performance standards are spelled out in §817.121 of SMCRA

The language on subsidence in SMCRA provides for a comprehensive and timely evaluation of the environmental impacts before underground mining begins. If underground mining is planned, mitigation measures are required to prevent damage due to subsidence to structures, renewable resource lands, and water supplies. Financial assurance can also be required to pay for possible damage from subsidence. Detailed plans and surveys are required to develop a subsidence control plan and meet performance standards. Certain areas are deemed unsuitable for mining that is likely to create subsidence. Water supplies are specifically protected.

The language in SMCRA dealing with subsidence would seem to be directly applicable to subsidence caused by hard-rock underground mining. Although there are some key differences between underground coal mining and underground metals mining, it should be possible to modify the language in SMCRA to address federal regulation of subsidence caused by hard-rock mining.

It has been common industry practice in coal mines to develop a long-term mine plan that address and accounts for eventual subsidence. Coal mines are typically planned and financed for periods of up to 20 years or more. Hard-rock mines typically operate with less well developed plans that rarely address or account for eventual subsidence, even in cases where mining techniques are used which inevitably will result in significant surface subsidence. In addition, discontinuities such as faults and fracturing are more frequently encountered and, consequently, it can be much more difficult in underground metals mining to predict where and when surface subsidence will occur.

Although there are significant differences in developing a mine plan for an underground coal mine and an underground metals mine, enough similarities exist to allow for a consistent regulatory framework for both types of underground mining. For example, establishing criteria for lands unsuitable for any type of mining is addressed directly in SMCRA (§762[federal] and §764[state]). Specific language in SMCRA deals with prime farmlands [§716.7 and §785.17], alluvial valley floors [§785.19], and other areas (schools, churches, urban areas, bodies of water >20 acre-feet, domestic water supplies). These areas are given a higher level of protection under SMCRA in recognition of the higher use values and safety issues associated with each one.

4.4.2 Hydrology

SMCRA requires hydrologic information and has hydrologic performance standards for surface and underground coal mines on federal and Indian land. Two different sections in SMCRA deal with hydrologic impacts caused by underground coal mining. The § 784.14 a permit applicant to submit hydrologic information including a determination of consequences and cumulative hydrologic impact assessment. If the permit is granted and hydrologic impact becomes part of the mining plan, another part of SMCRA, § 817.41, requires a hydrologic-balance protection plan.

The probable hydrologic consequences determination, cumulative hydrologic impact assessment, hydrologic reclamation plan, and surface water and ground water monitoring plans must be submitted as part of the permit application package well in advance of any actual mining. If the permit is granted and hydrologic impacts are part of the mining plan, another section of SMCRA specifies the performance standards.

The language on hydrologic impacts in SMCRA provides for a comprehensive and timely evaluation of the environmental impacts on ground water aquifers and surface water before underground mining begins. If underground mining is planned, mitigation measures are required to prevent damage to the hydrologic system. Financial assurance can also be required to account for the cost of hydrologic reclamation. Detailed plans and baseline monitoring are required to develop a hydrologic control plan and meet performance standards. Certain areas are deemed unsuitable for mining that is likely to create hydrologic impacts. Water supplies are specifically protected.

Although there are significant differences between underground coal mining and underground metals mining, enough similarities exist, particularly in terms of similar environmental affects, to develop a consistent environmental regulatory framework for both types of underground mining. A prudent set of regulations that can be applied to the unique conditions at each mine would allow for comprehensive environmental management. For this reason, a key conclusion and recommendation of this report is that a SMCRA-type federal regulation for hard-rock metal mines, with participation at the state level, is both necessary and appropriate, and should be of the highest priority. Any new regulations must also be supported by adequate funding and professional staff to fully and consistently enforce such regulations.

5.0 Summary and Conclusions

Based on the information contained in the literature and the case studies, the following conclusions and recommendations are made with respect to subsidence and hydrologic impacts at underground hard-rock metal mines. The conclusions made are confirmed by the information previously cited in this report that confirms the null hypothesis "Underground hard-rock mining causes surface subsidence and hydrologic impacts that negatively impact the environment." This report demonstrates the hypothesis to be both true and factual.

5.1 Conclusions

General

- Underground hard-rock metals mining has caused significant environmental impacts, which may be exacerbated due to the mining methods and large scale of many existing (and proposed) major underground mining operations.

Hard-rock Mine Characterization

- Most hard-rock mineral deposits exhibit extensive faulting and intrusions by dikes, stocks, and sills; hydrothermal alteration of rocks caused by ore-bearing solutions; clays and clay-like minerals, with a subsequent reduction in rock strength. Sulfide ore bodies are often strongly weathered by acid generation, resulting in reduced rock strength.

Subsidence

- Subsidence is an inevitable consequence of underground mining and it will result in impacts to the overlying strata.
- Dewatering can result in the formation of cavities and may result in subsidence as the hydro geological properties of the associated strata are changed.
- Mining at any depth can result in subsidence, and the affected surface area is generally larger than the extraction area. Greater depths of overburden do not prevent subsidence, but may prolong the time period before subsidence effects are observed at the surface.
- There is a direct relationship between the thickness of the extracted materials and the amount of surface subsidence that possibly results. A greater thickness results in a greater amount of surface subsidence.
- Geologic discontinuities such as faults, folds and other inconsistencies in the overlying and surrounding strata may increase subsidence potential. Mining can trigger movement along a fault plane. Joints and fissures in the strata also affect subsidence.
- The effects of water significantly reduce the strength and stiffness of the overlying and surrounding rock strata, and any pillars left in the mining area.
- The amount of subsidence has been observed as a direct function of time. Even in cases where vein deposit mining methods are employed in competent rock at great depths with low extraction ratios, the surface expression of subsidence is not eliminated, but may not appear for some time.
- Other factors that affect subsidence include nature of overburden; surface and near-surface geology; degree of extraction; surface topography; ground water; mining method; and backfilling.

Subsidence Impacts to Hydrology

- Mining subsidence induces fissuring in overlying and surrounding strata which influences hydrologic systems in ways that cause changes to both water quality and quantity.
- Subsidence-caused fracturing of overlying strata can enhance vertical flow, which could lead to drainage of overlying aquifers. Permeability increases when fractures reach the ground surface, which may lead to increased ground water recharge and surface water depletion.
- Surface and near-surface soils and unconsolidated materials are an important factor relative to hydrologic impacts because they affect the exchange of surface water and ground water.
- Ground water drainage gradients may be altered by disturbance of the strata around mine areas. Rocks may become weakened by saturation and erosion patterns could change.
- Where surface water is present it may migrate more easily to fractures and fissures in the strata and into the mine area and may induce subsidence.
- Subsidence can cause the formation of open cracks, fissures, or pits which, if connected either directly or indirectly to surface water (streams, lakes, ponds), may lead to partial or complete loss of water that is drained to lower strata or mine workings.
- Ground water can be affected by mine subsidence by lowering of ground water levels; changes in flow rates; and impacts to water quality.
- Dewatering can result in the formation of cavities and may result in subsidence as the hydro geological properties of the associated strata are changed.

Subsidence Impact to Land Use

- Surface land uses that may be affected by mining subsidence include: agricultural areas; surface watersheds; aquifers and areas of recharge for underground waters; surface waters that support aquatic life or supply water for public use; and lands which might be used by wildlife or for human recreation.

Subsidence Mitigation

- Subsidence damage may be controlled by alteration in mining techniques; postmining stabilization; architectural and structural design; and comprehensive planning. However, none of these measures entirely prevents subsidence.

Subsidence Reclamation

- There is little or no documentation of the reclamation of areas impacted by hard-rock mining subsidence. There is evidence that subsided areas, at least in part, cannot effectively be reclaimed and that reclamation overall may be problematic.

Hydrology

- The major influences of underground mining on hydrology are to reduce the protective layer of the aeration zone; raise or lower the water level above the surface in flooded areas such as wetlands; alter hydraulic gradients causing changes in flow direction and speed; alter natural retention features; and create turbid ground water due to rock bursts.
- Discontinuities such as faults and fracturing are more frequently encountered in hard-rock mining. Consequently, fracture flow occurs, making it much more difficult in underground metals mining to predict where and when hydrologic impacts will occur.

- Water-table drawdown predictions are generally based on the assumption that geologic materials transmit water equally in all directions (isotropic) and that they are the same over a great distance (homogenous). However, these conditions are generally not the case in hard-rock mining formations as structural features such as faults and fractures may control, magnify and extend drawdown in selected directions.

Hydrology - Ground water

- Ground water quantity is affected by depletion of the aquifer when dewatering from underground mining drains and lowers the water table.
- Ground water depletion at underground hard-rock metals mines can occur over a large area and impact larger aquifers by draining water from the surrounding aquifer into the cavity.
- There is typically a direct relationship between the depth of mining and its relation to the resulting static water level. In general, water levels will decline more as the mine goes deeper. Water levels will also decline relative to the location of the mine both aerially and vertically relative to recharge/discharge sources.
- Factors that affect ground water quality at underground mines include; flow paths that result in movement of surface water to ground water, geochemistry, and geochemical barriers.
- Ground water seeping into the mine can contact fresh rock surfaces that may contain reactive and soluble minerals and can lead to the formation of acid generation and metals contamination.
- With sustained withdrawal of ground water at a rate significantly greater than the natural recharge rate, impacts may happen over a large area and over many years.

Hydrology - Surface Water

- Factors that affect the impact of underground mines on surface water include: size of water body; nature and thickness of strata between water body and mine workings; geological features and structural discontinuities; stress distribution mode; and water pressure.
- Depletion of surface water resources can impact their suitability (quality and quantity) as well as impact aquatic life forms and other life dependent on surface water systems.
- Surface flow can be affected by water table changes caused by surface subsidence and mine dewatering and by the discharge of inflows into surface water from mine dewatering.
- Spring, seep and stream flows may be reduced as a result of ground water depletion in an adjacent unmined aquifer due to depressurization of dewatering of the mined area.
- Underground mine dewatering, by changing in the volume of ground water inflow to surface water, could have an effect on its chemical balance, and consequently, the biology of lakes.
- Underground mining impacts that alter flow regimes can affect the timing and amount of surface runoff.
- Upstream, local flows and downstream flows, both on and off the mine site, can be affected by underground mining-caused hydrologic impacts.
- Changes in surface water quantity and timing can change the frequency, magnitude, and duration of flood events and natural baseline flow conditions.
- Discharge of mine inflows can lead to downstream impacts including stream channel scour and sedimentation, disruption of aquatic habitats, and changes in both quantity and quality of water resources.

Hydrology – Mitigation Measures

- Because it is not possible to incorporate all the factors in the design of a protective layer, mitigations that use buffer zones would likely be ineffective in preventing impacts to aquifers or watersheds in which underground mining is proposed.
- In order to be effective, seal designs should be site-specific, performance-based and address geomechanical and hydro geological considerations.
- In sensitive or highly valued areas where impacts to hydrology are either not allowed or undesirable, based on an appreciation that irreplaceable ground water and surface water resources must be protected from mining impacts, banning mining activities from those areas may be the only protective recourse, even if it results in the loss of the mineral deposit.

Hydrology - Time Effects

- The permeability and other factors affecting a particular flow system largely dictate time effects. The time effect on springs and streams controlled by shallow flow systems has been shown to range from hours to days. The time effects on deep flow systems generally runs from decades to hundreds of years.

Hydrology - Regulation

- With respect to hydrologic impacts, state water rights law has typically been viewed as the legal remedy, although such laws were never intended to address environmental impacts from mining.

Reclamation Plans and Financial Assurance

- Current reclamation and financial assurance plans at operating underground hard-rock metal mines do not adequately address subsidence or hydrologic impacts other than water quality.
- Subsidence and hydrologic impacts may be uninsurable due to uncertainty with respect to risk, consequences, and cost, making financial assurance problematic.

5.2 Recommendations

1. Additional investigative and research efforts are needed to provide a sound basis for scientific, regulatory, industry and public opinion with regard to subsidence and hydrologic impacts at underground hard-rock metal mines. Study is needed on the causes and effects of mine subsidence and hydrologic impacts and on mitigation techniques to reduce or minimize them.

2. A comprehensive federal law similar to SMCRA should be enacted to deal with the social and environmental impacts caused by hard-rock metal mines. The law should include specific sections dealing with subsidence and hydrologic impacts. It should be possible to modify the language in SMCRA to address federal regulation of hard-rock mining.

3. State hard-rock metal mining regulations should be modified and then enforced to address subsidence and hydrologic impacts.

4. Language should be drafted and included in state and federal regulations to not allow underground mining in areas beneath or adjacent to protected natural areas including National Parks, Wilderness Areas, culturally sensitive areas and valuable surface and ground water resources, and other areas where any significant impacts are not acceptable.

6.0 Case Studies

The systematic study of environmental impacts 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 ground water aquifers and surface waters. The following case studies illustrate hard-rock metals mining examples under a wide variety of geologic, hydrologic, and physiographic conditions that can contribute to surface subsidence and hydrologic impacts.

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). 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). 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 ore body. 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.

6.1 San Manuel Copper Mine, Arizona

6.1.1 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). 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 thesis (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.

6.1.2 Mine Geology and Hydrology

The San Manuel geologic terrain 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;

Hatheway, 1968). This conglomerate, which forms a wedge-shaped caprock over the ore body, figures most prominently in the surface expression of subsidence at San Manuel.

The ore body at San Manuel consists of quartz monzonite and granodiorite porphyry. One key factor in deciding to mine an ore body 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). Clays and sericite are well known as agents destructive of rock strength. Fracture spacing in the ore body at San Manuel ranges from about three inches to six feet. Extensive fracturing combined with intensive hydrothermal alteration have created an ore body 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). 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 ore body 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). 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). 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 ore body, 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). The combination of younger, high-angle faults intersecting older low-angle faults creates ideal conditions for both block caving and large-scale surface subsidence.

6.1.3 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). 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).

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 ore bodies, respectively. In 1965 the subsidence pit over the South ore body was more than 500 feet deep, 3000 feet long, and 2000 feet wide (Hatheway, 1968). Each subsidence pit was surrounded by a series of near vertical tension fractures. The South ore body, largest of the three ore bodies 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 ore body (Johnson and Soule, 1963). Subsidence has continued to occur over both the North and South ore bodies 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 ore body 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]. 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 ore body, west pit) have been substantially different from those of the other two pits (South ore body and North ore body, 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). 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 ore body, 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). Peripheral tension cracks have extended laterally to a greater distance than in the other two pit areas. Similar to the other two pits, the fault 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). 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) 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%.

6.1.4 Environmental Impacts

Johnson and Soule (1963) 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).

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 two 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.

6.2 Henderson Molybdenum Mine, Colorado

6.2.1 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 ore body 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.

6.2.2 Mine Geology and Hydrology

The Henderson ore body is a stockwork molybdenite deposit located within multiple rhyolitic-granitic intrusions of the Red Mountain igneous complex (Stewart and others, 1984). 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 ore body. 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).

The Henderson ore body 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 was included on the hydrology of the Henderson and Urad ore bodies.

6.2.3 Subsidence History

Panel caving of the Henderson ore body 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).

The caved zone at the mine crosscut Henderson ore body-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 ore body rocks (Stewart and others, 1984).

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 mine staff surveyed the growth of the glory hole. 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 has 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).

6.2.4 Environmental Impacts

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). 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.

6.3 Miami (Inspiration) Copper Mine, Arizona

6.3.1 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's copper and 3.7% of U.S. copper (through 1968)[Olmstead and Johnson, 1968].

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). 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).

6.3.2 Mine Geology and Hydrology

The geology at Inspiration is relatively simple. The ore body 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]. The Miami fault to the east truncates the ore body, and the Pinto fault to the southwest of the ore body 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 ore body and caprocks have been strongly altered by extensive fracturing, silicification, and kaolinization along the numerous fault planes and slip surfaces.

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

6.3.3 Subsidence History

F.W. Maclennan (1929) 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).

The angle of draw ranged from 46º to 83º over the East 250 ore body, from 42º to 73º over the West ore body, and from 44º to 75º over the EO ore body (Fletcher, 1959). From 1929 to 1959 the subsidence angles had flattened considerably over each ore body. 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).

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). 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). The swell factor for subsided material ranges from 1.0 (same density as in-place ore) to 1.6 (Fletcher, 1959). By 1968 the subsidence area was depicted in plan view on a map by Olmstead and Johnson 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 ore body (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). 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 ore bodies at Inspiration. An uneven draw or too wide a spacing of the draw point can cause piping. 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.

6.3.4 Environmental Impacts

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.

6.4 Climax molybdenum mine, Colorado

6.4.1 Site Description and History

The Climax molybdenum mine is located on Fremont Pass at the head of Tensile 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). 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.

6.4.2 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).

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).

None of the studies consulted for Climax mention the depth to ground water 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). Henderson (1945) also mentions on page 200 that, "A great amount of water comes through the caved area during spring runoff and spills from the chute are fairly common."

6.4.3 Subsidence History

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). 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 10-40 feet in the southern area. Vertical escarpments in the caved area were from 50 to 100 feet high (Vanderwilt, 1945).

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).

By 2001 the subsidence 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). 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.

6.4.4 Environmental Impacts

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 ground water into underground workings.

6.5 Athens iron mine, Negaunee, Michigan

6.5.1 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). A special system of mining was developed for the Athens mine that combined top slicing and sublevel caving of an ore body that was 500 feet wide, 300 feet thick, and 2000 feet long.

6.5.2 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 ore body of soft hematite, which in turn overlies a footwall of slate (Allen, 1933). A vertical diorite dike forms the north boundary to the ore body, while a near-vertical (95°) fault bounds the ore body on the south.

A large amount of water (~225 gpm) was encountered at the lowest part of the ore body (Allen, 1933). 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).

6.5.3 Subsidence History

The main shaft at the Athens mine was sunk north of the ore body 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). 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 ore body. 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]. 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 innundation 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). Apparently, the cave opened a new water course above the ore body through the fault dike to the impervious footwall of slate (Allen, 1933).

Two dikes, the "north" dike and "fault" dike, bounded the ore body 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).

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 in advance of 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).

Local geologic factors were responsible for the unexpected caving at the Athens mine. A fault (dip~ 95°) and a dike (dip~ 91°) bounded the ore body 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).

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.

6.5.4 Environmental Impacts

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 ore body 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.

6.6 Butte, Montana copper/silver mines

6.6.1 Site Description and History

Mining in Butte began in 1864 when prospectors from Virginia City, Montana discovered placer gold deposits along Missoula and Dublin Gulches and Silver Bow Creek (Miller, 1973). By 1870, the focus had shifted to the location of lode claims on the Butte Hill. In 1882 the discovery of a "chalcocite blanket" of ore grading 45% copper in the Anaconda mine marked the emergence of Butte as one of the world's largest copper mining districts. The uppermost part of the Butte Hill, Walkerville, was also a world-class producer of silver from 1875-1893. By 1900, thousands of lode claims had been staked and hundreds of mines were operating to produce nearly 20% of US copper. Large production continued through WWI and through the 1950s when the Berkeley pit was first developed.

From 1973, when the Anaconda Company lost its assets through nationalization in Chile, the production has steadily declined and today (2002) there are no longer any operating copper mines in Butte. As many as 4,000 lode claims were staked in the Butte district (Butte-Silver Bow County Clerk & Recorder's office, 2001). Numerous discovery and production shafts are concentrated on the Butte Hill. In addition to production shafts, many mines had ventilation shafts and auxiliary workings that were sunk adjacent to the main shafts. Added to the legally located mines and workings were numerous illegal operations in the Walkerville silver district. None of these shafts were formally recorded in stope books later developed by the Anaconda Copper Company. Many of these "wildcat" mines would follow a vein until the stope "daylighted" at the surface. As a consequence of both legal and illegal mines, thousands of miles of shafts, stopes, raises, winzes, crosscuts, and drifts underlie the Butte Hill. The uptown portion of the city of Butte overlies hundreds of backfilled and capped mine shafts, some of them opening into the basements of uptown buildings like the Acoma.

From 1955 to 1982 most mining in Butte was done in the Berkeley pit. The Continental pit was mined for copper and molybdenum from 1986 to July 2000 and is now inactive. Silver mines in the Walkerville district were relatively shallow (<1000 feet deep), but copper mines were often developed to depths of 2,000-5,000 feet. Among the deeper mines in Butte are the Mountain Con (5400 feet), the Kelley (4800 feet), and the Belmont (4200 feet).

6.6.2 Mine Geology and Hydrology

Ore deposits in Butte are hosted in the 60-million-year old Butte quartz monzonite which is a pluton within the Boulder batholith, a composite, shallowly intruded calc-alkaline body of rocks that covers an area of 2000 square miles (Guilbert and Zeihen). Butte mines produced copper, zinc, manganese, molybdenum, lead, silver, gold, cadmium, and bismuth and from 1880-1972 produced 452,216,624 tons of ore (Miller, 1973).

Ore in Butte was mined from veins during early underground mining and, later, by larger scale techniques like block caving and open pit mining. The first tests of block caving in Butte were done in 1944. From 1947-1952 the Greater Butte Project used block caving to produce 15,000 tons/day of ore from the 3000-foot level of the Steward mine and through the Nos. 1 and 2 Kelley shafts (Miller, 1973). The Kelley Block Cave Project ran from April 1952 to December 1962 and produced 32,500,000 tons of ore averaging 0.99% copper. Total production from Butte mines by block caving was 601,400,000 pounds of copper (Miller, 1973). Block caving for the Kelley

Project was suspended in late 1962 to avoid creating slope stability problems for the Berkeley pit (Miller, 1973).

The original hydrology in Butte was relatively simple before mining. Local hydrology is now very complex. An 800-foot-deep lake filling the Berkeley pit with ~200 billion gallons of acid mine water greatly complicates the flow and quality of water. Water in the bedrock was encountered 300 feet below the surface in the Anaconda mine in 1882. The elevation of ground water on the Butte Hill varied widely due to numerous veins and faults, most of which strike east-west across the Hill. The headwaters of Silver Bow Creek, a tributary of the Clark Fork of the Columbia River, are located about 10 miles northeast of the uptown Butte area. Silver Bow Creek used to flow through the area now disturbed by the Berkeley pit. The pit captures this headwater flow and Silver Bow Creek now begins on the east side of Butte where Blacktail Creek joins from the south. Underlying Silver Bow Creek is a shallow alluvial aquifer that gains water from the creek and from flow off the Butte Hill.

Because the Berkeley pit intersected several of the underground mine workings around its perimeter, flows were re-directed into the pit. Before the pumps were turned off in the 4800-foot level of the Kelley mine in 1982, water from most of the mines in Butte was collected in the Kelley and pumped to the Weed Concentrator where it was used in the tailing circuit and in leaching operations. Once the pumps were shut off in January 1982, the Berkeley pit began to fill to its current elevation of ~5400 feet mean sea level (msl). The critical water level (cwl) has been defined by the EPA to be 5490 feet msl (US EPA Record of Decision for Berkeley pit mine flooding, December 1993). The cwl is the elevation at which the water in the pit may begin draining by capillary action into the alluvium on the southeast wall of the pit. If this were to happen, the alluvium of Silver Bow Creek, which is being reclaimed, would become contaminated once again. Before water reaches the cwl, a treatment plant must be built, tested, and ready for operation. This is expected to happen by 2015.

6.6.3 Subsidence History

Subsidence in Butte has been a problem since the late 1800s. Stope mining of near surface ore bodies occurred often, particularly in the silver mines of Walkerville. Many of these stopes were never properly capped and filled and they continue to open each spring when the ground thaws. When the Kelley Block Cave Project operated from 1952-1962, few surface caves were noted. However, the project was ultimately discontinued when block caving threatened to undermine the stability of the west highwall in the Berkeley pit (Miller, 1973).

Another large project in the 1950s, mining of the Emma vein for manganese, created an area that extended from the Travona property to the Colorado shaft. This mining occurred within 100-200 feet of the surface and created what the Anaconda Company referred to as the "Central Subsidence Zone." Many houses and other structures were damaged in a square-mile area as chronic subsidence caused cracked walls and foundations and the occasional loss of a garage or shed into an open stope (S. Blodgett, personal communication, December 2001). In the 1950s the Anaconda Company reached out-of-court settlements with many property owners in the area south of Mercury St. between Main and Montana Streets. Deed restrictions were added to properties to prevent future owners from litigating against the Company.

During the 1990s approximately 5-10 stopes caved in each year from April-June during the spring thaw (S. Blodgett, personal communication, December 2001). Another 1-2 large shafts can be expected to cave each year, especially those that were not properly backfilled and capped. Butte-Silver Bow County commissioned one study in 1996 (Tahija, 1996) that reviewed the extensive stope books kept by the Anaconda Company from about 1910-1977. This review was done to identify problems in two areas planned for residential housing development—the Tullamore and Brittania subdivisions. The study concluded that development could proceed, but the County began to develop a set of guidelines for development on the Butte Hill to prevent building over unstable ground and on top of reclaimed areas.

6.6.4 Environmental Impacts

As the Berkeley pit continues to flood and water levels continue to rise in mines underlying the Butte Hill, the problems from subsidence are likely to get worse. The Butte Hill, with the uptown area housing 10,000 people, is one of the most heavily mined ore deposits on earth. Hundreds of deep shafts, many haphazardly backfilled or capped, connect with thousands of miles of underground workings. Acid mine water (pH~2-3); sericite, argillite, and kaolinite alteration; blasted rock that is fractured and faulted extensively; and runon water from the surface all create conditions that will weaken the remaining rock in place underground. When the Anaconda Company was still in business they provided labor, equipment, and materials to backfill open stopes or shafts. Once the Company was bought by ARCO in 1977, such services stopped. Now the County Public Works Department fills new holes with grant money from the legislature unless the holes are too large. The largest existing shaft collapse is the Belmont. The collar has collapsed and swallowed ore carts and some track. Cleaning out the collapsed collar and equipment and plugging and capping the shaft properly will cost ~$100,000. The owner of the Belmont, Montana Resources, is currently inactive, with the shutdown of the Continental mine in July 2000.

Long-term subsidence in Butte will require a formal management program that includes mapping, continuing research of the stope books and historic mining records, and the filling and capping of collapsed shafts and stopes in residential areas. The effects of flooding the Berkeley pit and the adjacent underground workings will also require further study to determine possible impacts on surface subsidence.

6.7 Other Case Studies

The following case studies address the incidence of hydrologic impacts to surface water from underground mining operations.

6.7.1 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.

6.7.2 Kentucky-Utah Tunnel, Utah

The 2.7–km-long Kentucky-Utah Tunnel was constructed in the 1940s to drain excess ground water from overlying hard-rock 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].

6.7.3 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 reserves. 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 ground water 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).

6.7.4 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).

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