



Subsurface Mine Reclamation for Urban Construction

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ABSTRACT

Urban encroachment on historic metalliferous mineral claims has resulted in the need for a coordinated approach towards mine reclamation that involves numerous areas of expertise including the geologic, engineering, biological and environmental sciences. With the continued growth of urban communities, reclamation activities are anticipated to increase in sophistication and multidisciplinary needs, complicating efforts to reduce safety concerns and provide structural stability for residential, commercial and industrial sites. A model developed for exploration and reclamation of mining sites provides an understanding of mine reclamation activities that coordinates multiple scientific disciplines to successfully identify, explore and reclaim abandoned mining sites. The model is effectively used to reclaim abandoned patented and nonpatented claims for private and commercial development. The model requires identification of the claim status and ownership; provides suggestions for researching ore structures and development histories; suggests methods for the successful exploration, excavation and reclamation of mine workings; discusses environmental management considerations for waste tailings and process operations; reviews success in geophysical techniques for subsurface mine working identification; and provides guidance for the inclusion of proactive habitat management during and subsequent to the mine reclamation process. Construction suggestions are provided for mine working exploration and reclamation to increase efficiency and maintain cost control while reducing the potential for future mine working failures.

INTRODUCTION

Much of the growth of the western United States can be attributed to the historic development of the region's mineral resources. Extraction and beneficiation of metalliferous mineral resources included copper, lead, gold, manganese, mercury, molybdenum, nickel, silver, tungsten and zinc. Methods of extraction varied depending upon the ore type, method of mineralization and timing of mining activity. Although most familiar mineral development on the largest scale occurred with

encroachment of western culture, records indicate that Native Americans extracted metalliferous deposits for ornamental and trading purposes before the arrival of the Spaniards in the 15th and 16th centuries.

Once isolated and remote, many historic mining areas are recognizing renewed interest. This time, however, the interest is associated with the encroachment of urban and suburban communities expanding municipal boundaries to accommodate ever increasing populations. Subsurface mine workings left abandoned by previous prospecting and extraction operations pose unique hazards for development of residential, commercial and industrial structures. These hazards increasingly require abatement and demand a new approach to the research and reclamation of historic mining sites.

The identification and reclamation of these historic mining sites involves the application of numerous areas of geologic expertise, including research and interpretation of methods; location and extraction processes of the ore body; development of an understanding of the genesis and geometry of the mineralized deposit; and the application of engineering geology and geophysics to determine the most successful reclamation method to accommodate structural development. In addition to geologic applications to mine reclamation, numerous other environmental and engineering disciplines are required. These disciplines may include mining engineering for mine exploration and reclamation closure plan development, biological services for habitat identification and mitigation, and environmental sciences for waste management, treatment and regulatory compliance.

This paper introduces a practical model that is useful in coordinating and completing the investigation and reclamation of abandoned mining sites for urban development on private land and adjoining public lands (Figure 1). The model focuses on buried and abandoned mine workings associated with mineralized deposits which are markedly different than reclamation activities associated with open pit operations. The model is based on the successful application of reclamation activities completed by the author at numerous patented claims throughout the southwestern United States.

BACKGROUND RESEARCH

Reclamation activities are considered part of the active mining process and all technical, financial and legal aspects of active mining activities apply to reclamation.

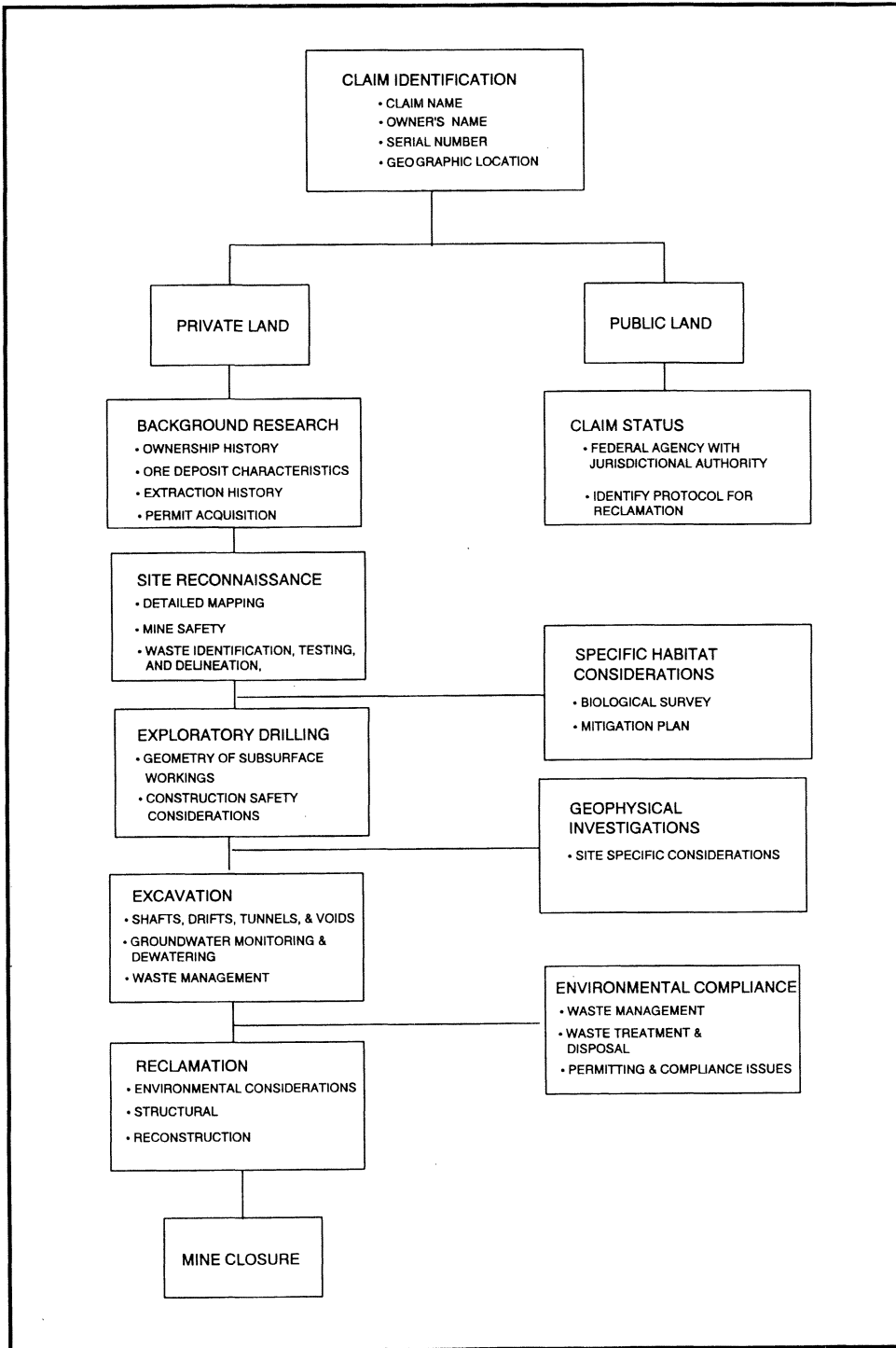


Figure 1. Mine reclamation matrix.

Reclamation requires the owner to identify and understand the available information regarding the historic mining activities, the type(s) of mineralized deposits and related workings, the ownership of the patented and/or non-patented lands both within and adjacent to the reclamation area and the mining laws of the state. These factors control the cost and successful outcome of the reclamation construction activities.

Developing a thorough understanding of the historic mining activity may be difficult due to the age of the mine. Many mines in the west date back to the mid-1800s, although as previously mentioned, some minor workings may predate the arrival of European culture. Nevertheless, as with most subsurface investigations, the acquisition of information prior to reclamation typically translates to reduced construction costs.

The status of the claim and land ownership must be defined prior to initiating reclamation activities. It is not uncommon for patent disputes on claims and adjoining lands to be both complicated and entangled in the courts. In some cases mineral and property rights may not coincide. Unpatented claim recordation procedures may require completion to enable reclamation should the mineral rights not be held by the landowner or if the existing claims have expired. Recordation of unpatented claims provides a clear title to the mineral rights, and is required by 43 CFR 3833 prior to initiation of mining activities.

All mining permit requirements must be clearly identified and agencies with jurisdictional authority must be contacted and informed of the reclamation activities. Examples of other agencies interested in reclamation activities may include the BLM for registration and reclamation of abandoned sites on federal land administered by the agency; the Forest Service for entry and operational permitting, biological and habitat disruption studies and engineering requirements for access; the Fish and Wildlife service for endangered or threatened species surveys or mitigation plans; state environmental quality departments for stormwater permitting, waste management and other environmental permitting needs; and state water resources agencies for mine dewatering and water rights issues. State mining and minerals permitting agencies may also require notification of intent to perform active mining activities. Should the planned development encroach on utility or transportation corridors or easements, notification of the public works agency involved will be required.

A tremendous variety of background information sources are available to assist in developing an understanding of the reclamation requirements for a claim. These sources include the following.

1. *United States National Archives and Records Administration*—Much of the early mineral claim patents filed with the Department of the Interior are archived with the National Archives and Records Administration. Plat numbers, patent numbers, mineral survey numbers, ownership names, geographic locations and claim names assist in accurate record retrieval. These data should be accessed as early as possible during the investigation and data gathering phase since the records may require many months to secure.
2. *United States Department of the Interior, Bureau of Land Management (BLM)*—The BLM maintains records of patented and nonpatented mineral claims, mineral surveys and land ownership status. Claims are listed alphabetically by claim name, alphabetically by owner's name, geographically by Township, Range, Section and meridian and by serial number (the state claim number assigned by the BLM). Claim information includes boundary surveys and the extent and type(s) of subsurface workings anticipated to be on the claims, status records and case files. It should be noted that the information provided by the claimant was typically used to assess fees for mineral extraction. As a result, many of these documents may provide an underestimation of actual subsurface workings.
3. *United States Geological Survey*—Information regarding regional mineral surveys, geologic conditions, mineral petrogenesis and structural controls can be found in mineral surveys, maps and publications. Specific information regarding the ore body may be available depending upon the size and operational status of the claim(s).
4. *State Geological Surveys*—Because the financial base of many states is heavily dependant upon benefits derived from mineral extraction, state geological surveys typically have detailed information regarding mineral deposits.
5. *State Mine Inspector's Office*—Although the State Mine Inspector is traditionally responsible for mine safety issues, the Mine Inspector typically maintains archived files regarding mine workings and ore geology. The reclamation process is also considered part of an active mine operation and must be permitted with the State Mine Inspectors office.
6. *Public and Private Libraries*—The library, either at a university campus or at a local facility near the mine site, may contain historic information regarding mine site activities, annual production volumes and mine feature openings. Given the age of many mines, local historical societies that have archived information in the local library may represent the only source of reliable historic information.
7. *Mining Companies*—Although most mining companies are traditionally reticent to provide confidential information regarding subsurface workings, ore body geometries and other sensitive data, they are typically the best source of information regarding an historic claim. Most mining companies have thoroughly researched the ore body prior to investment, and may still employ personnel with historic knowledge of the mine requiring reclamation.
8. *Universities*—Local universities and state colleges may provide technical information relating to geologic and metalliferous mineral deposits. Information regarding the petrogenesis of ore bodies, structural

and stratigraphic details and other geologic data are typically maintained within the geologic libraries and departments.

9. *Aerial photographs*—Photographs provide information regarding the site history and may assist in identifying surficial openings, lineaments associated with subsurface workings, waste rock volumes and other surface disturbances. Historic photographs may provide valuable information regarding the location and tonnage of materials potentially removed from mine workings subsequently covered or closed by later mine activities. Aerial photographs also provide useful mapping and surveying aids.

Background research should, at a minimum, provide information regarding the type(s) of metalliferous deposits anticipated to be encountered to assist in determining the petrogenesis and likely geometry of the ore body. For example, geometries of magmatic differentiates or contact metamorphic deposits will differ substantially from vein and residual deposits (LeRoy, 1977). The mineral extraction activity associated with each geologic depositional environment must be determined not only for the property requiring reclamation, but must also be understood for adjacent mineral producing claims that may interconnect with workings on the claim.

SITE RECONNAISSANCE

A detailed survey of the site must be prepared prior to initiating reclamation construction activities to identify mine locations, the condition of mine workings, potential safety hazards associated with shallow or unsupported overburden, open voids and unsafe shoring. Due to the nature of the mining activities, subsurface mine workings may not be readily apparent at the surface. The development of detailed site specific geologic information regarding the ore body may provide clues regarding the extent and location of subsurface workings.

Site Mapping

Mapping techniques should be used to locate and describe each mine related feature. Mapping should include locating each mine related feature, developing geologic sections illustrating both the configuration of the opening and geology exposed in the walls of the excavation, estimating volume and location of waste rock associated with the workings, identifying existing or historic equipment (such as headframes, rails or remnants of these features) and determining other information that may be suggestive of subsurface workings. Careful mapping of these features will assist in determining the geology and geometry of ore bodies and provide an understanding of the physical characteristics

of the rocks. Additionally, these data can be used to determine the beneficiation methods likely to have been used for mineral extraction.

There are a number of other features that may be present that are indicative of subsurface mine workings. Vegetation anomalies, especially in arid environments, may suggest the presence of surface subsidence associated with upward stoping of subsurface voids. Incident precipitation, combined with the typically higher permeabilities of fissured and disrupted soils, induces greater soil moisture retention and increased vegetation (Brose, 1986). Naturally occurring geochemical differences and residual chemicals associated with mineral processing and beneficiation activities may also enable the completion of geobotanical surveys to assist in identifying and defining mineral deposits and workings (Bloom, 1977).

Aerial photography and surface mapping may reveal lineaments, sinkholes and increased vegetation that provide evidence of subsurface voids associated with mine workings. Stereo coverage enables accurate determinations of mine waste volumes that may indicate the relative volume and size of subsurface mine workings.

Due to the age of many mines, secondary infilling of shafts, adits and inclines may mask the presence and locations of subsurface mine workings. Following the completion of mining activities, most vertical shafts have typically been utilized for trash and waste disposal. If present, these wastes create unstable working conditions during exploration and reclamation and present a solid and/or hazardous waste disposal problem when the materials are removed. Non-engineered backfill materials that were placed in open voids in the past in an effort to reduce the owner's liability may also obscure voids and create unstable conditions, especially when the fill materials are bridged in vertical shafts.

Mine safety is governed by Federal Metal and Nonmetallic Mine Safety and Health Administration (MSHA) requirements outlined in 30 Code of Federal Regulations Parts 56 & 57. The oversight authority for mine safety inspections and operational safety typically rests with the individual State Mine Inspector's Office. Physical entry into any mine related feature should be restricted as much as possible during the field reconnaissance and mapping activities. Subsurface mine entry, if required to define limits of subsurface workings, must be restricted to personnel with appropriate MSHA training and experience.

Endangered/Threatened Species Considerations

A preliminary habitat study may be required to be completed to identify and mitigate the presence of threatened or endangered species. Several threatened and endangered species of bats may be encountered in drifts, inclines and adits. Currently, the *Leptonycteris curasoae*

(Lesser long-nosed bat) is a federal listed endangered species commonly encountered in mines and caves. Proposals have not been filed for numerous other species that occupy abandoned mine workings due to a lack of sufficient or current information to support categorical listings. These species include the *Choeronycteris mexicana* (Mexican long-tongued bat), *Macrotis californicus* (California leaf-nosed bat), *Idionycteris phyllotis* (Allen's lappet-browed bat), *Myotis ciliolabrum* (Western small-footed myotis), *Myotis evotis* (Long-eared Myotis), *Myotis lucifugus occultus* (Occult little brown bat), *Myotis thysanodes* (Fringed Myotis), *Myotis velifer* (cave Myotis), *Myotis yumanensis* (Yuma Myotis) and the *Plecotus townsendi pallescens* (Townsend's big-eared bat) (Kingsley, 1995).

Waste Investigation and Management

Most historic mining operations did not utilize closed circuit systems for mining and milling, and effluent discharges may have impacted large areas of subsurface soils, bedrock and ground water. Mines typically use(d) some type of hazardous materials in exploration and beneficiation, including toxics, corrosives, flammables, reactive substances (typically oxidizing agents) and explosives (Bureau of Land Management, 1992). Exploration of these issues becomes costly and must be coordinated with other regulatory agencies and hazardous materials compliance programs.

Mine dumps, leach pads, ancillary operations and other potential areas of solid or hazardous waste must be identified and clearly delineated to determine accurate remedial costs. A sampling schedule may be required to be developed to identify the presence of elevated or toxic concentrations of metals, cyanide or other process related by-products. Sampling may include testing the waste materials, process areas and underlying soils and bedrock to determine the geometry of any leaching impacts. Sampling should be consistent with Resource Conservation and Recovery Act (RCRA) or Comprehensive Environmental Response, Cleanup and Liability Act (CERCLA) protocol to ensure consistent and legally defensible results.

Summary

The background research and field mapping activities should provide an inventory of mine related features that includes estimates of the extent of the mine feature, known depths of shafts, potential for drifts or other lateral extensions of the mine and the geology of the target ore body. The locations of all mine related features should be accurately surveyed on a scaled map to enable location of the feature during reclamation. The inventory should include detailed sections of accessible mine features. Additionally, the elevation of existing mine

features should be compared to planned grading activities to assist in determining reclamation requirements.

All non-mine related requirements (such as solid and hazardous waste removal and handling, dewatering requirements, habitat disruption, permit requirements, etc.) should be identified so that contingency plans for abatement requirements may be included in the construction schedule. Information obtained during the reconnaissance should be sufficient to develop a preliminary construction schedule providing construction reclamation equipment requirements, preliminary construction scheduling and an approximate range of costs associated with the reclamation activities.

SITE INVESTIGATION

As stated above, mine reclamation activities are considered active mining operations. All permitting and safety considerations must be included in the investigation efforts. Following the development and inventory of the mine features and prior to the inception of subsurface investigations, the mine site should be secured to preclude unauthorized entry and reduce vandalism. Perimeter fencing, barricades and notices should be placed and posted around openings or suspected areas of shallow overburden at a minimum.

Further, daily inspections of mine workings are required and the inspections must be documented. These should be coupled with daily site safety meetings to inform workers of changes in site conditions, altered or modified investigation strategies or additional hazards that may have been encountered.

Prior to initiating invasive site investigation activities, locations of all inventoried features should be compiled on a site map of sufficient scale to represent features that may be encountered during reclamation including shafts, trenches, drifts, adits and inclines. It is recommended that the precise locations of mine features be located by professional surveyors so that future lot lines, utility easements, streets, parks and other planned development features can be precisely identified in relation to the mine. The location(s) and elevation(s) of future improvements should be superimposed over current knowledge of the site to assist in defining the reclamation requirement for a particular mining feature and to provide loss control management for potential liabilities.

Mine workings can be investigated using a wide variety of conventional construction equipment and techniques. Construction for reclamation is unique in that *in situ* consolidated and undisturbed bedrock is typically penetrated to uncover voids and openings, in comparison with construction that is performed to penetrate to bedrock or firm materials for footings. As a result, most excavation proceeds through undisturbed bedrock with the goal of identifying underlying voids.

The reclamation activities serve to minimize potential subsidence or rock failure due to unstable conditions. Subsidence and near-surface stoping features must be eliminated to provide adequate bearing for footings, utilities and other improvements. Shafts, drifts and other voids must be explored to identify feasible techniques for removal of unsatisfactory debris, fill and overburden, and accommodate placement of engineered fill and/or structures such as collars, plugs and caps.

Exploratory Drilling

Initial investigations in crystalline bedrock may be rapidly accomplished using rotary air percussion hammer drilling equipment. Penetration rates in crystalline rock may reach several hundred feet per hour, providing rapid and detailed investigations in the vicinity of suspected mine workings. Mining codes must be reviewed to determine the minimum setback for structures from mine openings, and investigations should extend beyond this distance to account for future stoping and collapse of mine features from the localized rock fabric, joint spacing, weathering patterns and other subsidence features. Additionally, mining codes must be utilized to determine the depths of investigation which should be referenced to the proposed grading of the site.

Boreholes are typically completed during the initial site characterization to define subsurface features at the following locations: a) along the strike of known mineralized ore bodies to determine drift and void locations associated with mineral extraction; b) normal to the strike to assist in determining the presence and configuration of inclines and interconnecting drifts used for ore movement and ventilation; c) in shafts to assist in determining the vertical depth of excavation; and d) in locations suspected of having interconnecting drifts due to surface shaft configurations. Voids, rock debris and ground water are rapidly identified using the rotary air percussion hammer drilling technique, and each feature identified must be documented to assist in developing an understanding of the subsurface geometry of the mine workings.

Exploratory drill holes may be completed as monitor wells to enable ground-water sampling or piezometric elevation monitoring during excavation activities. Ground-water sampling may be necessary to determine discharge or treatment requirements. Monitoring of ground-water elevations during construction may reveal interconnections, such as drifts or shafts, not readily observable by other techniques.

The air drilling results should provide a detailed understanding of subsurface mine geometries and enable a refinement of the estimates of construction costs, equipment needs and reclamation timing. Further, the

air drilling activities will identify hanging wall/footwall geometries and patterns that must be considered when placing heavy construction equipment over shallow voids to avoid collapse. A consideration of these factors will enable the development of a construction plan that accommodates worker safety, excavation locations, staging areas and perimeter security requirements.

Excavation

Following utilization of a rotary air percussion hammer drilling program, conventional construction techniques may be used to excavate and reveal subsurface mine features. Construction techniques for mine investigations may vary widely and are based on the mine feature anticipated to be encountered or as identified by the site investigation activities described above.

Vertical shaft exploration methods are predicated upon the anticipated depth of the mine, and include:

1. Backhoe or trackhoe exploration for shallow exploration related features (10 to 50 ft in depth);
2. Bucket auger exploration for features anticipated to range from fifty to one hundred feet in depth;
3. Crane auger exploration for workings anticipated to extend to depths in excess of one hundred feet.

Shallow drifts and inclines with floors at elevations up to fifty feet below ground surface can be safely explored using a backhoe or trackhoe, although benching may be required to provide equipment access. Adequate exploration must also consider potential failure zones caused by instability resulting from unsupported *in situ* unconsolidated soils or bedrock fracture patterns. Where collapse areas appear to be present, either through the identification of unsupported areas, ground cracking or other similar features, trackless equipment providing adequate worker safety should be utilized. Determination methods of safety zones for equipment and workers can be found in Simpson and Kuhns (1989).

The geometry of the ore body should be considered during excavation to allow continued excavation at locations where subsurface workings intersect. A variety of earth moving equipment, such as loaders and scrapers, may be required to move waste rock to staging areas. Care must be taken to provide adequate staging for overburden removed during the investigation process to reduce multiple handling of waste rock.

In all cases, excavation activities should reveal undisturbed bedrock, identify columns or other undisturbed bedrock mine related features, and each feature must be mapped and logged by a competent geologist. Excavated mine features may require entry to identify minor ancillary workings and confirm termination of voids or backfilled areas. All mine entry must be restricted to MSHA trained personnel. During excavation

and exploration, each mine related feature must be bermed to preclude accidental entry by vehicles, and personnel working in the area of vertical features must be tethered. Adequate air quality monitoring must be performed prior to and during mine entry and investigation.

Ground-Water Monitoring and Subsurface Dewatering

Where ground water is encountered in mine workings, a dewatering schedule should be developed to enable observations of subsurface workings. Ground-water extraction permits must be obtained prior to discharge, and analytical testing of ground water for metals, cyanide and other parameters may be required by the discharge permit. Ground-water rights issues may also be required to be addressed should the site be located within an adjudicated or over appropriated basin. Ground-water discharge locations must be identified to preclude flooding of adjacent workings and minimize particulate pollutant loading in surface runoff.

Ground-water extractions should be carefully monitored in all available mine openings to assist in determining the degree of interconnection between subsurface voids. A vertical shaft undergoing dewatering is essentially a large diameter well, and an extensive body of knowledge exists governing flow to wells (Green-slade, 1979). Interconnections, voids and other mine related features can be monitored using standard pumping test protocol, and water level changes monitored in the different features used to provide information regarding boundary conditions, bedrock transmissivities and enhanced permeabilities caused by voids. Although boundary and recharge effects can be calculated using discharge/drawdown graphs versus time/drawdown graphs (Driscoll, 1986), infilling of drifts and voids by debris, loosely placed fill or stoped bedrock debris may impact distance drawdown relationships and be confused with impacts of other regional hydrogeologic features such as recharge areas, seeps, and other sources of discharges. Ground-water production volumes greater than those determined by modeling the anticipated void extent and volume(s) suggest the possibility of other unidentified workings.

Differences in ground-water quality during pumping activities may also provide useful information regarding interconnections and recharge and discharge locations. Field measurements of pH, conductivity and water temperature may be sufficient to identify differing ground-water sources. More sophisticated analyses may be required if ground-water quality differences are minor and geochemical differences in the ore bodies impact ground-water quality.

Twelve groups of typical mine related water contaminants include the following (Bureau of Land Management, 1992):

1. Organic Reagents
2. Oils
3. Cyanides
4. Acids and Alkalis
5. Base Metals
6. Fluorides
7. Dissolved Solids
8. Anions and Cations
9. Suspended Solids
10. Turbidity
11. Thermal
12. Radioactivity

The possible combination of these pollutants may result in acid mine drainage, alkaline and saline mine drainage, heavy (toxic) metal pollution, eutrophication and deoxygenation. If the planned development will rely on ground-water resources derived from the general mining area, the potential for these pollutant loads must be determined and engineering solutions must be developed for extraction and treatment.

Waste Management and Handling

Special staging areas are also required for solid and hazardous waste materials removed during mine entry. Many mines have been utilized for waste dumping and a wide variety of regulated materials may be generated during the reclamation activities. All equipment associated with historic mine activities must also be removed from the site to accommodate the placement of engineered structures, fill and grading during subsequent reclamation and construction.

Solid waste staging areas should be bermed to preclude runoff, preferably lined with plastic and located in a secure area where transportation off-site can be easily accommodated. Hazardous materials, if encountered, require investigations to characterize the type and extent of waste. Further, the wastes require additional environmental, health and safety precautions for removal and on-site staging and management of the wastes. A determination of a regulatory generator status and generator identification for removal, treatment and disposal may also be required.

In most cases waste dump rock areas will be removed for general grading purposes. Should reclamation activities be performed for residential construction, special care must be exercised to remove wastes containing elevated concentrations of metals, cyanide or other process chemicals used for beneficiation activities.

GEOPHYSICAL METHODS OF EXPLORATION

Numerous investigations have attempted to identify subsurface tunnels and voids using a variety of geophysical techniques, both for mine safety interests as

well as for military defense purposes. The information obtained from these investigations suggests that the application of geophysical techniques for exploration of subsurface mine investigations is speculative, and may be best utilized following the completion of initial drilling and exploration programs (Hauser and Friedel, 1993). Even with subsurface data regarding the locations of voids, an integrated approach using several techniques may provide the most effective approach (Friedel and Hanson, 1990). Geophysical techniques may also be utilized to determine pre-existing subsurface topographies over waste and tailings piles to assist with determining volumetric estimates for waste remediation activities (Snodgrass and Lepper, 1993).

In most instances, geophysical models are developed to support data gathered after the geometry of the subsurface openings are known or partially explored, typically following a drilling program. With most geophysical techniques, prediction of the geometry of voids and openings that are unknown may be masked by many other factors. These factors may include voids that have been infilled from surface sources or as a result of upward stoping and collapse of debris; drifts, shafts and other voids that are filled with water or, when overburden and bedrock characteristics are incompatible with the technique. Specific geophysical methods that may be used in mine exploration, including method advantages and limitations, are discussed below. A thorough discussion of geophysical techniques and their relative success in subsurface void detection can be found in Hauser and Friedel (1993).

Resistivity Surveys

Because increased conductivities are encountered in mineralized ore bodies, areas of anomalous conductivity may be used as an indication of mineralized veins and potential locations of subsurface workings. An air filled void theoretically causes current to diverge, representing a high resistivity anomaly. Resistivity surveys may be of limited value where mineralized ore bodies have been removed or if stoping has occurred and the stoped debris has similar properties as the host rock. The resistivity survey results may be misinterpreted if ground water is present in voids, fractures and unconsolidated alluvial overburden (Holmer, 1977).

Electromagnetic Surveys

Recent improvements in electromagnetic image surveying provide promise for utilization of this technique in quantitative data collection for underground mine working identification. Electromagnetic imaging can be completed at variable frequencies, including ground conductivity profiling and radar imaging using ground penetrating frequencies above 100 MHz. Ground

conductivity profiling results are typically inconclusive for reclamation construction estimating, although larger features (such as infilled glory holes, room and pillar excavations and similar mining features) may be more clearly identified.

Ground penetrating radar appears to be the most useful in identifying subsurface voids located in terrain covered by shallow, relatively isotropic overburden materials, and may provide detailed information regarding the presence of shallow, narrow workings. Experience has shown that ground penetrating radar, which operates at a lower frequencies, may provide more conclusive imaging of subsurface features. However, the depth of penetration may not provide sufficient information to identify deeper workings for reclamation purposes.

Microgravity

Microgravity techniques may provide the most dependable cavity detection method available (Hauser and Friedel, 1993). Microgravity techniques are influenced by natural changes in bedrock compositions and densities, and detect contrasts created by low density (void) spaces. The size of the anomaly detected depends upon the depth of burial and the density differences between the host rock and void or void infilling. Insufficient contrast for void detection may occur in situations where narrow, stoped voids are present or where infilling of open voids has occurred by materials similar in composition to the surrounding host rock. Targets often express themselves as anomalies in the 5–10 μgal range, and excellent vertical control is required to minimize station errors.

Magnetic Gradiometry

Advances in magnetic field measurements enable sophisticated measurements of changes in the earth's magnetic field caused by subsurface voids if the host rock is magnetic. While the method appears to provide poor resolution for void geometry interpretation, the presence of subsurface metallic objects remaining from mine activities (such as ore carts, railings, etc.) may provide sufficient anomalies for mapping purposes (Hauser and Friedel, 1993).

Seismic

Seismic reflection, refraction and microseismic monitoring studies may provide useful information regarding the configuration of mine workings. During seismic surveys compressional waves generated by an artificial source may be damped by the presence of voids and unconsolidated infilling. The monitoring and interpretation of the arrival of these waves can provide information regarding the location of voids which

disrupt compressional wave transfer. Although the technique attempts to identify subsurface workings, a reasonable understanding of the subsurface geometry of the workings is typically required prior to the survey to develop a model to plan the survey and explain the data. The investigator must know the approximate locations of workings and plan a traverse normal to and along voids for useful data recovery. The data obtained may be extremely difficult to interpret if complex or anisotropic geologic conditions are present.

Microseismic monitoring measures energy released from strain releasing events and may be useful in areas undergoing prolonged or continued stoping, bursting or other rock strain release phenomena. Given the age of many abandoned and unreclaimed mine workings, most workings have reached a point of relative stability and monitoring such energy releases from strain releasing events may not provide useful information within a reasonable reclamation time frame.

Crosshole Transmission Tomography

The seismic crosshole technique provides a method of investigating potential void locations by interpreting the travel time of seismic waves induced in one borehole and monitored in adjacent boreholes (Ivansson, 1987). Changes in the attenuation of seismic waves are controlled by a number of variable rock characteristics, including rock density, fracture spacing, voids, thermal variabilities and pore pressure differences. Large voids impede P wave velocities and decrease signal amplitude. Simple geometric solutions for locating significant voids may be attempted using combined travel time determinations from several source and receiver arrays. The technique has also been successfully applied to fracture identification beneath building foundations, tunnel and cave identification, dam investigations, ore body determinations and stress monitoring in mines, and in support of nuclear waste repository siting.

Video Surveys

Video logging of shafts provides access below ground-water elevations and assists in identifying lateral mine features extending away from the shaft. The depth of the features can be accurately determined and the apparent configuration and size of the void can be determined. The technique is limited by access, air opacity and ground-water turbidity. Additionally, the introduction of equipment in an unstable shaft may result in falling debris or failure of structural supports.

MINE RECLAMATION

Abatement and reclamation of mine related features must be accomplished following excavation and

identification of mine openings. Reclamation goals are predicated upon the anticipated use of the site following reclamation. An experienced underground mining engineer should review the reclamation closure plan for consistency with applicable state and federal standards. Periodic inspection of the closure activities and specific inspections of engineered structures such as plugs, caps, grouts and fill should be accomplished to ensure proper construction standards are met.

Environmental Factors

Closure must consider ground-water sources and discharge locations. If potable water discharges from mine workings, closure activities should provide for continued discharge. If contaminated water discharges from a mine feature, closure activities must include engineered provisions for preventing continued discharges or the reclamation activities must include a treatment strategy to reduce the pollutant loading to acceptable concentrations prior to release.

Mine gas accumulation may be significantly altered during reclamation and final closure. Mine gases include methane, carbon monoxide, carbon dioxide, nitrogen and hydrogen sulfide. Other gases may be present where solid or hazardous wastes have been disposed in openings. The location and type of gas encountered is a function of the gas density, the unique ventilation geometries of the mine workings, the chemistry of the ore body, the ground-water chemistry and the interaction of these factors with the introduction of air following excavation. Any of the gases may migrate through diffusion into voids with variations in barometric pressures or from changing ventilation patterns. Further, additional gas may form during reclamation as undisturbed bedrock is exposed to the atmosphere.

Continued ventilation of mine gases may be required when entrances are sealed during reclamation. In the absence of positive ventilation, gases may diffuse into unventilated voids in utility trenches, buildings and bedrock cracks and fissures. Vent pipe fitted with flame arresters and protected by lightning conductors may be required to allow gas to escape and prevent the accumulation of gas in the void near a cap or plug (Bureau of Land Management, 1992).

As previously discussed, access for habitats unique to mine workings may also be required. Types of closures, public access, security and safety considerations must be determined for the closure method(s). These decisions may require the input of several regulatory agencies.

Structural Closures

Peripheral mine features not located within an anticipated area of development may not require extensive investigation and reclamation. Since structural

loads are not anticipated in these areas, mine reclamation activities focus on improving the safety of open or unstable workings. Reclamation measures may involve simple filling of shallow workings, isolation of deeper workings through the installation of large rip rap and fill in the opening of the mine, and covers or gated closures to enable access for bats and reduce human interference. Examples of recent mine and cave opening gating may be found in Tuttle (1995).

Structural reclamation requires a detailed understanding of the mine feature, anticipated grading, location of anticipated structures, and sufficient set back for future improvements involving excavation such as utilities, swimming pool installations or landscaping. Engineered structures for mine reclamation must be designed to incorporate existing geologic and mine conditions, and, as a result, are specific for each mine. In general, engineered reclamation structures are installed to reduce the potential for further subsurface erosion, subsidence or instability and increase the load bearing capacity of bedrock and engineered fill materials.

The Bureau of Land Management has provided suggestions for structural closure of mines in their *Solid Mineral Reclamation Handbook* (H-4042-1)(Bureau of Land Management, 1992). Details are provided for structural closures using controlled filling, enclosures, covers, caps, plugs, collars, slurries and grouts. Structural support for mine features may include plugs, caps and collars for areas where voids at depth are impractical to excavate and present a low potential for upward stoping. Slurries and grouts may be used for drifts and voids that are difficult to excavate due to depth, competency of bedrock or width of the feature or are impractical to fill with engineered fill. Granular fill should be used to fill open vertical voids in conjunction with plugs or caps to reduce the potential for settlement and lateral collapse. Detailed examples for closure of a variety of geologic conditions can be found in the BLM Handbook (Bureau of Land Management, 1992).

Collars, plugs and caps consist of concrete that may or may not require reinforcement. Care must be taken to consider the potential for deterioration of reinforcement due to corrosion. Plugs and caps can be placed in open shafts, on drift floors and in inclines where access to conventional construction equipment cannot be accommodated. Plugs and caps must be keyed into competent bedrock materials and should be engineered to accommodate anticipated loads. Plugs have been utilized to successfully isolate lower portions of deep shafts that extend beyond the investigatory reach of equipment or capital resources. Caps have been utilized to isolate stoping of lower level drifts from encroachment onto overlying excavated and filled voids.

Cement slurries and grout mixtures can be placed through access holes drilled using air percussion techniques to reduce stoping potentials and increase the

load bearing capacity of shallow bedrock undermined by ore removal. Slurries must be thin enough to flow without significant mounding, and may require pressure placement if narrow, elongate voids are present.

Engineered fill must be placed in all opened voids where feasible. Although placement of the fill in narrow and deep voids may prove time consuming, fill materials may be derived from screening waste materials excavated during the investigation phase of the project. Care must be used in the placement of fill materials with dimensions greater than approximately 12 to 15 inches to avoid damaging mine supports left in place and reduce the potential for bridging in open voids. The volume of fill materials should be closely monitored to verify void infilling and confirm the absence of bridges. Fill materials should be resistant to chemical attack and have reasonable bearing capacities.

Mine features must be closed and graded for safety prior to closing the site as a mining activity and implementing rough grading. All structural reclamation improvements should be coordinated closely with anticipated grading activities to reduce the potential for disturbance. Utilities, footings and other improvements must be considered so that the reclamation improvement does not present an impairment to construction or restrict a landowners use of the property.

Further, all final reclamation features including daylight excavation lines, structural features and other reclamation activities should be surveyed on a scale map to accurately locate the reclamation activity for future reference (Herness, 1977). Additionally, a detailed photographic record of preconstruction, excavation and post-reclamation conditions should be maintained to document the subsurface conditions encountered and reclamation measures undertaken.

Reconstruction

Reconstruction activities are required as part of reclamation activities on federal and state lands. Reconstruction may include erosion prevention and control, contouring and grading, revegetation, erosion infiltration control and maintenance. Following completion of reclamation activities on private land, the mine can be permanently closed. Subsequent reclamation activities are typically not required on private land with planned development following closure of the mine, since municipal building codes provide guidance for subsequent development. Additional surface reclamation requirements may be necessary for reclamation activities on Bureau of Land Management land, including soil management, erosion prevention, revegetation, and water and waste management. Similar surface reclamation activities may be required for National Forest, United States or state-owned lands.

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