

Geologic, Geophysical, and Seismic Characterization of the Luttrell Pit as a Mine-Waste Repository

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Chapter E3 of

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Contents

Abstract.....	477
Introduction	477
Purpose and Scope	478
Setting	478
Methods	478
Geological Characterization	480
Setting	480
Faults	481
Joints	482
Airborne Magnetic and Electromagnetic Data.....	482
Seismicity	484
Helena Earthquakes of 1935.....	484
Earthquake Data	486
Interpreted Fracture Mapping from Remote Sensing Data.....	487
Linear Feature Analysis	488
Hydrological Implications.....	489
Conclusions	493
References Cited	493

Figures

1. Map showing location of the Luttrell mine-waste repository, in the Boulder River watershed	479
2. North-south cross section near north end of Luttrell pit	481
3. Color-shaded relief map of reduced-to-pole magnetic anomalies for Luttrell pit study area	483
4. Color-shaded relief map of 7,200 Hz apparent conductivity for Luttrell pit study area	485
5. Iseismal map from main shock of Helena earthquake of October 18, 1935.....	486
6–8. Maps showing:	
6. Peak acceleration in percent of gravity that has a 10 percent probability of being exceeded in 50 years.....	487
7. Earthquake epicenters in Rocky Mountain region defining Intermountain seismic belt and Centennial tectonic belt	488
8. Earthquake epicenters and fault plane (nodal) solutions for Helena area	489
9. Rose diagrams and statistical analysis of lineament orientations in Luttrell pit study area	490
10. Digital map showing wet soils in the study area draped over a digital elevation model and combined with mapped lineaments.....	491
11. Color map of 7,200 Hz apparent conductivity superimposed with linear features described in this study.....	492

Chapter E3

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Abstract

Integrated geologic and geophysical studies conducted near the Luttrell pit at the former Basin Creek mine provide geotechnical information that characterizes the area of the mine-waste repository. The geologic setting, fracture patterns, potential ground-water flow paths, and historical seismicity were examined using mining company records, geologic and geophysical data, and remote sensing images. Interpretation and analysis of airborne geophysical data suggest a much greater structural and lithologic complexity than indicated by the geologic mapping. The bedrock in the immediate area of the Luttrell pit does not have high acid-neutralizing potential as interpreted from the airborne geophysical data. Although the region is an area of high seismic activity, little historical seismic activity has been recorded near the pit. Regional stress suggests that northeast-trending fractures may be preferentially open but local stress conditions at the mine-waste repository are unknown. Although faults in the area were active before and after mineralization, no recent movement was evident in the structures exposed by the pit mining. Structures inferred from geologic mapping, from airborne geophysical data, and from lineaments mapped using remote sensing images define a northeast-trending structural zone located 0.25 miles south of the pit. This zone may influence the local flow of ground water in fractures and would be a possible area for bedrock ground-water monitoring. The potential for enhanced ground-water recharge or discharge may be greater in areas where the geophysical data indicate high electrical conductivity and mapping indicates the presence of linear features or structures.

Introduction

Mine wastes and mill tailings produced during historical mining activities commonly were discarded with little regard for any potential effect on the landscape and resources. Runoff from or direct erosion of these wastes is a primary cause of environmental degradation in many watersheds, like the

Boulder River watershed, that have been affected by historical mining. Repositories are a common type of facility used to consolidate and contain mining wastes. Repository-siting studies are therefore an important component of investigations designed to characterize abandoned mine lands prior to remediation activities.

Siting of repositories requires consideration of a complex array of environmental, economic, engineering, and political factors. As a part of the overall siting investigation, geotechnical studies (geology, geophysics, seismicity, and linear feature mapping) can provide important information for assessing each of these factors. Geologic information provides the basic framework for understanding the underpinnings of the repository and is critical for understanding the hydrogeology and potential fate of any contaminants released from the repository. Geologic information also provides information on the presence of faults and potential seismicity of the area. Geophysical data are useful for examining the subsurface geology of an area in greater detail than is possible from surface mapping. Geophysics and geochemistry provide a means to estimate surface and subsurface acid-neutralizing potential. Linear feature mapping using remote sensing images provides additional detail not easily obtained from traditional geologic mapping.

In the late 1990s, land-management agencies considered several potential repository sites near major historical mines in the Boulder River watershed for consolidation of mine wastes. Initial studies of some of these sites demonstrated that the region's granitic bedrock could neutralize potential releases of acidic leachate (Desborough and Driscoll, 1998). However, further investigation of these sites was curtailed when the opportunity arose to utilize an open pit at the former Basin Creek mine. The Luttrell pit is centrally located (fig. 1) as well as sufficiently large to contain historical mining wastes from several drainage basins. The agencies initiated investigations to identify and evaluate geotechnical characteristics that would affect site engineering. Reported here are results from those studies which have implications for the potential fate of contaminant releases and the possibility of earthquake activity destabilizing the repository.

Purpose and Scope

This report describes and interprets selected geotechnical characteristics in the area of the Luttrell pit mine-waste repository, which are important considerations in engineering design. In particular, the goals of the report are to

- Describe the geology, alteration, mineralization history, joints, and faults
- Examine airborne geophysical data to determine the nature of subsurface rocks and geologic structures
- Provide preliminary conclusions about possible seismic hazards, and
- Interpret linear features from remote sensing images to identify possible structures that could control ground-water flow paths to or from the repository site.

Setting

The Luttrell pit was one of three open pits at the Basin Creek mine, which is located on the Continental Divide near the northern boundary of the Boulder River watershed study area (fig. 1). The site is near the headwaters of several drainage basins (fig. 1) where historical mining has occurred.

Gold was mined by underground and open-pit heap-leach operations in various locations within 1 mi of the Luttrell pit (fig. 1) intermittently from about 1892 to 1991. From 1915 to 1926, the Basin Creek underground mine was operated by the Anaconda Minerals Company. During 1988 and 1989, Pangea Resources Ltd. conducted the first open-pit heap-leach operations, called the Columbia and Paupers pits, in the general location of the Paupers Dream mine southwest of the Luttrell pit. Pegasus Gold Corporation purchased the mine operations in 1989 and formed Basin Creek Mining, Inc. (a wholly owned subsidiary). The Paupers and Columbia pits were backfilled during mining of the Luttrell pit and subsequently capped with clay from the site (Dan Adams, Basin Creek Mine, Inc., oral commun., 1999); the Luttrell pit had not been backfilled when mining ceased in 1991.

Based on the results of our work and other studies, use of the Luttrell pit as a mine-waste repository began in 1999. During 1999 and 2000 approximately 140,000 loose cubic yards of mine-waste material was placed in individual cells. Each cell has a composite liner and a leachate collection and removal system (URS, Greiner Woodward Clyde, written commun., November 1999). The repository has room for additional wastes that will be removed from nearby inactive mines and mills in the future.

Methods

The geologic description in this chapter was compiled from published mapping (Ruppel, 1963), unpublished data

primarily from Pegasus Gold Corporation reports, and observations made during geologic field investigations (O'Neill and others, this volume, Chapter D1). M.W. Reynolds (Thamke, 2000) compiled geologic mapping of bedrock in the Helena area including the Luttrell pit area.

Airborne magnetic and electromagnetic surveys were flown over the site in 1996 and 1997 (Smith, McCafferty, and McDougal, 2000; McCafferty and others, this volume, Chapter D2). The airborne geophysical data along flightlines have been gridded with a 120-ft cell size, which is about 1/5 of the flightline spacing (Smith, Labson, and Hill, 2000). This cell size was required because of the difference between the flightline separation (600 ft) and the sampling interval along flightlines at 9 ft. The gridded data have been used to produce color maps discussed here.

The total-field airborne magnetic data have been processed and reduced to the pole as described by McCafferty and others (this volume). Reduction to the pole produces magnetic maps where the causative source for magnetic anomalies is directly beneath the high or low. Magnetic highs are caused by a greater abundance of magnetic minerals (primarily magnetite) in comparison to surrounding lithology. Conversely, relative magnetic lows are caused by an absence of magnetic minerals relative to surrounding lithology. McCafferty and others (this volume) give additional details about geologic features and processes that can be associated with magnetic anomalies. In addition, they give a statistical estimation of the magnetic properties of the geologic map units and their distribution in the Boulder River watershed.

Electromagnetic data were reduced to apparent resistivities (Fraser, 1978) and converted to apparent conductivities at three frequencies (900 Hz, 7,200 Hz, and 56,000 Hz). The apparent conductivity was computed based on a homogeneous half space (an electrically conductive and homogeneous Earth). The use of the term "apparent" reflects the fact that the Earth is not homogeneous and the calculated conductivities are an estimate of the true electrical conductivity. The depth of investigation varies inversely as a function of frequency and conductivity of the subsurface (Spies, 1989). For rocks that have an intermediate conductivity (5 millisiemens per meter), the lowest frequency provides information from a depth of at least 200 ft. The highest frequency provides information from a depth of 10–30 ft. In this study, the apparent conductivity map at 7,200 Hz was used because it provides information from an intermediate depth (30–100 ft), which is the zone that typically would immediately underlie a mine-waste repository.

Electrical conductivity of subsurface materials is determined by a variety of physical and electrochemical properties of the underlying rock and pore fluids (Olhoeft, 1985). Pore fluids affect subsurface conductivity primarily because of the charged ions that are dissolved in the water. Conductivity of the pore fluid increases as the dissolved-solids concentration increases. Therefore, the presence of ground water creates higher conductivity in rocks below the water table than in similar but unsaturated rocks above the water table. If ground water has high concentrations of dissolved solids, subsurface

Figure 1. Location of the Luttrell mine-waste repository, in the Boulder River watershed. Base modified from U.S. Geological Survey 1:250,000 Butte, 1947, and White Sulphur Springs, 1958.

conductivity can be much higher than in rocks with fresh (potable) water. The amount of pore space (porosity) in rocks also can affect subsurface conductivity because conductivity increases as more pore space within rocks is filled with fluids. Mineralogy of rocks is important in determining subsurface conductivity. For instance, the presence of clay tends to increase conductivity. In addition, some clay minerals such as montmorillonite that have large cation exchange capacity can have higher electrical conductivity than clay minerals such as kaolinite that have small cation exchange capacity. Glacial moraines, some types of soil, and weathered volcanic rocks can contain significant amounts of clay minerals. Massive or interconnected metallic mineral deposits are another cause of high conductivity. Power lines, some fences, and pipelines also can cause high conductivity anomalies. McCafferty and others (this volume) estimated the apparent electrical properties associated with each of the mapped geologic units.

Seismicity interpretations were based on published peak ground acceleration, epicenter, and isoseismal maps (Neumann, 1937). These data were compared with Quaternary fault maps to determine location of active faults near the Luttrell pit and to predict earthquake activity of faults mapped in and near the study area. These data also were used to predict geologic controls of active faults and possible local surface disturbances during earthquakes.

Fracture studies were based on published data (Ruppel, 1963; Becraft and others, 1963) as well as mapping and interpretation of linear features from remote sensing imagery. Two data sets were used to generate base images for lineament mapping. Landsat Thematic Mapper (TM) (≈ 100 ft spatial resolution) and India Remote Sensing (IRS) 1-C panchromatic (17 ft spatial resolution) data were processed and filtered to enhance linear features (McDougal and others, this volume, Chapter D9). Linear features considered to represent faults, fractures, or other linear geologic features were mapped as a vector coverage from each base image. The azimuth and line length were calculated from the endpoints of each mapped vector. A digital map showing wet soil types (wetland areas; McDougal and others, this volume) was draped over a digital elevation model (DEM) and combined with the map of linear features to identify areas where there is an overlap of a high occurrence of fractures and saturated soils. These are areas of possible ground-water recharge or discharge.

Geological Characterization

Setting

Geologic information provides the basic framework for assessing many important geotechnical and hydrologic characteristics of a potential repository site. The Basin Creek mine (fig. 1) is in the northern part of the Late Cretaceous Boulder batholith–Elkhorn Mountains Volcanics complex, which is an important geologic feature of west-central Montana (O’Neill

and others, this volume). The Basin Creek mine site is underlain at depth by the Butte pluton of the Boulder batholith (Lund and others, 2002). The Late Cretaceous volcano-plutonic complex was intruded and overlain by Eocene dikes and volcanic rocks of the Lowland Creek Volcanics episodes and by Eocene-Oligocene volcanic necks and volcanic rocks of the Helena volcanic field (O’Neill and others, this volume, pl. 1).

At the Basin Creek mine, a series of Eocene-Oligocene purplish-gray and purple pyroclastic rhyolite tuffs and flows (O’Neill and others, this volume, pl. 1) of the Helena volcanic field overlie the Butte pluton and are the primary host of the gold deposits. These rhyolitic rocks are commonly porphyritic and contain phenocrysts of sanidine and biotite. They are characterized by spherulitic and fiamme textures of welded tuffs. The rocks are dated about 34 Ma (Chadwick, 1978; O’Neill and others, this volume) and originated as deposits from local vents near the Basin Creek mine. Recognized vents are in an east-northeast-trending zone and include, from west to east, the peak west of the Josephine mine, Pauper Peak, Luttrell Peak, and Red Mountain (O’Neill and others, this volume). The Eocene-Oligocene rhyolites were deposited nonconformably on the Late Cretaceous Butte pluton. Prior to deposition of the rhyolites, the plutonic rocks were exposed to erosion and weathering from about Late Cretaceous to late Eocene (for as long as 38 m.y.), and a thin carbonaceous clay was locally deposited on them (O’Neill and others, this volume). This clay was probably developed in a basin which was later in-filled by the Helena volcanic rocks, which metamorphosed the clay to shale (Dan Adams, Basin Creek Mine, Inc., written commun., 1999). This young sediment is age equivalent to the Oligocene siltstone and sandstone described by O’Neill and others (this volume). After deposition of the volcanic materials, a north-trending set of minor down-to-the-west normal faults dropped the depositional contact zone to the west (fig. 2). Hydrothermal mineralization and alteration followed the faulting. The Paupers and Columbia pits are located entirely in the Eocene-Oligocene pyroclastic rhyolites. The Luttrell pit, the westernmost pit, is in the faulted contact zone between the rhyolitic rocks and the underlying plutonic rocks (O’Neill and others, this volume).

Disseminated gold deposits exploited at the Luttrell pit were localized primarily along the contact between plutonic and Helena volcanic rocks: hydrothermal fluids moved along the weathered upper surface of the plutonic rocks, up the minor down-to-the-west normal faults, and into the base of the rhyolites (fig. 2). The hydrothermal solutions resulted in argillic alteration that changed feldspars to clays throughout the mineralized areas, including most of the Luttrell pit area. Mineralization at the Basin Creek mine produced disseminated pyrite and cassiterite in the host rocks. Gold occurs as inclusions in pyrite (and possibly arsenopyrite) grains as well as free gold in zones where the pyrite had oxidized. The Eocene-Oligocene deposits at the Basin Creek mine are notably different in mineralogy from Late Cretaceous quartz-vein and Eocene breccia-pipe mineral deposits found elsewhere in the Boulder River watershed (O’Neill and others, this volume; Lund and others, 2002).

Figure 2. North-south cross section near north end of Luttrell pit, showing geologic interpretation and gold values exceeding 0.01 oz/ton from drill hole data (provided by Pegasus Gold Corporation). Dashed lines are interpreted surfaces and faults, queried where uncertain. No horizontal scale.

Faults

The presence of faults, particularly possible active faults, near a mine-waste repository is important in characterizing the area because they present important engineering constraints. Faults also can be conduits for or barriers to ground-water flow and therefore can significantly influence the hydrology of a repository site. The northeast-trending Butte-Helena fault zone is an important structural feature in the regional tectonic setting of the Luttrell pit (O'Neill and others this volume, fig. 1). McDougal and others (this volume, fig. 6) suggest that the pit is located near the north edge of this structural zone. On a more local scale, Ruppel (1963) described four types of faults that can occur in the area of the Luttrell pit: (1) east-trending fault zones, (2) north-trending faults, (3) north 20° east-trending faults, and (4) northeast- and northwest-trending faults. The latter faults have been the most recently active since they offset glacial deposits. They also control some post-glacial drainages and are marked by prominent fault scarps 50–300 ft high.

The largest mapped fault near the Luttrell pit is an east-northeast-trending normal fault that traverses the south side of the Basin Creek mine and cuts the upper Basin and Banner Creek basins (O'Neill and others, this volume, pl. 1). This fault is shown on the Basin quadrangle mapped by Ruppel

(1963) and continues a short distance to the east-northeast in the geologic map of the Jefferson City quadrangle (Becraft and others, 1963). It is grouped with the northeast-trending faults described by Ruppel (1963). In general more faults are shown on the Basin quadrangle (Ruppel, 1963) than on the Jefferson City quadrangle map (Becraft and others, 1963), reflecting the presence of more geologic units to show offset. Our geologic interpretation is that a fault zone controls the northeast trend of Eocene-Oligocene vents. Consequently we have extended the fault shown by Ruppel (1963) and Becraft and others (1963) east-northeast to the general area of Chessman Reservoir. The fault zone that contains this structure is likely composed of several other structures that may have different traces associated with the different ages and possibly styles of faulting. The entire northeast-trending fault zone is covered, so the east-northeast fault shown by O'Neill and others (this volume, pl. 1) is approximately located.

Interpretation of the geologic map suggests that four periods of movement have taken place along this fault from middle Tertiary through Holocene time and that the direction of movement may have reversed through time. Characteristics of the fault which suggest this are:

1. The fault parallels the Eocene-Oligocene vents located along the east-northeast trend from the peak west of the Josephine mine to Red Mountain, suggesting that

the fault was active before the Eocene-Oligocene eruption and may have served as a conduit for the magmas and hydrothermal mineralizing fluids.

2. The Eocene-Oligocene rhyolites are preferentially preserved north of the fault, indicating post-Oligocene (but pre-Pleistocene) down-to-the-north offset after deposition of the rhyolite.
3. The fault also appears to bound the Basin Creek basin along its north edge and may have controlled preservation of glacial deposits on the south side. This would indicate a possible episode of Pleistocene movement.
4. As mapped by O'Neill and others (this volume, pl. 1), the fault cuts the glacial deposits in upper Basin Creek with down-to-the-south movement. Thus, it may have had a fourth episode of movement that included Holocene postglacial activity.

In summary, the long east-northeast-trending fault is part of a larger fault zone that trends northeast. The normal faulting has been active, at least intermittently, for more than 34 m.y. as well as within the last 10,000 years. Therefore, future movement within the fault zone is possible.

A second set of faults in the Luttrell pit area consists of a north-trending zone of minor, down-to-the-west faults (fig. 2) that cut the contact between the Butte pluton and overlying rhyolitic rocks. Movement along these faults preceded mineralization, which took place about 34 Ma. That the faults do not offset mineralized rocks indicates that no movement has occurred on these particular faults since mineralization. Therefore, movement along these faults is highly unlikely to occur in the future. Other short northwest- and northeast-trending faults also cut the contact between the Eocene-Oligocene rhyolites and the Late Cretaceous plutonic rocks (O'Neill and others, this volume, pl. 1). These do not appear to be part of larger fault systems or zones, have only minor offsets, and, from our data, likely have not been active since 35 Ma.

Joins

Joins or fractures occur in almost all rocks. The orientation, intensity, and permeability of joins are important factors in controlling movement of ground water as well as leachate that may be lost from a repository. Orientation and intensity of joins are characteristics that are relatively easy to define. Estimating the permeability of fractured rock requires a more detailed investigation that was beyond the scope of this study.

The Eocene-Oligocene rhyolites that host the Basin Creek mine are relatively free of joins in comparison to either the Late Cretaceous Elkhorn Mountains Volcanics (O'Neill and others, this volume, pl. 1) or the Butte pluton. Many of the joins in the Eocene-Oligocene volcanic rocks are primary features that include cooling joins, some of which are columnar joins. The other common types of joins are platy joins that

formed secondarily along the flow and compaction layering in the pyroclastic rocks (Ruppel, 1963).

The underlying plutonic rocks of the Butte pluton have a complex joint pattern (O'Neill and others, this volume, fig. 11) and are more extensively weathered along these surfaces. Several major and minor joint sets have been reported (Ruppel, 1963). Joins of a steeply dipping north-trending set are generally spaced about 1–5 ft apart and those of a steeply dipping east-trending set are spaced about 5–10 ft apart. Joins of the gently dipping east-trending set are spaced about 1–15 ft apart. Several other orientations of joins are present but are not as common. Many joins are probably related to shrinkage during cooling of the magma, and some have been intruded by late-stage aplite dikes (Becraft and others, 1963; Ruppel, 1963). The preferred orientation of the joint sets indicates that they formed in response to regional stress patterns either during or after cooling (O'Neill and others, this volume). Although jointing is pervasive in the Butte pluton, most joins are thought to be tight at depths greater than about 50 ft. Therefore, we hypothesize that little ground water moves through the pluton relative to the amount that flows in the overlying shallow unconsolidated deposits and weathered plutonic rocks (McDougal and others, this volume).

Airborne Magnetic and Electromagnetic Data

Airborne magnetic and electromagnetic data for the Basin Creek mine area (Smith, Labson, and Hill, 2000; McCafferty and others, this volume) provide additional information about the subsurface lithology, structure, and ground water of the area. Reduced-to-the-pole magnetic field data are shown as a color-shaded relief map (fig. 3). The sun angle used to produce the shading is from the northwest in order to enhance north-east-trending features. McCafferty and others (this volume) give a detailed discussion of the interpretation of the magnetic field data, some of which also appears herein. Figure 4 is a color-shaded relief map (northwest illumination) of the 7,200 Hz apparent conductivity for the Luttrell repository study area.

A number of linear features are defined by anomalous conductivity and magnetization (figs. 3, 4) that we interpret primarily as faults or lithologic contacts. Many more linear features are imaged in the geophysical data than are shown as mapped structures on the geologic map (O'Neill and others, this volume, pl. 1). The main reason for this greater density of possible structural features in the geophysical maps is that much of the bedrock in the watershed is covered by glacial or other surficial deposits and is thus not mappable by surface inspection.

None of the linear features shown by geophysical maps in figures 3 and 4 trend through the Luttrell pit. Thus, although numerous small faults have been mapped in the area by mine geologists (fig. 2), none appear either to have a geophysical

Figure 3. Color-shaded relief map of reduced-to-pole magnetic anomalies for Luttrell pit study area. Red filled circle is the location of the mine-waste repository. Dashed line shows linear feature discussed in text. A part of the linear feature is shown in the enlargement to give greater detail (no scale).

signature or to be part of a regional structure defined by a geophysical signature.

A linear geophysical feature observed about 1,600 ft south of the Luttrell pit is defined by remarkably intense and narrow (less than 150 ft) magnetic low and conductivity high anomalies (dashed line, figs. 3, 4). The northeast-trending feature is obvious on 1:24,000-scale geophysical maps, portions of which are shown at a smaller scale in figures 3 and 4. An enlargement of a portion of the geophysical map is shown in each figure in order to better display its character. Though many other linear and curvilinear features are seen on the airborne geophysical maps, these anomalies are important not only for their relatively unique geophysical signature but also for their correlation with geologic features, as discussed herein. The narrow magnetic low is probably caused by alteration that has destroyed magnetic minerals along a possible structural zone. The relative high conductivity might be associated with alteration that produced clays, or water with high concentrations of dissolved solids in ground water along a structure, or both. No unusually high concentrations of dissolved solids have been measured in springs around the area. Therefore, the anomalously high specific conductance of shallow ground water is not a likely cause of the electrical conductivity high. If the high conductivity is caused by moist clays, then the linear feature might be a subsurface barrier to ground-water flow.

The long fault south of Luttrell pit that trends east-northeast toward Chessman Reservoir (O'Neill and others, this volume, pl. 1) probably controlled the spatial location of intrusive rocks. Small, closed magnetic high and apparent conductivity low anomalies probably caused by the young, shallow intrusive igneous rocks define the east-northeast trend of the structure shown on the geologic map. This trend may indicate discrete structures that could control local ground-water flow in the crystalline rocks. The west end of this east-northeast geologic feature merges with the more northeast-trending narrow magnetic and apparent conductivity anomaly west of Scott Reservoir.

McCafferty and others (this volume) give an extensive discussion of the acid-neutralizing potential (ANP) of different lithologies in the Boulder River watershed. In summary, high ANP is associated with bedrock that has both high magnetic signature and low electrical conductivity. Conversely, low ANP is associated with rocks having low magnetization and high electrical conductivity. Desborough, Briggs, and Mazza (1998) and Desborough, Briggs, and others (1998) presented results of geochemical tests for ANP of soils and bedrock in the Boulder River watershed that were used by McCafferty and others (this volume) to develop an environmental geologic map of the study area.

Figures 3 and 4 show that the Luttrell repository (red dot in figures) is located in an area of moderate magnetic field and low apparent conductivity. Consequently, the area has low ANP based on the geophysical signature. This interpretation is supported by the observed high hydrothermal alteration of the Helena volcanics and the underlying Butte pluton. This

style of alteration would remove minerals that produce ANP (Desborough, Briggs, and Mazza, 1998).

Seismicity

Earthquakes have the potential both to compromise the integrity of mine-waste repositories and to cause release of the stored waste or leachate. Therefore, the seismicity of the area near the Luttrell pit is an important geotechnical parameter in site selection and repository design. The seismic characteristics of the area are particularly important because large earthquakes took place about 50 mi northwest of the Luttrell pit in 1925 (magnitude 6.6) and 1935 (magnitudes 6.25 and 6.0; Stickney and others, 2000). The repository is located in a highly active tectonic belt. Information on regional seismicity was obtained from reports of damage from nearby earthquakes, earthquake data, and maps of Quaternary faults. Unfortunately, little information about modern seismic activity within the Boulder batholith or the study area is available.

Helena Earthquakes of 1935

Devastating earthquakes occurred in 1935 within 12 mi of Helena, Mont. A sequence of four earthquakes with magnitudes greater than 5.5 took place between October 12 and November 28. The main shock of magnitude 6.25 occurred October 18 (Neumann, 1937; Stickney and others, 2000). The Mercalli intensities in the Helena area ranged from VI to VIII; observed damage from VIII intensity earthquakes is described by Neumann (1937, p. 36) as:

“****slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motorcars disturbed.”

Most of the damage from the 1935 Helena earthquakes was from ground shaking and not ground breakage. Newspaper accounts of the earthquake damage (O'Brian and Nava, 1998) indicate no reported damage in underground mines and little damage in areas underlain by the Boulder batholith during the Helena earthquakes. There were some reports of boulders falling in the mountainous areas (Schmidt, 1986).

The Luttrell pit is located approximately on the margin of the area of highest intensity activity on the isoseismal map constructed from data on the 1935 Helena earthquake (fig. 5). Because the isoseismal lines have been generalized, and based just on damage reports described, it is doubtful that the intensity of disturbance was as high as shown on the map in areas underlain by rocks of the Boulder batholith.

Figure 4. Color-shaded relief map of 7,200 Hz apparent conductivity for Luttrell pit study area. Red filled circle is the location of the mine-waste repository. Dashed line shows linear feature discussed in text. A part of the linear feature is shown in the enlargement to give greater detail (no scale).

Figure 5. Isoseismal map from main shock of Helena earthquake of October 18, 1935 (Neumann, 1937). Luttrell pit (solid circle) is located just on margin of highest magnitude disturbance.

Earthquake Data

A map depicting peak ground acceleration with a 10 percent probability of being exceeded over a 50-year period for Montana is in figure 6. Peak ground acceleration is shown in various levels of percent gravity (% g), ranging from less than 2 to more than 30 percent. This map can be viewed as a generalized seismic hazard map, where the highest peak acceleration is associated with the highest earthquake hazard. For the entire United States, the highest peak ground acceleration, greater than 100 percent gravity, occurs along the San Andreas fault system in California. In the Rocky Mountain region, the arcuate north-south Intermountain seismic belt has a high seismic hazard; in local areas in the Yellowstone Park region, peak ground acceleration could exceed 30 percent gravity. In the area of the Luttrell repository, peak acceleration is expected to be between 10 and 15 percent gravity.

In a regional context, the Luttrell pit is located within the Intermountain seismic belt and north of its intersection with the Centennial tectonic belt. These two tectonic features are defined by local faulting and earthquake epicenter distribution (fig. 7). Stickney and Bingler (1981) suggested that the Centennial tectonic belt poses the greatest seismic hazard in the area. This is also an area of high acceleration probability, as shown in figure 6. The tectonic feature is far enough to the south of the Luttrell pit that it is not a consideration in the seismic risk assessment of the mine-waste repository site.

A more detailed local map of earthquake epicenters is shown in figure 8. The sedimentary and younger volcanic rocks surrounding the Boulder batholith are sites of most of the recent earthquake epicenters (Stickney, 1998; Stickney and others, 2000). In general, the regional stress patterns in southwest Montana produce northeasterly expansion (Freidline and others, 1976). Recent fault plane solutions (Stickney, 1998; fig. 8) are consistent with northeast expansion, but this

Figure 6. Peak acceleration in percent of gravity (% g) that has a 10 percent probability of being exceeded in 50 years. Modified from Montana Bureau of Mines and Geology (2001a) at URL http://mbmgquake.mtech.edu/seismicity_in_montana.html.

direction of expansion is difficult to extrapolate to the faulting in the Luttrell pit area, for the following reasons: The younger faults in the batholith are normal faults rather than strike-slip faults defined by the fault plane solutions in figure 8. In addition, the fault plane solutions may not represent earthquakes within the batholith. However, the northeast regional expansion may indicate that northwest-trending faults may be preferentially open and more likely to be ground-water flow paths in the bedrock. A few faults that have a northwest trend are located 3 mi northwest of the Luttrell pit (O'Neill and others, this volume, pl. 1).

No regional-scale Quaternary faults have been mapped near the Luttrell pit (O'Neill and others, this volume, pl. 1; Stickney and others, 2000). The northwest-to-southeast-trending Bald Butte fault zone (fig. 8) is about 15 mi northeast of the mine-waste repository area, as shown by a recent geologic compilation (Thamke, 2000). This fault zone is suspected to be the source of the 1935 earthquakes (Schmidt, 1986). The youngest interpreted ground breakage along the faults is Pleistocene (Stickney and Bingler, 1981). No record exists of seismically active faults near the Basin Creek mine. In addition, no ground breakage features that would indicate recent activity on faults were noted in our fieldwork in the immediate area of the pit.

Epicenter locations (fig. 8) for earthquakes in the Helena area from 1982 through 1996 (Stickney, 1998) show few epicenters that come within 2 mi of the Luttrell pit. Earthquakes in the area southeast of Helena (fig. 8) are as large as magnitude 5 (Stickney, 1998) and may be associated with exposed local Quaternary faults (Stickney and others, 2000). The earthquakes may also be associated with the Butte-Helena fault zone (O'Neill and others, this volume), a regional tectonic feature. Earthquake hypocenters are poorly known, in part because the distribution of seismic stations was not ideal, and epicenter localities are uncertain. Schmidt (1986) stated that the Helena earthquakes occurred at a depth of about 10.5 mi, which is as deep as the Boulder batholith (O'Neill and others, this volume).

Interpreted Fracture Mapping from Remote Sensing Data

The statistical analysis of the orientation of interpreted linear features and their orientation presented here provides a general view of possible directions of preferential local ground-water flow in the bedrock aquifer by identifying

Figure 7. Epicenters from earthquakes in Rocky Mountain region defining the Intermountain seismic belt and the Centennial tectonic belt. Modified from Montana Bureau of Mines and Geology (2001b) at URL http://mbmgquake.mtech.edu/interm_s_b.html.

principal azimuths and locations of possible fractures. McDougal and others (this volume) give a detailed analysis of linear features and their hydrologic interpretation for the Boulder River watershed. The discussion of fracture orientation here is similar, but focuses on a smaller area near the Luttrell pit.

To identify and map all fractures and faults from remotely sensed data is not possible because of ground resolution limitations, vegetation cover, and glacial or other surficial cover. In most cases, to determine if a linear feature marks the surface expression of a fault, fracture, joint, mineralized vein, or lithologic contact is also impossible. Mapped linear features used in this study provide a representation of the spatial distribution and orientation of bedrock fractures near the Luttrell pit mine-waste repository. The interpretation is a statistical sample of naturally occurring linear features that could be related to surface expression of structures.

Linear Feature Analysis

The lineament azimuths, calculated from the geographic coordinates of the endpoints of each mapped vector, were used to generate rose diagrams for the Luttrell pit study area. Rose diagrams are polar histograms, which represent distribution of

the two-dimensional (horizontal plane) orientations of mapped linear features. The statistical parameters of total number of data points (N), maximum percentage, mean percentage, standard deviation, vector mean (direction), R magnitude, standard error of the mean, and the Rayleigh probability distribution were calculated for each diagram (McDougal and others, this volume). The R magnitude is a measure of the strength of the vector mean. Data sets with a large dispersion about the mean have small values for R , and data sets that are tightly grouped around the mean have a large value for R . The Rayleigh test was used to calculate uniformity within the data set. In this case, the chosen significance level was 0.1 (90 percent confidence interval). If the calculated value is less than 0.1, then the conclusion can be made that the data are non-uniform and show a preferred orientation (McEachran, 1990).

The diagram representing the primary lineament orientation (fig. 9A) for the Luttrell pit study area shows a vector mean of 81.2° . The small confidence angle of 7.51° , R magnitude of 0.564, and Rayleigh value of 0.00 indicate that the data have a moderate vector mean strength, and a strong preferred orientation. However, note in figure 9A that the distribution is strongly bimodal with peaks in the rose diagram at 85° and 105° .

Figure 8. Earthquake epicenters and fault plane (nodal) solutions for the Helena area (Stickney, 1998). Fault plane solutions for selected earthquakes are shown as circles whose solid areas denote direction of compression. Larger and darker symbols for epicenters show greater magnitudes for earthquakes.

Secondary lineament orientation was plotted by filtering out the azimuths within the vector mean of the primary bimodal orientation described preceding. The resulting diagram (fig. 9B) shows a possible secondary orientation with a vector mean of 39.6° . The larger confidence angle (31.32°) and Rayleigh value, and smaller R magnitude, indicate that the filtered data set is less preferentially oriented than the primary trend. A possible tertiary trend lies between approximately 110° and 140° . The 39.6° trend correlates with the general trend of the apparent conductivity and magnetic geophysical anomalies (dashed line in figs. 3 and 4). The interpreted geologic structure in the area of Scott and Chessman Reservoirs (O'Neill and others, this volume, pl. 1) trends northeast 55° , which corresponds to the main secondary orientation in figure 9. These linear features, together are collinear with the northeast-trending fault zone described in the geologic section.

Hydrological Implications

Ground-water flow near the Luttrell pit likely is consistent with the regional ground-water flow model developed for the Boulder River watershed (McDougal and others, this volume). Hydrologic characteristics of the bedrock north of the Luttrell pit have been described by Thamke (2000). The highest hydraulic conductivity occurs in the upper unconsolidated deposits and shallow weathered bedrock, which together form an unconfined aquifer. Oligocene sediments deposited locally on the Butte pluton (O'Neill and others, this volume) constitute a relatively unknown (not mapped) aquifer. Hydraulic conductivity generally decreases dramatically with depth within the rhyolitic rocks of the Helena volcanic field because fractures are filled with clays produced during weathering of the volcanic rocks. In the Basin Creek mine area, the Helena volcanic rocks are the host to mineralization which has

Figure 9. Rose diagrams and statistical analysis of lineament orientations in the Luttrell pit study area. *A*, primary lineament orientations; *B*, secondary lineament orientations.

accompanied intense alteration to clays; this clay alteration significantly reduced hydraulic conductivity. The clay has been used to construct a cap designed to reduce infiltration into the back-filled Paupers and Columbia pits (Dan Adams, Basin Creek Mine, Inc., oral commun., 1999).

In the underlying fractured granodioritic bedrock aquifer, hydraulic conductivity decreases because joints and fractures become increasingly tight with increasing depth. In areas of greater fracture density near fault zones, permeability may be somewhat higher. The direction of shallow ground-water flow is controlled by the hydraulic gradient, which likely mimics the topographic slope. Locally, topography slopes away from the Luttrell pit generally in all directions, and therefore, shallow ground water likely flows in all directions away from the pit. The direction of deeper ground-water flow also is a function of the hydraulic gradient, which may be controlled to some extent by fracture orientation. The regional and subregional fracture geometry observed in outcrops is generally heterogeneous and anisotropic, and the local ground-water flow regime near the Basin Creek mine is assumed to be associated with the orientation of these fractures. Recharge to the local ground-water system comes primarily from

approximately 30 in. mean annual precipitation (mainly as snowfall). Intense rainstorms in spring and summer can contribute sudden influxes of recharge.

The results of the lineament orientation analysis indicate that ground-water flow, assuming some control by fracture permeability, could have a preferred flow direction to the east-northeast or west-southwest, depending on the hydraulic gradient. Secondary and tertiary preferred flow directions to the northeast (southwest) and east-southeast (west-northwest), respectively, also are indicated by the rose diagrams.

The wet soils map (fig. 10) shows an area of inferred shallow ground water to the southwest of the Basin Creek mine site. Note that detailed soil mapping is not available north of the Boulder River watershed. This zone of wet soils coincides with a relatively high density of mapped linear features that indicate possible fractures, which may function as conduits for ground-water flow. This area of possible shallow ground water lies along the northeast fracture zone discussed in the previous geologic and geophysical sections. Observed springs in the area could also be associated with a lithologic contact between the Helena volcanics and the underlying Butte pluton. Potentiometric surface maps based on monitoring well

Figure 10. Digital map showing wet soils (blue) in the study area (McDougal and others, this volume) draped over a digital elevation model (DEM) and combined with mapped lineaments (black lines; McDougal and others, this volume) for Luttrell pit study area. Red dot, Luttrell pit.

data in and around the Basin Creek mine indicate ground-water flow directions to the north-northwest, northeast, and southwest (Olympus Environmental Science and Engineering, Inc., 1996). The combination of the wet soils map and linear feature orientation suggests that some ground water could flow from the Luttrell pit area to the southwest, and suggests a possible location where subsurface ground water could be monitored.

A high density of linear features also occurs at the Continental Divide south of the Luttrell pit (McDougal and others, this volume). This part of the northeast-trending structural

zone could serve to recharge possible fracture-controlled ground water in the area of the mine-waste repository, as it is an area of high topography.

Figure 11 shows interpreted linear features and mapped structures superimposed on 7,200 Hz apparent electrical conductivity. The intersections of areas of high electrical conductivity and interpreted linear features mark possible areas of ground-water discharge or recharge. High electrical conductivity may be caused by wet soils and rocks, and linear features may indicate fractures that control ground-water storage or flow. Increased fracturing may indicate increased

Figure 11. Color map of 7,200 Hz apparent conductivity superimposed with the linear features described in this study. Red dot, Luttrell pit.

interconnectedness and therefore increased permeability in the bedrock. The area of the Luttrell pit mine-waste repository does not show any of the features that would indicate local ground-water discharge or recharge.

Conclusions

Geologic studies indicate that faulting has occurred at least intermittently near the Luttrell pit from before the Oligocene through the Holocene. There is no evidence of recent rejuvenation of faults beneath the mine-waste repository, as drill information from premining development indicates that mineralized rocks are not offset by structures. An east-northeast-trending normal fault on the south of the Basin Creek mine has had a complex movement history from at least middle Tertiary through Holocene and may have localized bedrock fracturing. This structure is grouped with northeast-trending structures described in detail by Ruppel (1963). The northeast trend probably is a fault zone with a collinear trend with the Butte-Helena fault zone described by O'Neill and others (this volume) that controls the location of young intrusive rocks.

The airborne magnetic and electromagnetic survey provides information about variations in subsurface lithologies and structures. Many previously unknown structural trends are suggested from the geophysical data, but none actually intersect the pit area. A major northeast-trending linear feature defined by a narrow low magnetic and high conductivity signature starts about 0.25 mi southwest of the pit and trends northeast just south of Scott Reservoir. Another geophysical trend is associated with the east-northeast structure inferred from geologic mapping. Potential sites for fracture-controlled springs are indicated by the intersection of lineaments and high subsurface conductivity. None of these areas occur at the Luttrell pit. The airborne geophysical data interpretation in terms of environmental geology suggests that the mine-waste repository site is located in an area of low acid-neutralizing potential (McCafferty and others, this volume).

A high seismic hazard characterizes the region surrounding the Luttrell pit owing to (1) its location in the Intermountain seismic belt, (2) large historical earthquakes in the nearby Helena area, and (3) continuing earthquake activity in the Helena area and an area southeast of the mine-waste repository. Fault plane solutions for deep earthquakes suggest that northwest-southeast extension might cause northeast-trending fractures to be preferentially open. However, current stress patterns within shallow plutonic rocks and the younger volcanic rocks are a matter of speculation. Newspaper accounts (O'Brian and Nava, 1998) describing damage from the 1935 Helena earthquakes did not indicate any impact on the mines that were actively operating in the Boulder batholith. Therefore, seismic hazard at the pit is considered low.

No major lineaments that trend through the Luttrell pit were identified from remote sensing images or airborne geophysical data. Analysis of linear feature orientations suggests that preferential paths of ground-water flow have a primary azimuth to the east-northeast or west-southwest. Possible secondary and tertiary preferential flow azimuths may be to the northeast (southwest) and east-southeast (west-northwest) respectively. Wet soils and lineament maps suggest a possible preferential ground-water flow southwest of the Luttrell pit that could be considered in design of monitoring activities around the repository. Coincidence of linear features and subsurface high electrical conductivity might indicate areas of ground-water recharge or discharge. No such areas occur at the Luttrell pit mine-waste repository.

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