

Geophysical Characterization of Geologic Features with Environmental Implications from Airborne Magnetic and Apparent Resistivity Data

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Chapter D2 of

Integrated Investigations of Environmental Effects of Historical Mining in the Basin and Boulder Mining Districts, Boulder River Watershed, Jefferson County, Montana

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NOTE ON CONVERSIONS:

The scientific standard for measurements in this report is the metric system. To convert meters to feet, multiply by 3.28. To convert kilometers to miles, multiply by 0.62

Chapter D2

Geophysical Characterization of Geologic Features with Environmental Implications from Airborne Magnetic and Apparent Resistivity Data

By Anne E. McCafferty, Bradley S. Van Gosen, Bruce D. Smith, and Tracy C. Sole

Abstract

High-resolution magnetic and apparent resistivity data collected from airborne geophysical surveys characterize aspects of geologic features in and near the Boulder River watershed that have important environmental consequences. Physical properties of bedrock expressed in the geophysical maps as magnetic and apparent resistivity anomalies are intrinsically related to mineralogical and chemical properties that have the potential to neutralize or produce acidic metal-rich waters. In particular, assemblages of acid-consuming minerals are directly associated with varying amounts of the mineral magnetite. Magnetite is the main source for magnetic anomalies and, in part, resistivity anomalies. The recognition of the relationship of magnetite to geophysical anomalies, alteration mineral assemblages, and acid-neutralization and acid-generation potential is one of the most important results of this study. Mathematical transformations applied to the magnetic and resistivity data result in pseudo-mineral maps that display volume-percent magnetite and that facilitate direct estimates of the associated amounts of acid-consuming minerals present in most of the rock types in the Boulder River watershed. The geophysical magnetite maps infer areas in the watershed with varying degrees of acid neutralization and, in some cases, map the locations of the acid-generating rocks. Many areas with low- to zero-percent magnetite coincide with areas of known hydrothermal alteration, silica-rich rock, and (or) geologic units containing sulfide-rich mineral assemblages, such as the polymetallic quartz veins. Results suggest that about 30 percent of the volcanic and plutonic rock lacks appreciable minerals to provide neutralization for acidic water. In the absence of much subsurface drill data, the three-dimensional capability of the geophysical data provides information on the environmental properties of bedrock at depth. This study demonstrates the utility of geophysical surveying to address issues surrounding water quality, aquatic health, and selection of safe waste-rock repositories. The methods and approaches employed in this study can be applied to other watersheds with similar plutonic regimes containing acid-generating historical mines or source rocks.

Introduction

The watershed approach to study and remediate historical mining areas has many environmental and economic benefits (Buxton and others, 1997). Watersheds are much larger in area and have more diverse environmental characteristics than individual mine sites. Therefore, implementing a watershed approach requires a broader study framework than might be used at a single site. In particular, techniques that reduce the resources needed for watershed-scale data collection and facilitate data analysis over large areas are especially useful. Airborne geophysical surveying is one example of such a technique.

Several characteristics of airborne geophysical surveys make them particularly useful for studying watersheds containing historical mines. First, data are collected essentially continuously, providing the same type of information for the entire survey area. In comparison, other related field tools, such as ground geophysical surveys or geochemical sampling, may have access and logistical constraints and typically provide only a limited amount of information for discrete sites or small areas. Second, geophysical surveys provide a third dimension to surface-collected information, providing insight on geologic properties with depth. Although subsurface geology has an important bearing on a range of hydrogeologic and geochemical issues important to the study of these watersheds, adequate resources often are not available for extensive drilling. Airborne geophysical mapping is also not hindered by vegetative cover or unconsolidated deposits, which can obscure bedrock geology.

Airborne geophysical surveys traditionally have been used for mineral prospecting, for structural geology studies, and in some instances, for mapping plumes of contaminated ground water. To our knowledge, airborne geophysical surveying has not been used previously in abandoned mine land studies on watershed scales even though geophysical techniques have the potential to address several key environmental issues related to historical mining and repository siting. This study was undertaken to determine the utility of airborne geophysical surveys to assess environmental aspects of this

watershed. Results of this study define how the geophysical data relate to environmental properties for many types of rocks that crop out throughout much of southwest Montana. Therefore, we expect that these study results can be extrapolated to other mining areas with similar rock types.

During the last decade, significant research has focused on determining the environmental signature of metallic *mineral deposits* and their effect on water quality and aquatic and human health (du Bray, 1995; Wanty and others, 1999). Plumlee (1999) has provided a succinct summary on the “environmental signature” of mineral deposits and a discussion on key geologic characteristics that control the degree of impact of a mineral deposit on the environment. This report takes an analogous approach, but describes a methodology to evaluate the environmental signature of *bedrock geology* and its influence on mitigating the negative effects associated with acid-generating mineral deposits in the study area.

Purpose and Scope

The purpose of this report is to combine high-resolution airborne geophysical data with geologic information to address environmental aspects in watersheds affected by historical mining. In particular, magnetic and apparent resistivity data are used to characterize the amounts of acid-consuming mineral assemblages within specific plutonic and volcanic rock units in and near areas of historical mining. Acid-neutralizing potential is an important environmental property of bedrock that has bearing on the effects of historical mine sites on aquatic environment and selection of suitable sites for mine-waste repositories.

The area covered by the airborne survey includes most of the Boulder River watershed study area and parts of the adjacent Tenmile and Prickly Pear Creek watersheds. Where appropriate, we distinguish between the Boulder River watershed study area and the larger geophysical survey area (fig. 1).

Figure 1. Boulder River watershed (part) and area of airborne geophysical survey.

Two geoenvironmental maps were produced to portray the relative degree of acid-neutralizing potential of bedrock. One map is based on geologic information and the other on airborne geophysical data. The first map was derived from rock-sample mineralogy, where acid-neutralizing potential was assigned to specific rock units based on amounts of acid-consuming minerals. The second map, derived from the geophysical data, shows acid-neutralizing potential as a function of magnetite abundance. Magnetite abundance correlates well with the abundance of acid-consuming minerals and can be estimated from the geophysical data by the application of mathematical transformations.

Finally, the study combines the geology- and geophysics-based geoenvironmental maps to spatially portray bedrock characteristics that are important controls on the impact of acid-generating mineral deposits on shallow subsurface and surface environments. The resultant map has important environmental implications for abandoned mine land issues in the Boulder River watershed.

Airborne Geophysical Survey

During December 1996, a high-resolution airborne geophysical survey was flown by helicopter over parts of the High Ore and Cataract Creek basins. The following year, a second survey was flown to augment the 1996 survey over the Basin Creek basin on the west and also over the east side of the study area. Geophysical data were acquired at the beginning of the Boulder River watershed study so that maps and derivative products could help researchers prioritize ground investigations. The two surveys were flown with identical specifications for compatibility and were digitally combined to form one data set that is analyzed in this report.

Magnetic and apparent resistivity data were collected along flightlines spaced 200 m apart and flown along an azimuth of 160°/340°. The electromagnetic (EM) field was measured with three frequencies (900, 7,200, and 56,000 Hz) using horizontal coplanar transmitting and receiving coils towed in a "bird" or sensor that varied in elevation but generally was located at approximately 30 m above the ground surface. The helicopter towed the sensor at higher altitudes in populated areas, or where higher altitudes were appropriate for safe flying, for example, over powerlines. The magnetic-field sensor was mounted 15 m above the electromagnetic sensor.

Data were collected approximately every 3 m along the flightline. The flightline data for the magnetic anomaly and resistivity data were interpolated onto a 25 m interval grid. Digital flightline data, grids, and information on other derivative geophysical products from this survey are available on CD-ROM (Smith and others, 2000).

Apparent Resistivity Data

The electromagnetic sensor measures the electrical resistivity (or the reciprocal, conductivity) of rocks. The depth of investigation for EM measurements varies inversely as a square root of frequency and earth resistivity (Telford and others, 1976) with the highest frequency (56,000 Hz) having a depth of investigation from the surface to a few to 10 m. The mid-frequency (7,200 Hz) has a depth of investigation of approximately 30 m. The lowest frequency (900 Hz) can explore as deep as 60 m.

EM measurements can be affected by noise from cultural sources such as powerlines. For example, a series of linear anomalies caused by a large powerline in the southern part of the survey area is evident in the data for all three frequencies. In comparison to the other frequencies, noise from cultural sources is elevated in the 56,000-Hz data. However, noise is minimal in the 7,200- and 900-Hz resistivity maps and only data from these two frequencies were used in this report. A map showing apparent resistivities from the 7,200-Hz data is shown in figure 2. Resistivity signatures as defined in the 7,200-Hz resistivity map were used to distinguish geologic units and structures. Data from the 900-Hz apparent resistivity were used to derive a pseudo-mineral map of magnetite.

Magnetic Data Enhancements

Aeromagnetic surveying is based on mapping variations in the local magnetic field, which are caused by changes in concentration of various magnetic minerals in surface and subsurface rocks. In order to emphasize magnetic features from sources in the shallow geologic environment, a number of data enhancement techniques were applied to the magnetic data. The purpose of the enhancements was to transform anomalies into forms that can be directly compared with important rock mineralogical properties. This section describes enhancements that (1) correctly positioned anomalies over their causative sources, (2) increased the resolution of small-scale anomalies related to near-surface magnetic sources, and (3) converted data to a model of magnetic susceptibilities for comparison with rock mineralogical properties.

Reduction-to-Pole

The study area is located at a geomagnetic latitude where magnetic anomalies are shifted slightly to the southwest from their sources (assuming induced magnetization) and are represented by an anomaly pair determined, in part, by the inclination of the present-day Earth's field. To correct anomalies for this offset in symmetry and position, a filter called reduction-to-pole (RTP) was applied to the magnetic data (fig. 3) using programs available in Phillips (1997). Application of the RTP filter results in magnetic anomalies correctly positioned over their sources and, most importantly, allows for a more accurate interpretation of magnetic source location relative to geologic features.

Figure 2. 7,200-Hz apparent resistivity data showing lateral variations in electrical resistivity of rocks from surface elevations to approximate depth of 30 m. Data from this map were used to define resistivity characteristics of geologic units.

High-Pass Magnetic Anomaly

To aid interpretation of anomalies related to near-surface geologic units, a “match” filter was applied to the RTP data. Match filters facilitate first approximations of magnetic fields corresponding to sources at relative depths based on ranges of wavelengths. The filter was employed using methodology developed by Syberg (1972) with computer programs in Phillips (1997). Application of the filter for this study yielded a short-wavelength anomaly field that approximates the

magnetic response of a shallow magnetic source layer located within the upper 200 m of the Earth’s crust (fig. 4).

We focused our analysis on the magnetic response from the shallowest depth layer, defined here as the “high-pass” magnetic anomaly, because this shallow layer is related to near-surface geologic units and processes important to this study. Additionally, the depth range of the shallowest magnetic source layer corresponds most closely to the depths of investigation of the apparent resistivity data and to the depths where acid-neutralization reactions most likely occur.

Figure 3. Reduced-to-pole magnetic anomaly map. Data in this map were filtered to enhance magnetic anomalies associated with shallow magnetic sources (fig. 4) and produce models of magnetic susceptibilities and volume-percent magnetite (fig. 5).

Magnetic Susceptibility Model

A model of magnetic susceptibility was calculated from the high-pass magnetic anomaly data to approximate the causative physical property producing the anomaly field, and also as an intermediate step toward estimating volume-percent magnetite. Magnetic susceptibility is almost entirely related to the abundance of the mineral magnetite because other magnetic minerals such as pyrrhotite, maghemite, and ilmenite are scarce in rocks exposed in the Boulder River watershed study

area (Ruppel, 1963; Becraft and others, 1963). In addition, the susceptibility of magnetite is roughly 100 times the susceptibility of pyrrhotite (Dobrin and Savit, 1988). Therefore, we can be quite confident that the magnetic anomalies observed in the geophysical survey are overwhelmingly influenced by the distribution of magnetite.

Prior to estimating magnetic susceptibilities, we calculated a magnetization model from the high-pass anomaly data using a method from Blakely (1995) modified by J.D. Phillips (USGS, written commun., 2002). The method

Figure 4. High-pass magnetic anomaly map calculated from reduced-to-pole magnetic anomaly data (fig. 3). Map emphasizes short-wavelength magnetic anomalies caused by lateral variations in magnetic properties of rocks exposed on the surface to approximate depths of 200 m.

inverts gridded magnetic anomaly data to magnetization estimates. For this study, we defined a 200 m thick rock layer with an upper surface represented by topography. The thickness was defined from the estimated thickness given from the matched filtering process. To obtain a first estimate of magnetization, the high-pass data were divided by an appropriate factor that produced reasonable magnetization estimates. These data were used as a first approximation to a magnetization model. The magnetic effect of the first approximation for magnetization was calculated, and the output magnetic field was scaled against the high-pass anomaly data for a best fit in

terms of least squares. A difference grid was produced by subtracting the magnetic field calculated from the first approximation from the high-pass data. Magnetic values in the error grid were scaled to appropriate magnetization values and added to the first approximation to create a second approximation. This process was repeated until a minimum difference between the calculated field and high-pass magnetic field was achieved. The magnetic anomaly field resulting from the final magnetization model contained errors of less than 2 gammas for more than 95 percent of the grid. We converted magnetizations to magnetic susceptibilities by dividing the magnetization values

by the total intensity of the geomagnetic field and assuming induced magnetizations. The magnetic susceptibility model is shown in figure 5.

The range in model susceptibility values is significantly narrower than the range of susceptibilities measured in either field observations during this study, or from results of

magnetic-property laboratory studies of Hanna (1969). Susceptibility measurements taken at outcrop can typically range over orders of magnitude and can do so within the same rock type over short distances (within a few centimeters in some cases). The discrepancy between field and model susceptibility values is not surprising, however, and is controlled in large

Figure 5. Magnetic susceptibility and estimated volume-percent magnetite models calculated from high-pass magnetic data (fig. 4). Magnetic susceptibility characteristics for geologic units within airborne geophysical survey are given in figure 9. Values for percent magnetite at locations of rocks analyzed for acid-neutralizing potential are given in table 2. Low values of volume-percent magnetite (<1.4 percent) are shown in blue and infer areas of rocks with low acid-neutralizing potential. In contrast, red areas infer bedrock with high magnetite content and corresponding high acid-neutralizing potential.

part by scale. Field susceptibility measurements sample only a very small volume of rock, and values can vary greatly due to relatively small changes in magnetic mineral content. In contrast, the susceptibility model based on airborne surveying represents the integrated response of magnetic properties within a much larger volume of rock (illustrated in fig. 6). Magnetic susceptibilities from the model do, however, fall within the range of susceptibilities measured in laboratory and field. The model calculations are reasonable values for the types of plutonic and volcanic lithology present in the watershed, and they produce a magnetic field that closely approximates the observed field. These factors support the assumption that the model susceptibilities provide a reasonable representation of rock magnetic properties within the near surface.

Figure 6. Sketch illustrating concept of bulk magnetic susceptibility versus magnetic susceptibility measured at outcrop. Measurements taken from an airborne magnetic sensor integrate effects from a much larger volume of rock compared to measurements taken at outcrop.

Geophysical Signatures of Geologic Features

This section presents an overview of the apparent resistivity and magnetic susceptibility signatures for approximately 40 geologic units organized under six major lithologic groups. These groups include Quaternary deposits, Eocene-Oligocene Helena volcanic rocks, Eocene Lowland Creek Volcanics, Upper Cretaceous Elkhorn Mountains Volcanics, Late Cretaceous Butte pluton granitic rocks, and Late Cretaceous polymetallic quartz veins (fig. 7). In addition, statistical approaches were used to define geophysical signatures of the

polymetallic quartz veins and to quantify geophysical gradient trends related to geologic structures.

Geophysical signatures for the geologic units are presented as box plot diagrams that present summary statistics. The resistivity (fig. 8) and magnetic susceptibility (fig. 9) charts are effective visual tools to illustrate the range in physical property variation inherent in a single geologic unit, showing similarities, differences, and overlap in geophysical signature among multiple units. Interpretation of the physical property characteristics is described in terms of the geologic factors and processes that influence the range of resistivity and magnetic susceptibility values. The diagrams were produced by determining the physical property values that had overlap with a particular geologic unit from 100×100 m grids of geology (Ruppel, 1963; Becraft and others, 1963), 7,200-Hz resistivity (fig. 2), and magnetic susceptibility data (fig. 5).

Quaternary Unconsolidated Deposits

Unconsolidated deposits are mainly glacial deposits and alluvial sediments found primarily on the valley floors. Low electrical resistivities characterize the Quaternary deposits; values average approximately 180 ohm-m. In general, the surficial deposits are electrically conductive (resistivity lows) relative to bedrock because of contained water, interconnected pore space, and predominance of clays. The chemistry and amount of the contained water can be highly variable and have a significant effect on the electrical properties of rocks. For example, if interstitial water is dilute, that is, free from salinity and dissolved metals, and there is little connected pore space, high resistivities will result. Alternately, as is likely the case for most of these unconsolidated deposits, the abundant pore space is connected and the sediments are saturated, resulting in a decrease in electrical resistivity.

There is considerable overlap between the resistivity of the unconsolidated deposits and that of many other geologic units, especially the Tertiary volcanic units (fig. 8). This overlap can be attributed to similar amounts of clays, which developed either as part of hydrothermal processes or from low-temperature weathering processes. Both processes can produce clays with similar resistivity ranges (Telford and others, 1976). Local resistivity anomaly highs that occur in valley floors are interpreted to be the resistivity response of shallowly buried bedrock that projects from adjacent hill slopes.

Although resistivity anomalies are produced from electrical property changes in the unconsolidated deposits, magnetic surveying is relatively insensitive to magnetic property changes in the sediments. Rather, the magnetic anomaly map is dominated by magnetic properties in the underlying bedrock because the unconsolidated deposits are effectively magnetically transparent owing to the relatively thin mantle of unconsolidated deposits in comparison to the volumetrically large underlying bedrock (Ruppel, 1963; Becraft and others, 1963). Although magnetite is present in the unconsolidated deposits, the amount of magnetite is not sufficient to cause significant magnetic anomalies.

Figure 7. Main lithologic units within area of airborne geophysical survey over the Boulder River watershed study area and surrounding region. Generalized from Ruppel (1963) and Becraft and others (1963).

Eocene-Oligocene Helena Volcanic Rocks

Rocks mapped as rhyolite intrusives (Tri) in the Helena volcanic field are generally some of the most resistive rock units in the study area (fig. 8). The largest Tertiary intrusive body in the study area is exposed at Red Mountain (fig. 7). A sample of intrusive rhyolite from the top of Red Mountain contained more than 75 percent SiO_2 . An altered counterpart to the fresh rhyolite collected on the southeast slope of Red Mountain contains a slightly higher (81 percent) but comparable amount of silica (Becraft and others, 1963, p. 30).

The large amplitude resistivity high (fig. 2), moderately low amplitude magnetic anomaly (fig. 4), and mineralogy at Red Mountain are evidence that silica-rich fluids were introduced as part of the alteration event. Silica-rich rocks typically have low magnetic susceptibility owing to their decreased magnetite content and high electrical resistivities (Telford and others, 1976).

In contrast, intrusions that are part of the Helena volcanic field that exhibit a much different geophysical signature and show evidence of a hydrothermal event with more potassium-rich fluids exist in other parts of the airborne geophysical

Figure 8. Electrical resistivity characteristics from 7,200-Hz resistivity grid (fig. 2) for geologic units within airborne geophysical survey. Geologic unit symbols from Ruppel (1963) and Becraft and others (1963). Unit descriptions in table 1.

Figure 9. Magnetic susceptibility and volume-percent magnetite estimates shown in figure 5 modeled from high-pass magnetic anomaly data (fig. 4) for geologic units within airborne geophysical survey. Geologic unit descriptions from Ruppel (1963) and Becraft and others (1963) and in table 1.

survey area. The most prominent of these are located east of Bison Mountain and north of the Boulder River watershed study boundary, in the northwestern part of the airborne geophysical survey. Very large amplitude “bullseye” resistivity and magnetic anomaly highs ringed by distinct resistivity and magnetic anomaly lows (fig. 2 and fig. 3, respectively) are located here, representing both extremes in highest and lowest modeled magnetic susceptibilities and electrical resistivity values. Although undivided Tertiary rhyolite (Tr) is mapped here (Ruppel, 1963), we interpret the geophysical anomalies to represent the response of a vent area with a large intrusive body at shallow depth. Geologic evidence for other vent areas along a northeast trend occurs in this area (O’Neill and others, this volume, Chapter D1). The resistivity anomaly high is interpreted to represent the electrical response of a more silicified cap over the intrusive center. Emplacement of the inferred intrusive has significantly altered the surrounding host rock resulting in the magnetic and resistivity lows that surround the circular geophysical highs. Additionally, the resistivity lows surrounding the source suggest that the hydrothermal fluids were not silica rich. Other areas with similar geophysical signatures occur over outcrops of undivided rhyolite rocks exposed at Lava Mountain and at Spruce Hills (fig. 7).

Eocene Lowland Creek Volcanics

Resistivity values have the greatest variability in rocks that form the Eocene Lowland Creek Volcanics. Relatively high resistivity values characterize the lapilli tuff (Tll) unit of Ruppel (1963), whereas very low resistivities characterize the volcanic sandstone (Tls) unit of Ruppel (1963). Chemical analyses of a sample of Tll (Ruppel, 1963, p. 49) showed exceptionally high percentage of silica, which is in agreement with the overall high resistivities that characterize this rock (fig. 8). Extremely low apparent resistivities occur over the volcanic sandstone unit (Tls). Average resistivity for this unit is 120 ohm-m and is consistent with resistivities expected for clays (Telford and others, 1976), which suggests that clays are well developed in this unit. Additionally, sedimentary rocks typically have lower resistivities compared to igneous rocks, owing to increased porosity.

The Lowland Creek Volcanics are characterized by low magnetic susceptibility values (fig. 9). The low values are the combined response from remanent magnetization and non-magnetic mineralogy. Total magnetization is a vector sum of induced (also called normal) magnetization (M_n) and remanent magnetization (M_r);

$$M_t = M_n + M_r$$

where normal magnetization is the product of the Earth’s magnetic field (H) and magnetic susceptibility (k);

$$M_n = kH$$

The magnetic susceptibility model (fig. 5) was calculated assuming that remanent magnetization is not a dominant factor in the plutonic and volcanic rocks in the study area and that normal magnetization, which is primarily a function of

magnetic susceptibility, is the main contributor to magnetic anomalies in the study area. This is true for most rock types in the study area. However, remanent magnetization is present in some units within the Lowland Creek Volcanics (Hanna, 1969), but it is of such low intensities that its contribution to total magnetization is minimal. Of more importance in explaining the magnetic anomaly lows (and low magnetic susceptibilities) that typify much of the outcrop of Lowland Creek Volcanics is the nonmagnetic mineralogy of the rocks. Average susceptibility for more than 80 outcrop measurements of Lowland Creek Volcanics is 0.00005 (cgs), which is 20 times lower than average susceptibilities of Elkhorn Mountains Volcanics, and 50 times lower in value than average susceptibilities measured in Butte pluton granitic rocks.

A large area of magnetic lows occurs over outcrops of Lowland Creek Volcanics in the vicinity of the Wickes mining district, located southeast of the Boulder River watershed, where rocks are pervasively altered (Becraft and others, 1963). The cause of the magnetic anomaly and magnetic susceptibility lows is the destruction of magnetite due to introduction of hydrothermal fluids, which have chemically removed magnetite.

Upper Cretaceous Elkhorn Mountains Volcanics

The range of resistivity and the magnetic susceptibility values for the units of Elkhorn Mountains Volcanics are similar in overall geophysical character to those of the Butte pluton units. However, some notable differences can be seen. As discussed in O’Neill and others (this volume), only the ash flow deposits of the middle member of the Elkhorn Mountains Volcanics were derived from the relatively silica rich magma that produced the Butte pluton. The other volcanic units in the group were derived from more mafic phases of the Boulder batholith, are less voluminous, and lie outside the geophysical study area.

Three units were grouped on the generalized geologic map by O’Neill and others (this volume, pl. 1) to define the middle member, Kevm; these include Kva1, Kva2, and Kv2 (table 1). The magnetic susceptibility ranges of the three map units (fig. 9) are almost identical, so a geophysical rationale exists for grouping these three units into one composite unit. Resistivity ranges for the three units also overlap (fig. 8). However, some areas of unit Kva2 have significantly higher resistivity values, suggestive of a more silica rich composition than the other two middle member map units have. Additionally, in the geology-based geoenvironmental map section (p. 110), we show that Kva2 is significantly different in chemical composition, enough to warrant a separate classification from the other units in this volcanic group.

Assuming that the middle member map units in the Elkhorn Mountains Volcanics were derived from a more silica rich phase of the Butte pluton, we expect that their magnetic susceptibilities would be lower and their resistivities higher in comparison with upper member units presumably derived

Table 1. Map symbols, descriptions, and average sum of percent calcium and iron from whole-rock chemical analyses of samples collected in and around the Boulder River watershed study area.

[Sum of calcium and iron reflects the presence of calcic and mafic mineral assemblages that provide significant ANP to low pH waters. Rocks with higher percentages of calcium and mafic minerals possess higher ANP. The chemical data are used to create the geology-based geoenvironmental map shown in figure 14. Relative ANP is defined in varying degrees: H, high; MH, moderately high; M, moderate; ML, moderately low; L, low. Leaders (--), samples not available for chemical analyses and no ANP assigned]

Geologic map symbol		Description	Percent Ca+Fe	Relative ANP
Original ^{1,2}	Generalized ³			
Quaternary alluvium and glacial deposits				
Qg ¹	Qg	glacial deposits	--	--
QTst ¹	Qg	gravel veneering strath	--	--
Qal ¹	Qal	alluvium	--	--
Qst ¹	Qal	fan gravel	--	--
Tertiary Helena volcanic rocks; rhyolite				
Trl ¹	Trl	lapilli tuff	--	--
Tri ^{1,2}	Tri	intrusive	1.9 ²	L
altered Tri ²	Tri	altered intrusive	0.6 ²	L
Trf ^{1,2}	Trf	flow	1.5 ¹	L
Trb ¹	Trb	flow breccia	--	--
Tr ^{1,2}	Tr	undivided	--	--
Tertiary Lowland Creek Volcanics; quartz latite				
Tli ¹	Tli	intrusive rocks	3.2 ^{1,2}	ML
Tlt ^{1,2}	Tlt	tuff	--	--
Tls ¹	Tls	sandstone	--	--
Tll ¹	Tll	lapilli tuff	0.5 ¹	L
Tlf ¹	Tlf	lava flow	--	--
Tlcd ¹	Tlcd	clastic dikes	--	--
Tla ¹	Tla	welded tuff	3.2 ¹	ML
Cretaceous Elkhorn Mountains Volcanics				
Kvt ¹	Kev	crystal tuff	--	--
Kv1 ¹	Kev	lapilli tuff	--	--
Kv ^{1,2}	Kev	undivided volcanics	--	--
Ki ²	Kei	rhyodacite porphyry	6.5 ²	MH
Kvi ¹	Kei	intrusive andesite	--	--
Kvib ¹	Kei	intrusive basalt	--	--
Kva1 ¹	Kevm	lower dark-gray and greenish-gray welded tuff	6.3 ^{1,4}	MH
Kva2 ¹	Kevm	upper medium- and light-gray welded tuff	5.1 ¹	M
altered Kva2	Kva2	upper medium- and light-gray welded tuff	1.3 ⁴	L
Kv2 ²	Kevm	light-greenish-gray to light-gray welded tuffs	6.1 ⁴	MH
Kv3 ²	Kevu	well-bedded dark-gray tuffs	9.1 ²	H
Kvs ¹	Kevu	andesitic sandstone	--	--
Cretaceous Butte pluton granitics				
cm ²	Kbm	undivided coarse and medium grained	6.3 ^{2,4}	H
altered cm ⁴	Kbm	undivided coarse and medium grained	2.3 ²	ML
cl ²	Kbm	coarse-grained light-gray biotite-hornblende	5.8 ^{2,4}	MH
cla ²	Kbm	coarse-grained light-gray biotite-hornblende	6.5 ²	MH
md ^{1,2}	Kbm	medium grained dark gray	5.7 ^{1,2,4}	MH
altered md ⁴	Kbm	medium grained dark gray	1.8 ²	L

Table 1. Map symbols, descriptions, and average sum of percent calcium and iron from whole rock chemical analyses of samples collected in and around the Boulder River watershed study area.—Continued

Geologic map symbol		Description	Percent Ca+Fe	Relative ANP
Original ^{1,2}	Generalized ³			
Cretaceous Butte pluton granitics—Continued				
mda ²	Kbm	medium grained dark gray	7.0 ²	MH
mdb ¹	Kbm	medium grained medium gray with pink tint	7.1 ¹	MH
mdc ¹	Kbm	medium grained with abundant mafic minerals	6.9 ¹	MH
ml ²	Kbm	medium grained light gray	3.1 ²	ML
mla ^{1,2}	Kbm	medium grained light gray, reddish-brown tint	4.4 ^{2,4}	M
ml ^d	Kbm	medium grained light gray with abundant biotite	--	--
g ¹	Kbm	fine to medium grained, dark gray	7.9 ¹	H
fl ^{1,2}	Kbf	fine grained light gray	5.0 ^{1,2}	M
fla ^{1,2}	Kbf	fine grained light gray porphyritic	--	--
flb ^{1,2}	Kbf	fine grained light gray with pink tint	4.6 ¹	M
flc ²	Kbf	fine grained light gray	4.3 ²	M
fd ^{1,2}	Kbf	fine grained dark gray	5.0 ^{1,2}	M
fda ²	Kbf	fine grained dark gray porphyritic	4.6 ²	M
a ²	Kba	alaskite, aplite, and pegmatite	0.8 ²	L

¹Ruppel, 1963. ²Becraft and others, 1963. ³O'Neill and others, this volume. ⁴Desborough, Briggs, Mazza, and Driscoll, 1998.

from a more mafic magma. However, the geophysical data suggest that the middle member units are more similar in geophysical character to the other units than the interpretation of the rock chemistry suggests.

Late Cretaceous Butte Pluton Granitic Rocks

In comparison to other granitic plutons of similar mineralogy, the Butte pluton is characterized by lower than normal resistivity values. The relatively low resistivity values initially puzzled us given that typical resistivities for similar granitic rocks are in the thousands of ohm-meters range (Telford and others, 1976). Resistivity for most of the Butte pluton granitic rocks ranges from approximately 300 to 800 ohm-m (fig. 8). The lower than average resistivity values determined from the airborne survey imply that the pluton has been greatly affected by surficial weathering, hydrothermal alteration, and fracturing within its upper 60 m. Clays, which result from either low-temperature weathering or hydrothermal processes, tend to lower the resistivity of igneous and volcanic rocks. Consequently, altered volcanic and plutonic granitic rocks are typically less resistive (more conductive) in comparison with their fresh unaltered state. Direct current electrical resistivity soundings made from ground measurements on the Butte pluton confirm that the electrical resistivity of the first 30 m is on the order of 200 to 300 ohm-m in many places, again much lower than expected (Smith and Sole, 2000).

Studies of magnetic properties of Butte pluton granites show that these rocks possess normal polarity and that intensities of remanent magnetization are negligible (Hanna and others, 1994). The intensities present in the form of normal

magnetizations are strong enough to contribute significantly to magnetic anomaly intensities. Consequently, magnetic anomalies over the pluton can be chiefly explained by magnetite content. Granite that contains more magnetite has a stronger magnetization and results in a more positive (larger amplitude) magnetic anomaly. In granite that has undergone chemical alteration, whether hydrothermal or deuteric, primary magnetite has been destroyed and the rock is associated with a more negative (lower amplitude) magnetic anomaly (Hanna, 1969). Alteration typically causes conversion of magnetite to nonmagnetic, more highly oxidized and hydrated iron-oxide minerals such as limonite (Ruppel, 1963). In cases where redox conditions are reducing, magnetite can be destroyed as its iron is reduced. The resulting ferrous iron is combined with sulfur to form pyrite (Desborough and Driscoll, 1998). Overall, the resulting geophysical effect of the alteration processes is a reduction in magnetization and a corresponding lowering of the intensity of the magnetic anomaly. A detailed analysis of magnetite content within the environmentally important Butte pluton follows in a later section.

Late Cretaceous Polymetallic Quartz Veins

Two types of veins cut the Butte pluton granitic rocks of the study area. East-trending polymetallic quartz veins host the ore deposits exploited by mining. Generally northeast trending chalcedony veins that are not mineralized also cut the granitic rocks. Geologic characteristics associated with mining the east-trending polymetallic quartz veins exert the most negative impact on the surface-water quality in the Boulder River watershed study area. Water draining from mines, adits,

and waste associated with the polymetallic veins is a major source for acidic and metal-rich surface waters (Nimick and Cleasby, this volume, Chapter D5; Kimball and others, this volume, Chapter D6). Geophysical characteristics that define these mineralized veins include low magnetic susceptibilities (fig. 9) and moderately high resistivities (fig. 8). The statistical summaries presented in the resistivity and magnetic susceptibility diagrams are useful to view the range of physical properties that characterize a particular feature, but they do not allow for a comprehensive understanding of how “distinct” or characteristic these signatures are in comparison with geophysical signatures of other geologic features.

To quantify how characteristic (or not) low magnetic susceptibilities and high resistivities are of the mineralized veins, we applied a statistical approach using methodology developed by Lee and others (2001) to the resistivity (fig. 2) and magnetic susceptibility data (fig. 5). The approach uses a ratio of probabilities, also called weights (W), to describe the statistical likelihood of a class of a particular evidential layer having a spatial association with a given prototype area. For this study, the evidential layers are the magnetic susceptibility and resistivity data, and classes are defined as values within these data. Prototypes against which we compare the evidential layers include locations of polymetallic quartz veins and nonmineralized chalcedony veins (Ruppel, 1963; Becraft and others, 1963).

Weights fall within three general categories that describe the spatial association:

- a positive spatial association exists if $W > 1$;
- a negative spatial association exists if $W < 1$; and
- a random association is present if $W = 1$

To illustrate, a weight of 30 would suggest that a particular class, high values of resistivity, for example, within a geophysical data layer would be 30 times more likely to be associated with a particular mineral deposit than any other feature in the study region.

The geophysical signatures of nonmineralized chalcedony veins were examined to determine if the two vein types could be distinguished on a geophysical basis.

Histograms that describe the spatial association between the resistivity and magnetic susceptibility data and polymetallic quartz and chalcedony veins are shown in figure 10. Results show that moderately high resistivities, in the range of 1,750 to 2,500 ohm-m, characterize the polymetallic quartz veins. Resistivities for the nonmineralized chalcedony veins show a strong spatial association ($W > 1$) with a slightly lower resistivity range (1,050 to 1,700 ohm-m). High electrical resistivities that characterize both vein types may reflect the presence of resistive gangue minerals (quartz) and low porosity of the vein material.

Polymetallic quartz veins are characterized by very low magnetic susceptibilities (fig. 10). Model magnetic susceptibilities that characterize the mineralized veins range from -0.0059 to -0.0026 (cgs). This range of values is interpreted to be a combined effect of demagnetization of once magnetite-rich host rock from hydrothermal alteration processes and

the nonmagnetic mineralogy of the vein material. In contrast to the resistivity signature, no particular magnetic susceptibilities characterize the chalcedony veins as evidenced by the random spatial associations defined by weights that fluctuate around the value of 1 (fig. 10). The lack of distinct magnetic signature of the chalcedony can be attributed to the narrower alteration envelopes surrounding the chalcedony veins compared to the wider alteration envelopes surrounding the polymetallic quartz veins (Becraft and others, 1963). Fluids associated with the emplacement of the chalcedony veins only locally altered the country rock. In contrast, fluids associated with the emplacement of the polymetallic quartz veins had a more profound effect on the wall rock, resulting in larger alteration envelopes and greater modification of host rock magnetic mineralogy (Becraft and others, 1963).

Geologic Structures and Geophysical Trends

Obvious features in the geophysical maps are linear gradients that trend over kilometers. Many gradients and narrow elongate anomalies define faults and structures that map contacts between rocks with different resistivity or magnetic properties. Faults can be expressed as linear resistivity lows if the degree of fracturing is high (equivalent to high porosity), clay has developed from weathering or alteration processes, and (or) water is present. Alternately, fault zones that contain silicified fractures, are dry, and have little clay present commonly are expressed as resistivity highs. Resistivity values can be orders of magnitude higher in dry, unfractured rock in contrast to wet and fractured rock (Olhoeft, 1985). The magnetic expression of faults depends on the magnetic properties of the adjacent rocks. If a fault juxtaposes rocks with similar magnetic properties, no magnetic expression of the geologic contact is likely. However, if a nonmagnetic rock is adjacent to a highly magnetic rock type, a distinct magnetic gradient will mark the fault contact.

Geophysical gradient trends are defined as distinct linear and curvilinear elements that can be mapped from contours in the geophysical data (Grauch, 1988). Figure 11 shows geophysical trends calculated from grids of the 7,200-Hz apparent resistivity (fig. 2) and RTP magnetic anomaly data (fig. 3). Dominant geophysical trend directions are co-linear with the orientation of three major fracture systems in the region. These orientations include a set of northeast- and northwest-trending structures, and a third east-trending set. The three principal fracture systems likely reflect deep-seated and reactivated structures related to emplacement of the Boulder batholith and to have been active recurrently since the Proterozoic (O'Neill and others, this volume).

Dominant orientations of geophysical gradients are northwest and west-northwest. The northwest-trending gradients are partly co-linear with faults and lineaments mapped by Smedes (1966) and lineaments mapped from remote sensing data within and around the Boulder River watershed study area (McDougal and others, this volume, Chapter D9). Although

Figure 10. Statistical probabilities (weights) that describe the spatial association between *A*, resistivity, or *B*, magnetic susceptibility and mineralized polymetallic (red) or nonmineralized (blue) veins. The greater the weight, the stronger the spatial association. Low values of magnetic susceptibility, in the range of -0.0049 to -0.0022 , are two to fourteen times more likely to occur over the polymetallic veins than any other geologic feature in the study. Alternately, the nonmineralized veins have no characteristic magnetic susceptibility signature; a weak to random spatial association exists as evidenced by weights around the value of 1. Results of the modeling for resistivity data show that both vein types are strongly associated with moderately high values of resistivity.

Figure 11. Geophysical gradient trends from *A*, grids of reduced-to-pole magnetic anomaly (fig. 3) and *B*, 7,200-Hz apparent resistivity data (fig. 2); both plotted in 10 increments. Colors indicate increments of geophysical trends co-linear with trends of mapped geologic features.

the mapping performed by Smedes lies outside the Boulder River watershed study, a similar structural and geologic setting exists in our study area (O'Neill and others, this volume). The less dominant geophysical gradient trend direction is northeast, which is co-linear with trends of alaskite dikes and chalcedony veins mapped in the Jefferson City quadrangle (Becraft and others, 1963).

The preferred northwesterly trend in the geophysical data is not obvious in the geology or mapped structures for the area (Ruppel, 1963; Becraft and others, 1963) but is reflected in topography. Streams form a northeast-northwest rectilinear drainage pattern in parts of the study area, and some linear magnetic and resistivity lows follow segments of this drainage network. Details pertaining to the structures along the drainages are poorly understood because the structures are partly or entirely concealed by younger volcanic rock or surficial deposits.

One interpretation for the strong northwest-trending linear magnetic lows is destruction of magnetite in shear zones. Zones of major tectonic adjustment may be expressed in magnetic maps as linear magnetic anomaly lows, especially if

these zones were affected by recurrent thermal activity. Ruppel (1963) and Becraft and others (1963) interpreted the rectilinear drainage pattern to reflect structurally weak zones that have persisted as controlling structures since the Proterozoic. These zones are characterized by steeply dipping deep-seated faults that were first formed in the Proterozoic and reactivated during the emplacement of the Boulder batholith. The presence and distribution of elongate breccia pipes (Ruppel, 1963) provide supporting evidence of the northeast-trending structural zones.

East-trending resistivity and magnetic anomaly gradients define a third trend set (fig. 11). These geophysical trends parallel shear zones that host the polymetallic mineralized veins. Unlike the northwest- and northeast-trending magnetic gradients, which mostly coincide with the drainages, the east-trending shear zones cross a variety of topography. Many of the mapped mineralized veins coincide with linear magnetic anomaly lows and likely reflect the destruction of magnetite in adjacent wall rock and the nonmagnetic mineralogy of the vein material.

A fourth minor gradient trend set in the magnetic and resistivity data generally is co-linear with structures host to Tertiary dikes (Becraft and others, 1963) (this report, fig. 11).

The spatial association of linear magnetic and resistivity trends in the watershed with known geologic structures strongly implies that geophysical gradients mark locations of faults and fractures. As is evident in the resistivity and magnetic anomaly maps for the watershed (figs. 1 and 2), linear geophysical gradients greatly outnumber structures mapped at the surface (O'Neill and others, this volume, pl. 1). Implications for fractures and faults as related to the important issue of ground-water flow and quality are discussed in McDougal and others (this volume).

Geology-Based Geoenvironmental Map

Impact of a mine or mineralized terrain on the environment is controlled in large part by the geologic landscape. The environmental behavior of geology in a mineralized terrain is effectively portrayed in a study that assessed the potential impact of mining in Montana on surface water quality (Lee and others, 2001). The statewide study used geologic, geochemical, and geophysical information in conjunction with a predictive methodology to model the environmental behavior of geologic units that host metal-sulfide-rich deposits. An important aspect of the study included an effort to predict the environmental behavior of geologic units by classifying rocks in terms of acid-neutralizing or acid-generating potential, which was based on estimated amounts of calcium- or sulfide-bearing minerals expected for the various rock formations. Classifications used a ranking scheme (high, moderate, low) largely determined by knowledge provided by scientists with expertise and experience with Montana geology. The availability of new high-resolution geophysical data, detailed geologic maps, and whole-rock chemistry data in the Boulder River watershed study area allowed us to use an approach similar to the State study but at a more detailed scale.

Water quality is generally good in most of the major streams in the watershed based upon water-quality criteria established for aquatic life, although water quality is degraded downstream of some mine sites such as the Bullion, Crystal, and Comet mines (Nimick and Cleasby, this volume; Kimball and others, this volume). The effects of metal-rich, acidic mine drainage on surface water are thought to be naturally mitigated (Nimick and Cleasby, this volume) by acid-consuming minerals present in fresh granitic and volcanic rocks (Desborough, Briggs, Mazza, and Driscoll, 1998). Clearly, the mineralogy of the rocks in mine-waste piles and in those that underlie mine sites influences the quality of surface water and naturally exacerbates or mitigates the effects of high metal concentrations and acidity. We developed a geology-based geoenvironmental map portraying the rock unit characteristics to examine the

spatial relation between environmental characteristics of the geology and water quality.

Acid-Neutralizing Potential

Estimating Acid-Neutralizing Potential

Acid-neutralizing potential (ANP) is an important environmental property of rock units because it can greatly influence water quality in mineralized areas such as the Boulder River watershed. However, ANP is not mapped routinely by field geologists. Therefore, a method was needed to estimate ANP from geologic information traditionally collected in the field. For this study, we combined the geologic map units of Ruppel (1963) and Becraft and others (1963), based in large part on grain size and mineralogy within formations, with rock chemistry data to develop a geoenvironmental map showing ANP.

Ruppel (1963) and Becraft and others (1963) mapped the Butte pluton granitic rocks based on mineralogy, color, and grain size. Mineralogy and color are important for estimating ANP because these qualities have direct bearing on the abundance of mafic minerals related to acid-consuming mineralogical assemblages. Grain size is important not only because different grain-size phases contain different mineral assemblages but also because grain size influences the geophysical signature and allows geophysical data to distinguish rock units, as described in a later section.

In the Boulder River watershed study area, ANP is provided by a suite of acid-consuming minerals. Calcite is present in minor amounts as interstitial fillings in fresh Butte pluton granitic rocks (Desborough, Briggs, and Mazza, 1998). Calcite is an important acid-consuming mineral because of the acid-neutralizing potential of the carbonate ion. Mafic minerals—including biotite, hornblende, tremolite, chlorite, and feldspars—are also important (Desborough, Briggs, Mazza, and Driscoll, 1998) because acid is consumed and bicarbonate ions are produced as these minerals weather. In addition, some mafic minerals, such as biotite, tremolite, and chlorite, contain hydroxide ions. Both bicarbonate and hydroxide ions can neutralize acid and thus mitigate the effects of metals in water through chemical bonding.

Quantitative data on abundance of acid-consuming minerals are not available for the mapped rock units. However, chemical data for rock units are available. Concentration data for key major elements can be used as indicators of the abundance of the acid-consuming minerals. Calcium and (or) iron are important major elements in calcite, plagioclase feldspars, and mafic minerals but not in other minerals, such as quartz or potassium feldspar, which have little acid-neutralizing potential. Therefore, calcium and iron are used as indicator elements to estimate the relative ANP of the rock units mapped by Ruppel (1963) and Becraft and others (1963).

Iron and calcium percentages were obtained from (1) chemical analyses made during the original geologic mapping efforts that provide the geologic framework for this study (Ruppel, 1963; Becraft and others, 1963) and (2) analyses of samples and core analyzed for the Boulder River watershed study (Desborough, Briggs, and Mazza, 1998; Desborough, Briggs, Mazza, and Driscoll, 1998; Desborough and Driscoll, 1998). Figure 12 shows the relation between ANP measured in leachate studies, and the sum of calcium and iron concentrations in samples of plutonic and volcanic rock units. Although traditional ANP data expressed in percent calcite equivalent are not available for these samples, results of a leach experiment that used an acidic (pH=2.9) leachate demonstrate the relation between calcium, iron, and pH.

Whole-rock chemistry data are available for 26 geologic units that cover approximately 70 percent of the geophysical survey area. Sampling is admittedly sparse and restricted to a meager one to four samples per unit. Although too few samples are available to determine statistical significance, in

principle, the rocks collected were considered representative of the overall unit. Consequently, we assume that the chemical signature is generally representative for a given unit. A listing of map symbols and descriptions for geologic units referred to in this report, as well as the average sum of calcium and iron concentrations, are given in table 1.

A relative ANP rank was assigned to each map unit on the basis of calcium and iron concentration. These data also are shown in figure 13 (top chart). Geologic units not sampled and therefore not assigned environmental characteristics include unconsolidated Quaternary alluvial and glacial deposits with unknown, or perhaps heterogeneous, acid-neutralizing potential.

Relative degrees of ANP are portrayed in the geoenvironmental map (fig. 14) as shades of green—lighter hues indicate rocks with high acid-neutralizing potential (relatively high percent of mafic and calcic minerals) whereas dark green infers rocks with relatively low ANP (low percentages of mafic and calcic minerals).

Figure 12. Relation of calcium and iron content to pH of acidic mine-waste leachate after 24 hour exposure for fresh Butte pluton granitic rocks, Elkhorn Mountains Volcanics, and altered Elkhorn Mountains Volcanics (Desborough, Briggs, and Mazza, 1998).

Figure 13. Relative acid-neutralizing potential of geologic units. *A*, based on whole-rock chemistry (table 1); *B*, based on volume-percent magnetite calculated from the magnetic susceptibility model (fig. 5) for the same geologic units. Geologic symbols are from Ruppel (1963) and Becraft and others (1963) and described in table 1. Red squares in *B*, percent magnetite as measured from rock samples (Becraft and others, 1963). Data from *A* were used to make the geoenvironmental map in figure 14.

Figure 14. Geology-based geoenvironmental map showing relative acid-neutralizing potential of geologic units based on percentages of calcium and iron (table 1 and fig. 13). Acid-generating polymetallic quartz veins also shown.

Acid-Neutralizing Potential of Rock Units

The Butte pluton plays an important environmental role in the watershed. Geologically, it hosts the acid-generating polymetallic quartz vein deposits. Chemically, it contains minerals that provide significant acid-neutralization and thus has ANP comparable to that of many calcite-rich sedimentary rocks (Desborough, Briggs, and Mazza, 1998; Desborough, Briggs, Mazza, and Driscoll, 1998). This ANP likely is the reason that few streams in the Boulder River watershed study area have acidic pH (Nimick and Cleasby, this volume). Geographically, the Butte pluton is the largest pluton of the Boulder batholith, covering an area 17×51 km, which represents approximately 73 percent of the outcrop of the Boulder batholith in southwest Montana (O'Neill and others, this volume, pl. 1). It crops out in approximately 44 percent of the area covered by the geophysical survey, and 36 percent of the area within the Boulder River watershed; it also underlies younger rocks exposed at the surface.

Relative acid-neutralizing potential for the Butte pluton granitic rocks is variable but roughly correlates with age of emplacement; early-stage mafic intrusions have higher relative ANP compared to later stage silica-rich granitic phases (fig. 13). Rocks of the earliest stage of intrusion, designated as "g" in Ruppel (1963), have the highest relative ANP for all rocks in the Butte pluton and second highest relative ANP for rocks in the study area (fig. 13). The medium- to coarse-grained granitic rocks represent the most voluminous mafic phase of the pluton and are the dominant rock types in the study area, constituting more than 90 percent of the pluton outcrop. Most of the coarse- and medium-grained units contain 6–8 percent calcium and iron and are interpreted to have moderately high to high ANP (table 1). Volumetrically significant exceptions are the ml and mla units (table 1). These medium-grained units are rather widespread, making up approximately 7 percent of the area covered by the airborne survey, although much of the ml unit lies outside the Boulder River watershed in the adjacent Prickly Pear Creek watershed. Whereas most of the coarse- and medium-grained phases contain more than 6 percent iron and calcium, the ml unit is characterized by half as much iron and calcium. Both the ml and mla units are host to a number of mineralized veins. We would expect that acid- and metal-rich waters draining from veins hosted in these rocks would be neutralized, but not as quickly as similar contaminated water draining off veins hosted in the other coarse- and medium-grained phases of the pluton.

The fine-grained plutonic units (fl, flb, flc, fd, and fda) are chemically indistinguishable from each other and are characterized by iron and calcium contents that average 4.5 percent. These facies would be interpreted to have consistently lower relative ANP than most of the medium- or coarse-grained phases.

The most silica rich units in the pluton consist of aplite. The aplites represent a less mafic, more alkali rich phase interpreted to have been formed from a later stage magma (Ruppel,

1963). Aplitite is interpreted to have the lowest ANP of all the granitic phases in the pluton. It is also the least voluminous unit in the Butte pluton, at less than 2 percent of mapped outcrops.

Rock samples with the highest average percentage of iron and calcium and therefore interpreted to have highest ANP are those from rocks of the Elkhorn Mountains Volcanics (fig. 13). Samples of interbedded tuffs (Becraft and others, 1963, map unit Kv3) contain an average of 9 percent calcium and iron. The area of outcrop for this unit is quite large, covering approximately 5 percent of the airborne geophysical survey area, although the majority lies outside the Boulder River watershed in the Prickly Pear Creek watershed to the east. Overall, the mineralogy of the Cretaceous volcanic units is similar to that for the Butte pluton because both are part of the same magmatic system (Roberts, 1953; Klepper and others, 1957; Robinson, 1963; Smedes, 1966). However, one unit of Elkhorn Mountains Volcanics has relatively low ANP in comparison with the other volcanics. Samples of the upper welded tuff unit (Kva2) that crops out near Jack Mountain and is presumably unaltered contain less than 2 percent calcium and iron (fig. 13), similar to the Tertiary volcanics and altered plutonic rocks with lowest ANP in the study. Altered samples of the same rock type (altered Kva2) taken near the top of Jack Mountain (Desborough, Briggs, and Mazza, 1998) show even lower percentages of calcium and iron (slightly more than 1 percent).

The acid-neutralizing effect of the Cretaceous and Tertiary volcanic units on metalliferous and acidic water draining the mineral deposits exposed by mining and waste piles is not as critical as that of the Butte plutonic rocks. This is because the Cretaceous and Tertiary volcanic rocks are located stratigraphically and topographically above the acid-generating mineralized veins. Nonetheless, water draining through and downgradient from these rock units would presumably have some mitigating effect on water quality (O'Neill and others, this volume).

Along with providing an in-place understanding of environmental characteristics of the geology, an environmental geology map can provide scientific information for other uses. For example, information provided on the map could be used to evaluate rock suitability for engineering purposes. Some units in the Elkhorn Mountains Volcanics may be suitable sources for material to line a waste-rock repository given other cost and logistic considerations. So, although the Elkhorn Mountains Volcanics do not have as direct an influence on water quality, their geologic characteristics do have implications for other uses.

Rocks with the lowest percentages of calcium and iron and interpreted to have the lowest ANP in the study include Tertiary volcanic units within the Lowland Creek Volcanics and the Helena volcanic field (fig. 13). The volcanic rocks are characterized by high silica content (Ruppel, 1963) that provides little acid neutralization.

A significant reduction in iron and calcium minerals occurs when a rock is altered by hydrothermal fluids

(Desborough, Briggs, and Mazza, 1998; Desborough and Driscoll, 1998), resulting in low ANP. Iron and calcium percentages from altered rock samples are shown in figure 13 for four rock types (cm, md, Kva2, and Tri). In all four cases, the percent of calcium plus iron is significantly lower in the altered sample (30 to 60 percent less) compared to its unaltered counterpart.

Acid-Generating Potential

Acid-generating sources in the watershed are Late Cretaceous polymetallic quartz veins and associated waste piles that contain abundant pyrite and varying amounts of other sulfide minerals (Ruppel, 1963; Becraft and others, 1963; O'Neill and others, this volume). The veins cover less than 1 percent of the surface area in the Boulder River watershed, but oxidation of mine waste caused by near-surface weathering and mining activity has produced metal-rich acidic water. The metal-laden water that enters the main drainages and tributaries (Nimick and Cleasby, this volume) adversely affects aquatic health (Frag and others, this volume, Chapter D10).

Evidence for other acid-generating sources occurs (1) in the Helena volcanic rocks near the Basin Creek mine where disseminated pyrite is associated with mineralization (Ruppel, 1963) and (2) in altered Elkhorn Mountains Volcanics rocks near the Buckeye and Enterprise mines (O'Neill and others, this volume).

Effect of Acid-Neutralizing Minerals on Aquatic Health

The presence and quantities of iron and calcium in mafic and calcic minerals that are commonly found in the plutonic and volcanic rocks in the Boulder River watershed have a bearing on water quality and aquatic health. Iron or calcium is present in biotite ($(\text{K}(\text{Mg}, \text{Fe}^{+2})_3(\text{Al}, \text{Fe}^{+3})\text{Si}_3\text{O}_{10}(\text{OH})_2)$), tremolite ($(\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2)$), and chlorite ($(\text{Mg}, \text{Fe}^{+2}, \text{Fe}^{+3})_6\text{AlSi}_3\text{O}_{10}(\text{OH})_8$). These minerals also contain hydroxide ions (OH^-), which have the ability to raise water pH and mitigate deleterious effects of metals in the water. When hydroxide ions are exposed to acidic water, they are free to combine with hydrogen ions (H^+), raising the pH of the water. Chlorite has abundant hydroxide ions and is ubiquitous in the Butte pluton rocks. Chlorite is derived from primary mafic minerals such as hornblende and formed during regional metamorphism due to heating during late magmatic activity in the Boulder batholith.

Additionally, calcium is connected to the environmental signature of a rock through the role of bicarbonate ions (HCO_3^-) in the neutralizing process. Bicarbonate forms complexes with several potentially toxic metal ions (Cd, Cu, Zn), thereby reducing the toxicity of these metals in surface water to aquatic life. One source for bicarbonate is in minor amounts of interstitial calcite in fresh Butte pluton granitic rocks (Desborough, Briggs, and Mazza, 1998).

Calcium, Iron, and Geophysical Response

For volcanic and plutonic rocks in the Boulder River watershed study area, variations in calcium and iron content correlate with quantities of other minerals that strongly influence geophysical response, specifically silica and magnetite. Although electromagnetic and magnetic surveys are not sensitive to calcium content as such, elevated amounts of calcium correspond to a decrease in silica (fig. 5 in O'Neill and others, this volume). Silica acts as an electrical insulator; electrical current does not pass easily through it. Consequently, rocks with high amounts of silica will typically produce resistivity anomaly highs. Silica-rich rocks in the watershed study area also produce lower amplitude magnetic anomalies in comparison with more mafic rock phases, primarily owing to lower magnetite content.

As discussed in the previous section, iron in volcanic and plutonic rocks is derived from a number of minerals that provide acid neutralization. Iron is a main constituent in magnetite (Fe_3O_4), which does not provide acid neutralization but is present in association with the minerals that do. In the following section, we discuss the importance of magnetite in terms of geophysical signature and relate magnetite to acid-neutralizing potential.

Geophysical Magnetite Maps

“Cored rocks that had the highest acid-neutralizing potential (for example, near Bullion mine) had abundant magnetite in heavy-mineral concentrates made from these rocks, whereas those with low acid-neutralizing potential contained no magnetite in the heavy-mineral concentrates” (O'Neill and others, this volume).

This section investigates the hypothesis presented by our colleagues—that magnetite content may be indicative of granitic rock alteration and thereby relate to a rock's ability to provide acid neutralization. By transforming the resistivity and magnetic anomaly data to maps of magnetite distribution, we can make the geophysical magnetite maps function as proxy ANP maps. In the previous section, information from rock chemistry provided a mineralogical rationale to define acid-neutralizing potential. However, with so few rock samples and the presence of glacial, alluvial, and tree cover, variations in environmental properties of underlying bedrock were impossible to discern in the field for much of the study area. The detail provided in the geophysical survey and the ability of geophysical methods to “see” beneath much of the problematic vegetation and rock cover provide a means to continuously map major to minor variations in rock environmental properties. Information extracted from the geophysical survey can be used as an indirect measuring tool of mineralogical properties in that magnetite is used as an indicator for other important acid-consuming minerals.

Magnetite Estimates from Magnetic Susceptibility Model

Magnetic susceptibility is, to a large degree, a measure of magnetite content. For rocks whose concentrations of magnetite lie between 0.1 and 10 percent, volume percentage of magnetite (Vm) can be estimated from susceptibility (k in cgs) with the following equation:

$$Vm = 400k \text{ (modified from Balsley and Buddington, 1958)}$$

Estimates for volume percent magnetite were determined from the grid of magnetic susceptibility data using this equation. Model magnetic susceptibilities were given in relation to percent magnetite in the map shown in figure 5 and for geologic units in figure 9. Negative magnetic susceptibilities were set to zero.

Magnetite content derived from the magnetic susceptibility model was compared to magnetite content determined visually from thin sections for a limited number of rock samples. The lower chart in figure 13 shows rock sample percent magnetite for 12 rock samples (Becraft and others, 1963) compared to model susceptibilities. Analyses were available for nine Butte pluton units. Magnetite contents measured for the 12 rock samples fall either within or very near the range for a given unit (fig. 13B), signifying that the susceptibility model is, at the very least, a reasonable representation of magnetite distribution in the watershed.

Magnetite Estimates from 900-Hz Apparent Resistivity Data

Magnetite, because of its electrical properties, is the only mineral that causes observed negative in-phase anomalies in horizontal coplanar resistivity data. As part of the airborne survey contract with the USGS, estimates of apparent volume percent magnetite are available (Smith and others, 2000). Magnetite estimates were determined by identification of negative in-phase anomalies in the 900-Hz resistivity data and by application of a calculation based on methodology in Fraser (1981). The estimates are *apparent* because they are based on a theoretical model and provide only a relative gauge of magnetite content. Estimates for magnetite are restricted to rocks located to a maximum depth of 60 m.

The method has limitations under certain geologic conditions. The greatest constraint for use of this method in our study area relates to the low resistivities of many of the volcanic rocks. Unreliable magnetite estimates result for rocks with resistivities of less than 500 ohm-m (Fraser, 1981). For this reason, only pixels within the EM magnetite grid that coincide with resistivities greater than 500 ohm-m are shown in figure 15, with the consequence that 46 percent of the area within the airborne geophysical survey was excluded. Most of the excluded area is over rocks within the Helena and Elkhorn Mountains volcanic fields. The low resistivities of the volcanic units are attributed to the greater development of clays from surface weathering and alteration processes.

Magnetite estimates in the EM magnetite model are unrealistically low in comparison with magnetite concentrations determined from rock sample modal analyses (Becraft and others, 1963; Desborough, Briggs, and Mazza, 1998) but are interpreted to reflect *relative* amounts of magnetite within rocks located within 60 m of the surface. Attenuated (low) EM magnetite values can occur in rocks that are very magnetic, where error from strong magnetic polarization exists, and over rocks where the electromagnetic sensor height exceeds 45 m (Fraser, 1981).

Within the Boulder River watershed study area, the granitic units of the Butte pluton are characterized by high EM magnetite values and are in general agreement with high percent magnetite values calculated from the magnetic anomaly data (fig. 9). Outside the watershed boundary, in the adjacent Prickly Pear Creek watershed to the east and Tenmile Creek watershed to the north, most of the Butte pluton outcrop is associated with very low to zero-percent apparent magnetite anomalies. Much of the low percent magnetite occurs over the *m1* unit, west of Lava Mountain, which also has a correspondingly low magnetic signature (fig. 9) and low percent magnetite as determined from rock sample analysis (fig. 13B).

Relationship of Magnetite to Alteration Processes

Mineralization, metamorphism, and magmatic processes have altered the original mineralogical composition of plutonic and volcanic rocks in the study area. Locations of altered Butte plutonic rocks related to Late Cretaceous mineralization were mapped in the eastern part of the study area but are limited to narrow envelopes surrounding a select number of mineralized veins studied in detail in the Jefferson City quadrangle (Becraft and others, 1963). As part of the detailed study of polymetallic quartz veins and wall rock alteration, Becraft and others (1963) collected samples of Butte pluton granitic rocks adjacent to well-exposed mineralized veins, sampling from the veins outward to rock least affected by alteration processes. Results of our study provide an understanding of the relationship between alteration mineral assemblages and magnetite abundance. Within the alteration envelope, three zones are observed and include, from most altered to least altered, a sericitic zone, an argillic zone, and a chloritic zone. "Least altered" describes granitic rocks that appear unaffected by surface weathering or sulfide mineralization. Mineralogical analyses show that within zones of argillic alteration, magnetite is absent. This concept is illustrated in figure 16.

Evidence for alteration of the original mineralogy due to metamorphism is present in units of the Elkhorn Mountains Volcanics where chemical analyses show metamorphosed samples are more silicic (less mafic) than unmetamorphosed samples (Ruppel, 1963). Metamorphism was caused by the intrusion of the Butte pluton into the Elkhorn Mountains Volcanics. The metamorphosed samples also show a

Figure 15. EM magnetite anomaly calculated from 900-Hz resistivity data where resistivity is greater than 500 ohm-m. White areas within airborne geophysical survey are characterized by low resistivities and result in unreliable EM magnetite estimates. Values for percent magnetite are given at locations of rocks analyzed for acid-neutralizing potential (table 2). Low EM magnetite estimates are combined with areas of high resistivity to map locations of silica-rich rock units with inferred low acid-neutralizing potential.

significant (30–80 percent) decrease in iron oxides, which likely reflects a decrease in magnetite content as well.

Alteration in which hydrothermal fluids were dominantly silicic rather than potassic or alkalic is present in altered rocks within the Elkhorn Mountains Volcanics. Chemical analyses of altered rocks from the top of Jack Mountain show no magnetite present in heavy-mineral concentrates (Desborough, Briggs, and Mazza, 1998).

O'Neill and others (this volume) discuss two other alteration events that altered the mineralogy of some of the Butte plutonic rocks. Several areas mapped in the southern part of the study area contain zones of alteration, but no samples were collected to determine magnetite content.

Figure 16. Persistence of minerals in alteration zones from a suite of Butte pluton rocks measured from polymetallic quartz veins (most altered) outward to granitic rocks least affected by alteration. Modified from Becraft and others (1963) to show persistence of magnetite, corresponding geophysical signatures, and relative acid-neutralizing potential. Gradient regions indicate range of relatively high mineral abundance; solid lines indicate minor amounts of minerals.

Relationship of Magnetite to Environmental Rock Properties

Magnetite provides a means to connect geophysical signatures with important environmental rock properties. Geochemical investigations conducted as part of the Boulder River watershed study illustrate the connection between the presence of magnetite and corresponding acid-neutralizing potential for Butte pluton granitic rocks and other rock types. Rock samples of fresh and altered rock collected from drill core as well as surface outcrop samples were chemically analyzed to determine mineralogical characteristics associated with acid-neutralizing potential (Desborough and Driscoll, 1998; Desborough, Briggs, and Mazza, 1998; Desborough, Briggs, Mazza, and Driscoll, 1998). Table 2 compares the results of the leachate studies to determine ANP with values for percent magnetite as calculated from the geophysical data. Localities of the leachate samples are shown on the magnetic susceptibility model (fig. 5) and the EM magnetite map (fig. 15).

Although too few samples were analyzed to provide confident statistical conclusions, we can make some relevant and consistent observations regarding presence of magnetite, acid-neutralizing potential, and geophysical signature. For the 12 samples of unaltered Butte pluton granitic rock that lie within the airborne survey area, relatively high values from the EM magnetite anomaly data (0.24–0.86 percent, with an average of 0.44 percent) correspond with high acid-neutralizing potential as calculated from whole-rock chemistry. Percent magnetite derived from the magnetic susceptibility data for fresh Butte pluton rocks ranges from 1.12 to 1.83 percent, with an average value of 1.55 percent. All samples of these fresh rocks contain magnetite in the heavy-mineral concentrates. Unfortunately, no samples of *altered* Butte pluton granitic rocks were analyzed for acid-neutralizing potential.

Percent magnetite calculated from the apparent resistivity data for unaltered Elkhorn Mountains Volcanics shows that these rocks have slightly higher EM magnetite anomaly values (average 0.09 percent) than their altered counterparts (average 0.03 percent). Magnetite estimates for sample localities

Table 2. Relative acid-neutralizing potential from analyses of surface and core rock samples collected in and around the Boulder River watershed study area.

[Volume-percent magnetite values calculated from the EM magnetite data (fig. 15) and magnetic susceptibility model (fig. 5) are given at each sample location to illustrate the relation between the presence of magnetite, geophysical data, and relative acid-neutralizing potential. Leaders (---), unreliable EM magnetite estimates owing to high rock conductivity. Geologic map symbols in parentheses are described in table 1]

FMT012 and BKW are not available from the EM magnetite data owing to low resistivities at these locations. Magnetite estimates from the magnetic susceptibility data (fig. 5) for four samples of unaltered Elkhorn Mountains Volcanics average 1.65 percent. Alternatively, consistently lower values for (magnetic data) magnetite occur for the five samples of altered Elkhorn Mountains Volcanics (average 1.37 percent). Samples of altered Elkhorn Mountains Volcanics contain no magnetite as determined from the heavy-mineral concentrates (Desborough, Briggs, Mazza, and Driscoll, 1998; Desborough and Driscoll, 1998).

Associations between alteration mineral assemblages, magnetite, geophysical anomaly signature, and acid-neutralizing potential for alteration zones mapped in Butte plutonic rocks are summarized in figure 16. Magnetic susceptibility and EM magnetite anomaly intensity progressively decrease as granitic rocks are altered to argillic levels. Rocks having undergone alteration to sericitic levels are characterized by low magnetic susceptibility and EM magnetite anomalies near zero. Compositional changes in the granitic rocks caused by progressively higher degrees of alteration coincide with the absence of magnetite and chlorite. Chemically, the lack of chlorite also corresponds to a decrease in the acid-neutralizing potential of the rock (Desborough, Briggs, and Mazza, 1998; Desborough, Briggs, Mazza, and Driscoll, 1998).

Geophysical Refinement of Geoenvironmental Map

Geophysics-Based Geoenvironmental Map

A geophysics-based geoenvironmental map (fig. 17) infers locations of surface and shallow subsurface bedrock with low magnetite content. Geophysical magnetite lows were determined on geologic and statistical criteria. Solid red in figure 17 defines pixels with values of 0 percent from the EM magnetite grid (fig. 15) combined with resistivities greater than 500 ohm-m from the 900-Hz resistivity grid (not shown). Geologically, these areas coincide with mapped outcrops enriched with silica and low in magnetite from either primary mineralogy or from introduction of silica-rich hydrothermal fluids (Ruppel, 1963; Becraft and others, 1963). Examples include (1) altered rocks with known low acid-neutralizing potential such as the altered Elkhorn Mountains Volcanics at Jack Mountain (Desborough, Briggs, and Mazza, 1998) or (2) rocks interpreted to have low acid-neutralizing potential such as the silica-rich Tertiary rhyolite at Red Mountain. Other solid red areas in figure 17 are interpreted to share analogous electrical properties and map similar rock types.

Pixels with values less than 1.4 percent in the magnetic susceptibility magnetite grid (fig. 5) are shown in the red pattern in figure 17. Lowermost magnetite content (less than

1.4 percent) was defined statistically for most rock types (fig. 9). Geologically, results best characterized mapped outcrop of altered rocks (Becraft and others, 1963; O'Neill and others, this volume). Other areas corresponding to magnetic susceptibility magnetite lows include parts of the study area expected to contain altered rocks such as clusters of polymetallic quartz veins and contact zones between the Butte plutonic rocks and younger volcanic units. Many of the main streams and tributaries are coincident with linear geophysical magnetite lows, which may be sites that provide little or no neutralization to acidic water draining from the mined areas and thus may not aid mitigation of toxic metal loads to aquatic life. Coincidence of geophysical magnetite lows with polymetallic veins suggests that some of the low-percent magnetite domains are mapping locations of *acid-generating* rocks that are depleted in magnetite from intense sulfidization.

Geology- and Geophysics-Based Geoenvironmental Map

Combining the geophysics- and geology-based geoenvironmental maps provides maximum detail in bedrock acid-neutralizing potential. The combined geoenvironmental map (fig. 18) is a portrayal of the underlying geologic "landscape" that influences surface- and ground-water quality, the natural mitigation of metals and acidity, and, ultimately, the health of the ecosystem. Optimal geologic conditions are present where rocks with high acid-neutralizing potential (lightest green shades in figs. 14 and 18) do not overlap with geophysical magnetite lows or polymetallic quartz veins. Least desirable conditions may exist where polymetallic quartz veins lie within, uphill, or up gradient from rocks with low acid-neutralizing potential. These conditions identify places in the watershed that may be environmentally problematic to the mitigation of acidic metal-rich water.

Results of our study show that approximately 30 percent of the geophysical survey areas include rocks sufficiently depleted in magnetite to have low acid-neutralizing potential. Approximately 20 percent of the Butte pluton rocks within the Boulder River watershed study area are defined with low acid-neutralizing potential. From an environmental context, these areas characterize rocks that should not provide significant mitigation to acidic water draining downhill or down gradient from mined or undisturbed mineralized rocks. We also expect that, in areas containing altered Butte pluton, the potential for mitigation of metals toxic to aquatic life is reduced due to lack of calcic and mafic minerals to provide bicarbonate and hydroxide ions.

Large, contiguous areas of geophysical magnetite lows occur over volcanic rocks in the Eocene Lowland Creek and Eocene-Oligocene Helena volcanic fields. The largest area covered by geophysical magnetic lows is located in the southeastern part of the study area over silicic rocks within the Lowland Creek volcanic field (figs. 7 and 17). The geophysical data were especially useful in these rocks as no

Figure 17. Geophysics-based geoenvironmental map showing locations of inferred low acid-neutralizing potential based on low values of volume-percent magnetite calculated from airborne geophysical data.

Figure 18. Combined geology- and geophysics-based geoenvironmental map showing relative acid-neutralizing and acid-generating potential of rocks inferred from rock mineralogy (fig. 14) and volume-percent magnetite calculated from airborne magnetic and apparent resistivity data (fig. 17). White areas, no data available.

mineralogical data were available to determine amounts of acid-consuming minerals. Other large areas, in association with geophysical magnetite lows, occur within Tertiary volcanic rocks in the northern part of the study area. Evidence that these rocks are also low in acid-neutralizing potential is present in low calcium and iron (fig. 13) and high silica content.

Implications for Siting of Waste-Rock Repositories

Maps that portray pertinent environmental geologic characteristics, such as the map derived from this study (fig. 18), could be an information layer used in decision-making processes for locating geologically favorable waste-rock repositories. Cleanup of inactive mines is an important goal of State and Federal land-management agencies. The primary environmental impact of inactive mines is degraded surface-water quality in streams (Nimick and Cleasby, this volume) and resultant impairment of aquatic habitat caused by metals (Farag and others, this volume). Mine waste and mill tailings are the main contributor of metals to surface drainages in the study area (Church, Unruh, and others, this volume; Nimick and Cleasby, this volume). Therefore, an important component of any restoration plan will be finding one or more suitable repository sites where mill tailings and mine wastes could be consolidated and safely stored.

In the early stages of the project (1996–1999), providing information to land managers regarding geologically suitable repository sites for mine waste and mill tailings was a priority. The USDA Forest Service together with geophysicists, geologists, and geochemists from the U.S. Geological Survey evaluated particular sites chosen by both groups to determine their suitability for storing the mine wastes in the watershed. However, during the course of the study, the unexpected bankruptcy of Pegasus Mining and the existing presence of the Luttrell pit at their mining operation (Smith and others, this volume, Chapter E3) made the process of repository siting moot. The USDA Forest Service and U.S. Environmental Protection Agency have a joint agreement to move mine waste from the Boulder River watershed and adjacent Tenmile Creek watershed into the Luttrell pit, located along the Continental Divide between the two watersheds.

Although not a current issue in the Boulder River watershed, repository siting within the larger context of the Departments of the Interior and Agriculture efforts to coordinate restoration activities at other Federal lands affected by inactive mines is a current issue being faced in many watersheds in the western United States. Exercises to characterize the environmental properties of geologic units, such as the techniques presented here, provide a scientific strategy for repository siting in other areas where safe mine-waste storage is an issue. For example, placing a repository in rock that is located at or near a ground-water recharge area in bedrocks with little or no ANP could potentially result in disruption or destabilization of underground portions of a repository and contamination

of surface and shallow ground water. If a land-use manager is restricted to a particular tract of ground in which to bury metal-sulfide waste rock, the environmental geology map can be one layer, among others, that provides geologic guidance as to which “host” rocks provide the better environmental controls.

Summary

This report presents an empirical approach to extend the knowledge of geologic characteristics that exert fundamental controls on the natural environment with depth. In particular, high-resolution airborne geophysical data are used to map the surface and shallow subsurface distribution of acid-neutralizing minerals in igneous bedrock.

Enhancement techniques applied to the aeromagnetic anomaly data result in maps that emphasize magnetic rock properties in the uppermost surface to shallow subsurface. The statistical summaries describing the magnetic susceptibility and apparent resistivity signature for approximately 40 geologic units allow for comparison of geophysical variability within and across geologic units and provide a basis for discussion of important factors controlling the anomaly signature. Geophysical analyses show that the polymetallic quartz veins are distinctively characterized by very low magnetic susceptibilities and moderately high resistivities. Trends of geophysical gradients are co-linear with mapped structures and faults.

The geology-based geoenvironmental map, derived from mineralogical and geochemical data, shows variability in relative acid-neutralizing potential as a function of mafic and calcic mineral abundance. Representative rock samples used to produce the geology-based geoenvironmental map are limited in number but considered sufficient to provide an understanding of acid-neutralizing potential. Granitic and most volcanic rocks that are fresh or unaltered have abundant mafic and calcic minerals with significant acid-neutralizing potential. In contrast, rocks that are silica rich and (or) have been intensely altered by hydrothermal solutions have negligible amounts of mafic minerals, insignificant amounts of calcite, and little acid-neutralizing capacity. Known sources for acidic metal-rich water in the Boulder River watershed are the Late Cretaceous polymetallic quartz veins and associated mine waste. Potential acid-generating source rock may include areas of Tertiary volcanic rocks containing disseminated pyrite.

This study demonstrates that magnetite acts as a relative gauge for corresponding amounts of mafic and calcic minerals in igneous rocks that provide significant acid neutralization to acidic and metal-rich waters. In fresh (unaltered) Tertiary and Cretaceous granitic and volcanic rocks, magnetite is a common accessory mineral (Ruppel, 1963; Becraft and others, 1963) and is associated with mineral assemblages that provide relative degrees of acid neutralization (Desborough, Briggs, and Mazza, 1998; Desborough, Briggs, Mazza, and Driscoll,

1998). Where the igneous rocks are altered, the rock is devoid of magnetite and there is a corresponding depletion in acid-neutralizing potential.

Magnetite is ubiquitous in nearly all the Cretaceous- and Tertiary-age volcanic and plutonic rocks exposed in the Boulder River watershed. Although magnetite is a minor mineral constituent, it provides an easily measured property that can be correlated to measurable percentages of important acid-neutralizing minerals.

Mathematical filters convert magnetic anomaly and apparent resistivity data to pseudo-mineral maps to show surface and shallow subsurface distribution of magnetite. Magnetite is the main source for magnetic anomalies and contributes to the resistivity response of a rock. Magnetite estimates from the magnetic susceptibility model data are within realistic ranges when compared to values determined from rock samples. Estimates from the apparent resistivity data, however, are consistently lower in comparison with magnetite measurements from rock samples but are used in this report to reflect *relative* amounts of magnetite within rocks.

The geophysical magnetite models outline areas interpreted to indicate near-surface rocks lacking or depleted in magnetite. The magnetite depletion can be the result of high-temperature alteration of primary minerals or a silica-rich mineral composition. Absence of magnetite corresponds to low amounts of acid-consuming minerals. In some cases, low values in the geophysical magnetite data correspond with locations of acid-generating source rock such as sulfide-metal-rich veins. Alternately, areas with high values of magnetite from the geophysical models are interpreted to represent rocks associated with significant amounts of acid-consuming minerals.

The geophysical refinement to the geology-based geoenvironmental map results in an improved understanding of the spatial distribution of bedrock environmental characteristics. This report provides a summary of the geophysical signatures and geoenvironmental characteristics of volcanic and plutonic units, many of which extend well beyond the Boulder River watershed study area and crop out commonly throughout southwest Montana. Consequently, the methodology described here can be applied to watersheds that are geologically similar to the study area and which have water-quality degradation caused by historical mining like that in the Boulder River watershed.

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