INTEGRATED GEOPHYSICAL, GEOCHEMICAL, AND HYDROLOGICAL STUDY OF THE BUCKEYE MINE TAILINGS, BOULDER WATERSHED, MONTANA

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ABSTRACT

The Buckeye mine site is located in the Boulder River watershed along Basin Creek, in northern Jefferson County, Montana. This project is part of the Boulder River watershed Abandoned Mine Lands Initiative, and is a collaborative effort between the U.S. Geological Survey and Bureau of Land Management in the U.S. Department of the Interior, and the U.S. Forest Service in the U.S. Department of Agriculture. The site includes a large flotation mill-tailing deposit, which extends to the stream and meadows below the mine. These tailings contain elevated levels of metals, such as silver, cadmium, copper, lead, and zinc. Metal-rich fluvial tailings containing these metals, are possible sources of ground and surface water contamination. Geophysical, geochemical, and hydrological methods were used to characterize the sediments at the Buckeye mine site. Ground geophysical surveys, including electromagnetics, DC resistivity, and total field magnetic methods, were used to delineate anomalies that probably correlate with subsurface metal contamination. Subsurface conductivity was mapped using EM-31 and EM-34 terrain conductivity measuring systems. The conductivity maps represent variation of concentration of dissolved solids in the subsurface from a few meters, to an approximate depth of 30 meters. Conductive sulfides several centimeters thick were encountered in a shallow trench, dug in an area of very high conductivity, at a depth of approximately 1 to1.5 meters. Laboratory measurements of samples of the sulfide layers show the conductivity is on the order of 1000 millisiemens. DC resistivity soundings were used to quantify subsurface conductivity variations and to estimate the depth to bedrock. Total field magnetic measurements were used to identify magnetic metals in the subsurface. The EM surveys identified several areas of relatively high conductivity and detected a conductive plume extending to the southwest, toward the stream. This plume correlates well with the potentiometric surface and direction of ground water flow, and with water quality data from monitoring wells in and around the tailings. Core and bed-sediment samples also show that the highest levels of metals are downstream and in the direction of surface and ground water movement indicated by the electromagnetic data. The electrical geophysical data also suggests there has been vertical migration of high dissolved solids.

INTRODUCTION

Purpose

The Buckeye mine site (Figure 1) is located along Basin Creek, in northern Jefferson County, Montana. This project is part of the Boulder River watershed Abandoned Mine Lands Initiative, a collaborative effort between the U.S. Geological Survey and Bureau of Land Management in the U.S. Department of the Interior, and the U.S. Forest Service in the U.S.

Department of Agriculture. The Buckeye study, and the study of other sites in the watershed, is an example of the USGS "Integrated Science" approach to watershed characterization and contributions to remediation planning.

Basin Creek, one of the three main tributaries of the Boulder River, has been shown to contribute metals to surface waters in the Boulder River watershed. Wastes from metal-mining related activities have contributed to acid generation and toxic metal loading in the watershed. The main source of contamination, at the Buckeye site, comes from the weathering of the large, well exposed, tailings pile during spring snow melt and storm runoff events (Buxton and others, 1997).

During the summer of 1998 and 1999, ground geophysical surveys, including electromagnetic (EM), direct current (DC) resistivity, and total field magnetic methods, were used to examine the location and extent of high conductivities possibly related to metal contamination in the tailings and surrounding area. The geophysical data were also used to examine possible movement of metals associated with local ground water flow.

Under a contract with the U.S. Forest Service, nine test wells were drilled in and around the tailings in October of 1999 (Figure 2). A hand auger well was later drilled in the meadow area south of Basin Creek. The aquifer in the vicinity of the Buckeye mine was characterized in terms of ground water flow direction and water quality using the well data.

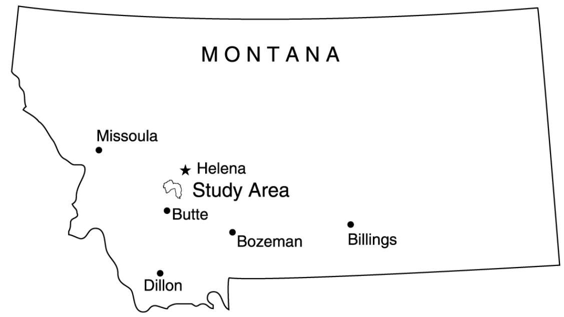
Geochemical analyses of 35 tailings cores and 6 stream-bed sediment samples were used to determine the concentrations of Ag, As, Cd, Cu, Pb, and Zn (Figure 3). These metals, in colloidal form, have been shown to be toxic to fish and their invertebrate food sources (Farag and others, 1999). The collected samples were analyzed by ICP-AES (inductively coupled plasma-atomic emission spectroscopy) using a mixed-acid digestion (Fey and others, 1999).

Historical Background

Vein deposits of gold were discovered at the Buckeye site in 1868. The Buckeye mine and adjacent Enterprise claim were worked during the late 1800's and early 1900's. An on-site gravity mill was used for concentration of the ore. The mined ore contained abundant disseminated and massive pyrite, locally abundant arsenopyrite, sparse chalcopyrite, and sparse, local galena and sphalerite. The 1.6 meter thick, sub-vertical, Buckeye ore vein was worked through shafts of 30 to 60 meter depths, and similar veins at the Enterprise were worked through a 122 meter vertical shaft (Ruppel, 1963). A mill was built during World War II to re-process the gravity tailings using flotation technology. The resulting tailings cover an area of about 3.3 acres of the Basin Creek floodplain, and have an estimated mass of 16,000 tons (Metesh and others, 1994).

Geologic and Geohydrologic Setting

The study area is located in a Late Cretaceous plutonic complex known as the Boulder batholith. The emplacement of the batholith progressed from initial mafic plutons to an extensive intermediate-composition main phase to a final alkali-rich felsic composition. The batholith is comprised of fifteen different plutons, but the Butte pluton forms the majority of the outcrop in the region. The dominant rock type in this pluton is a medium-to-coarse grained hornblende-biotite phase, and is classified as a granodiorite-tonalite. The Butte pluton is separated into eastern and western sectors by the Butte-Helena fault zone (O'Neill and others, 2000).



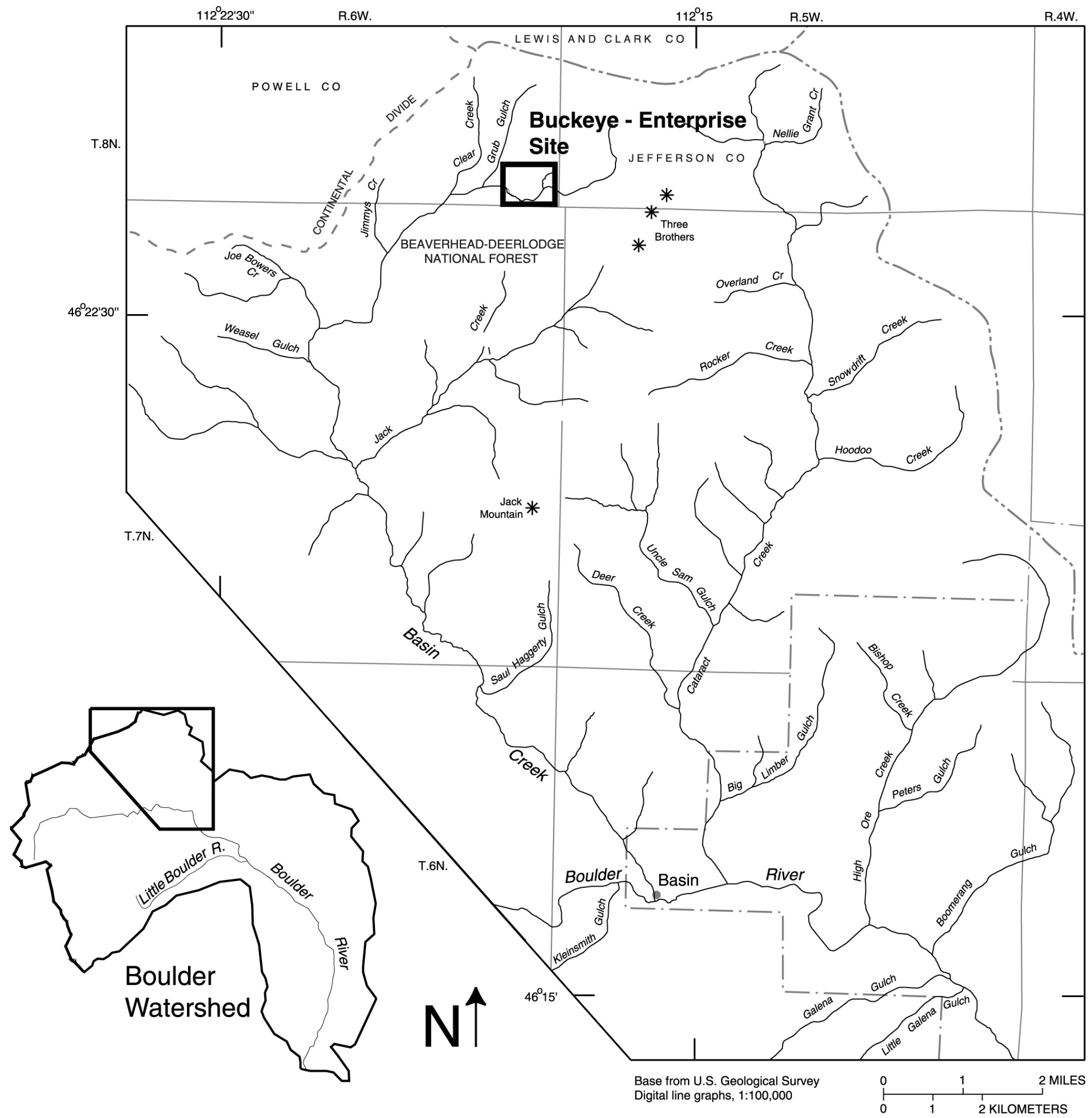


Figure 1. Location map of the Boulder watershed and Buckeye-Enterprise study area

In the vicinity of the Buckeye mine, glacial till, volcanic ash beds, and the mill tailings deposits overlie the pluton. Monitoring wells in and around the tailings penetrate coarse braided stream deposits, interpreted as glacial outwash sediments. These deposits are overlain by as much as 3 meters of thin stream sand and gravel lenses, and interlayered with levee, bog, and backswamp deposits of organic-rich sand, silt, and clay. The 6,700 year old Mazama ash deposit was encountered in one well at a depth of 1.1 meters (3.6 feet) in organic-rich sediments just south of the tailings.

Outcrops of aplite, formed during late-stage, alkali-rich felsic pluton emplacement (O' Neill and others, 2000), are also found near the mine. The main mineralized Buckeye vein and smaller adjacent veins occur in fault zones cutting the Butte pluton and the late-stage felsic pluton (Ruppel, 1963).

Ground water flow in the study area occurs in two hydrogeologic units. The primary aquifer is composed of till, alluvium, colluvium, swamp deposits, and volcanic ash. This aquifer is unconfined and movement of water is through interconnected pores (primary permeability). Permeability in the granitic rock is low, and ground water movement in this aquifer is through heterogeneous anisotropic faults and fractures (secondary permeability). Fracture permeability in these aquifers is a function of width, density, orientation, and interconnectivity.

Recharge to the ground water system comes from approximately 76 centimeters maximum annual precipitation (mainly as snowfall), and minor recharge from higher elevations to the east. Intense rainstorms can contribute sudden influxes of recharge primarily to the alluvium aquifer.

METHODS OF INVESTIGATION

Geophysical Surveys

Electromagnetic Surveys

An EM34 survey, done in 1998, and an EM31 survey done in 1998 and extended in 1999, was used to map subsurface conductivity of the tailings deposit, and the surrounding meadows and forested areas. The conductivity maps represent the distribution of conductive materials in the subsurface at depths from a few meters, to an approximate depth of 30 meters. Measurements at varying depths were achieved by using two different EM instruments. The Geonics EM31 has a fixed intercoil spacing of 3.7 meters, which results in an exploration depth of approximately 6 meters in the vertical magnetic dipole (VMD) orientation, and approximately 3 meters in the horizontal magnetic dipole (HMD) orientation. The EM34 has variable coil spacing. For this survey, the EM34 spacing was set at 10 meters, resulting in an approximate VMD depth of 15 meters, and an approximate HMD depth of 7.5 meters (McNeill, 1980).

A survey grid (Figure 2) was constructed by first selecting an origin point and siting a north-south baseline through the origin. Baseline stations for the 1998 survey were marked in 30 feet intervals, but were changed to 10 meter intervals for the 1999 survey. All east-west stations were measured at 10 meter intervals.

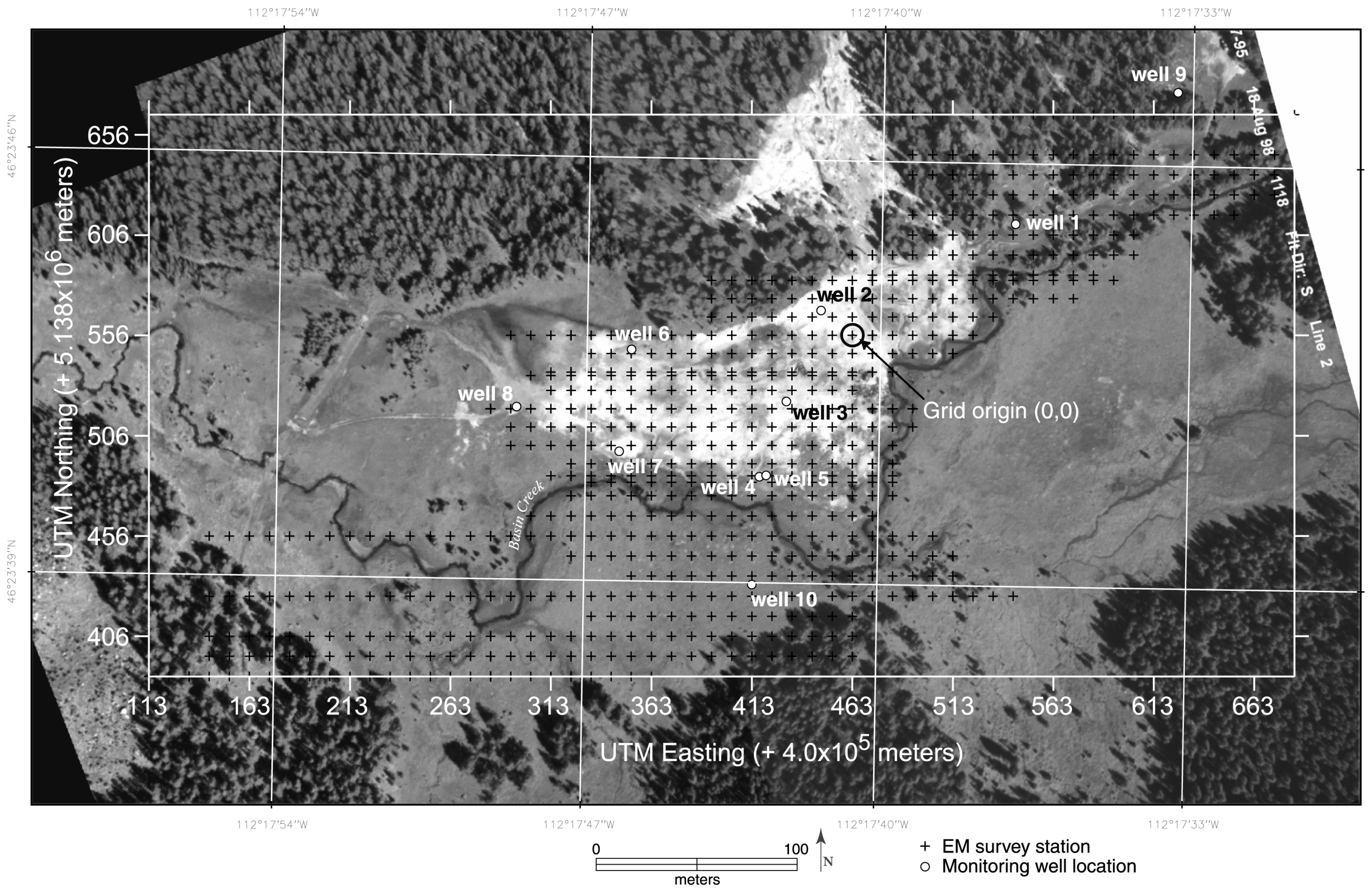


Figure 2. **Site map showing localities of monitoring wells and EM survey grid**

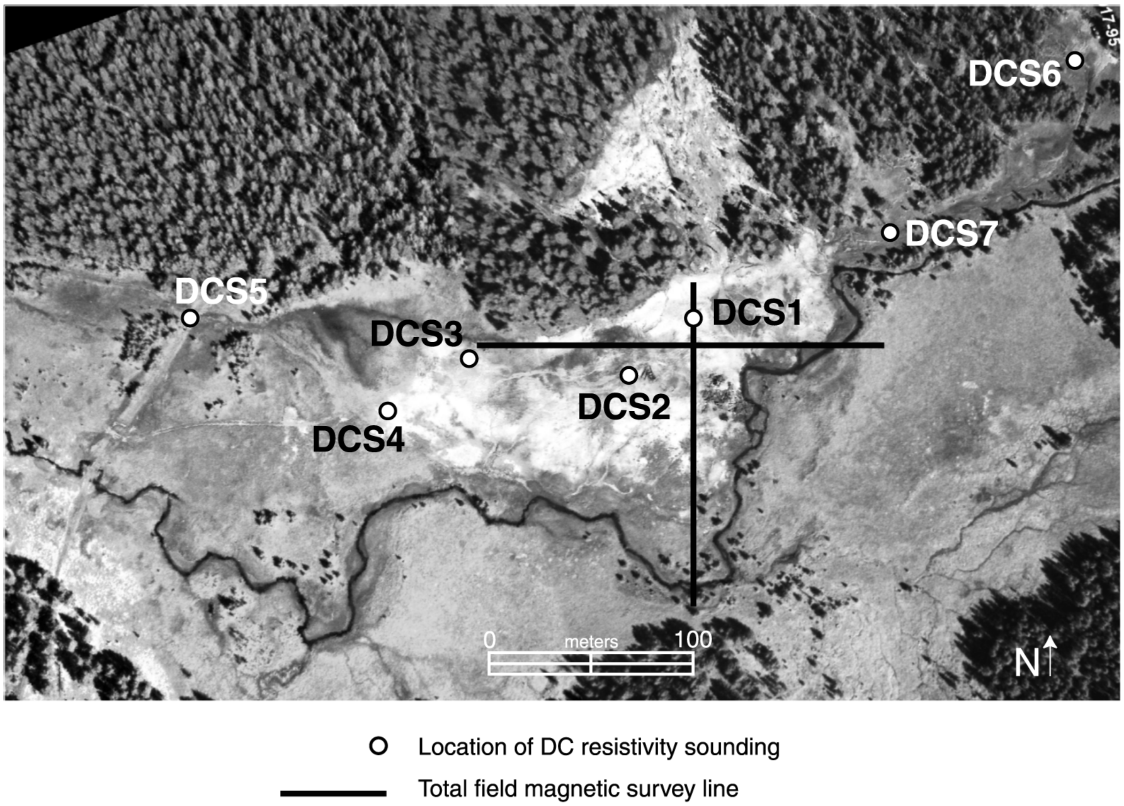


Figure 3. **Location map of DC resistivity soundings (DC sounding 8 is off the map to the north) and total field magnetic survey lines**

Magnetic Survey

During the 1999 fieldwork, a total field magnetic survey of the north-south and east-west base lines (figure 3) was conducted using a proton precession magnetometer (Telford and others, 1990). Measurements were made at 10 meter intervals. At each station, three measurements were taken and averaged, to account for diurnal variations in the earth's magnetic field. This reconnaissance survey was intended to detect buried magnetic metallic cultural artifacts, which might be the cause of local EM anomalies. Of particular interest was the area near the grid origin at 00 (local coordinates), where preliminary EM results indicated an area of high conductivity.

DC Resistivity Soundings

DC resistivity soundings were conducted in eight locations (figure 3) using an ABEM SAS DC resistivity system and a Schlumberger electrode array (Smith and Sole, 2000). Seven of these soundings were made on the flotation tailings in order to provide detailed information about the subsurface resistivity variations and to possibly define the depth to bedrock. Each of the soundings was done in the vicinity of the test wells made for ground water studies. Sounding number eight was made in an area of exposed bedrock about 3 km northwest of the tailings.

Current electrodes were spaced incrementally from about 1 meter to 40 meters. The sounding data were interpreted using software from Interpex (RESIXIP version 2.14, 1991) (Interpex, 1993).

Hydrology

Ground Water

Nine test wells, completed by Maxim Technologies Inc. in and around the tailings, were drilled into unconsolidated flood-plain deposits of Basin Creek (Figure 2). A hand auger well (well 10) was drilled in the meadow south of Basin Creek, where earlier EM data indicated an area of moderately high conductivity. Depths of the wells ranged from 1.5 meters to 9.5 meters (Table 1). Wells 4 and 5 were drilled adjacent to each other, at different depths, so that vertical head gradient and comparative water quality measurements could be made. The nine drilled wells were constructed of 5.1 centimeter (2 inch) diameter PVC casing and screen, with a 15.2 centimeter (6 inch) steel casing at the surface. Well 10 was also constructed of 5.1 centimeter (2 inch) diameter PVC, but was not cased at the surface.

Well Number	Total Depth Drilled (meters)	Latitude (d-m-s)	Longitude (d-m-s)
BTMW-1	3.3	46° 23’ 44.50”	-112° 17’ 36.68”
BTMW-2	7.6	46° 23’ 43.10”	-112° 17’ 41.40”
BTMW-3	3.4	47° 23’ 41.70”	-112° 17’ 42.15”
BTMW-4	9.5	46° 23’ 40.46”	-112° 17’ 42.64”
BTMW-5	2.6	46° 23’ 40.47”	-112° 17’ 42.59”
BTMW-6	3.0	46° 23’ 42.50”	-112° 17’ 45.75”
BTMW-7	3.4	46° 23’ 40.72”	-112° 17’ 45.94”
BTMW-8	4.0	46° 23’ 41.53”	-112° 17’ 48.36”
BTMW-9	5.2	46° 23’ 46.68”	-112° 17’ 33.07”
BTMW-10	1.5	46° 23’ 38.60”	-112° 17’ 43.20”

Table 1. Depth and location of Buckeye test wells

Surface Water

Intermittent measurements of discharge of Basin Creek were made near the Buckeye mine and Enterprise claim between May 1997 and September 1999 (M.R. Cannon, 1999, unpublished data). In May of 1999, synoptic water-quality samples were made at 25 sites in upper Basin Creek and it’s tributaries, under uniform hydrologic conditions, to determine sources, concentrations, and loads of metals in the creek near the Buckeye mine and Enterprise claim during high stream-flow. Field measurements included discharge, water temperature, specific conductance, and pH. Parameters measured in the USGS water-quality laboratory were common ions, hardness, alkalinity, dissolved metals, and total recoverable metals. Dissolved metal loads were calculated for each synoptic sampling site by multiplying the recorded discharge by the individual metal concentration.

Geochemistry

Streambed sediments and tailings cores

Six bed-sediment samples were collected from Basin Creek, upstream of, adjacent to, and downstream of the tailings. The bed-sediment samples represent the chemistry of eroded material upstream of each sample site, which has been deposited in the streambed. Samples from each site are composites of 10 to 20 subsites located within 15 meters of the plotted sample location (Figure 4).

Thirty-four 2.54 centimeter (1inch) diameter cores were collected from the surface of the tailings deposit (Figure 4), and, in 1998, an additional core was taken from the bottom of a 1.2 meter deep trench located near the origin of the EM survey grid. This trench was one of several that were dug through the tailings with a track-mounted backhoe. The trenches were used to help determine the thickness of the tailings, and to allow sampling in the lower part of the tailings. One 2-meter core was also taken from the thickest part of the tailings pile (Figure 4, 98-BMF-109) near the EM survey grid origin.

The main sampling traverse extended approximately 200 meters with a bearing of N74^{o}E. Three additional traverses (A, B, and C) were run perpendicular to the main traverse. Core depths were typically 50 to 60 cm. Core samples were separated into subsamples (by depth), based on common mineralogy, organic content, and apparent oxidation zones. A core compaction factor was calculated so that the actual depth of each subsample could be determined (Fey and others, 1999).

The bed-sediment samples, leach residues from the bed-sediment samples, and tailings core subsamples were digested with a mixed-acid procedure, and analyzed for 32 elements using ICP-AES (Crock and others, 1983; Briggs, 1996). This procedure effectively dissolves most minerals, including silicates, oxides, and sulfides.

RESULTS AND ANALYSIS

Data collected from the EM34 survey were used to produce contour maps of conductivity for vertical and horizontal magnetic dipoles (figure 5). The VMD map shows an area of negative conductivity near the survey grid origin (0,0), and the HMD map indicates high conductivity for the same area.

The conductivity anomaly was initially thought to be the result of a buried conductive metallic object or by lateral heterogeneity in the layered tailings deposits. The total field magnetics survey indicates several metallic objects at the surface that cause local magnetic anomalies along the north-south magnetic survey line. However, there are no significant sharp magnetic anomalies along the east-west line, and no significant magnetic anomalies were found in the area of the grid origin (0,0) (Figure 6). Therefore, we conclude that buried magnetic metallic cultural artifacts are not a likely source of the high conductivity anomalies in the area of the grid origin.

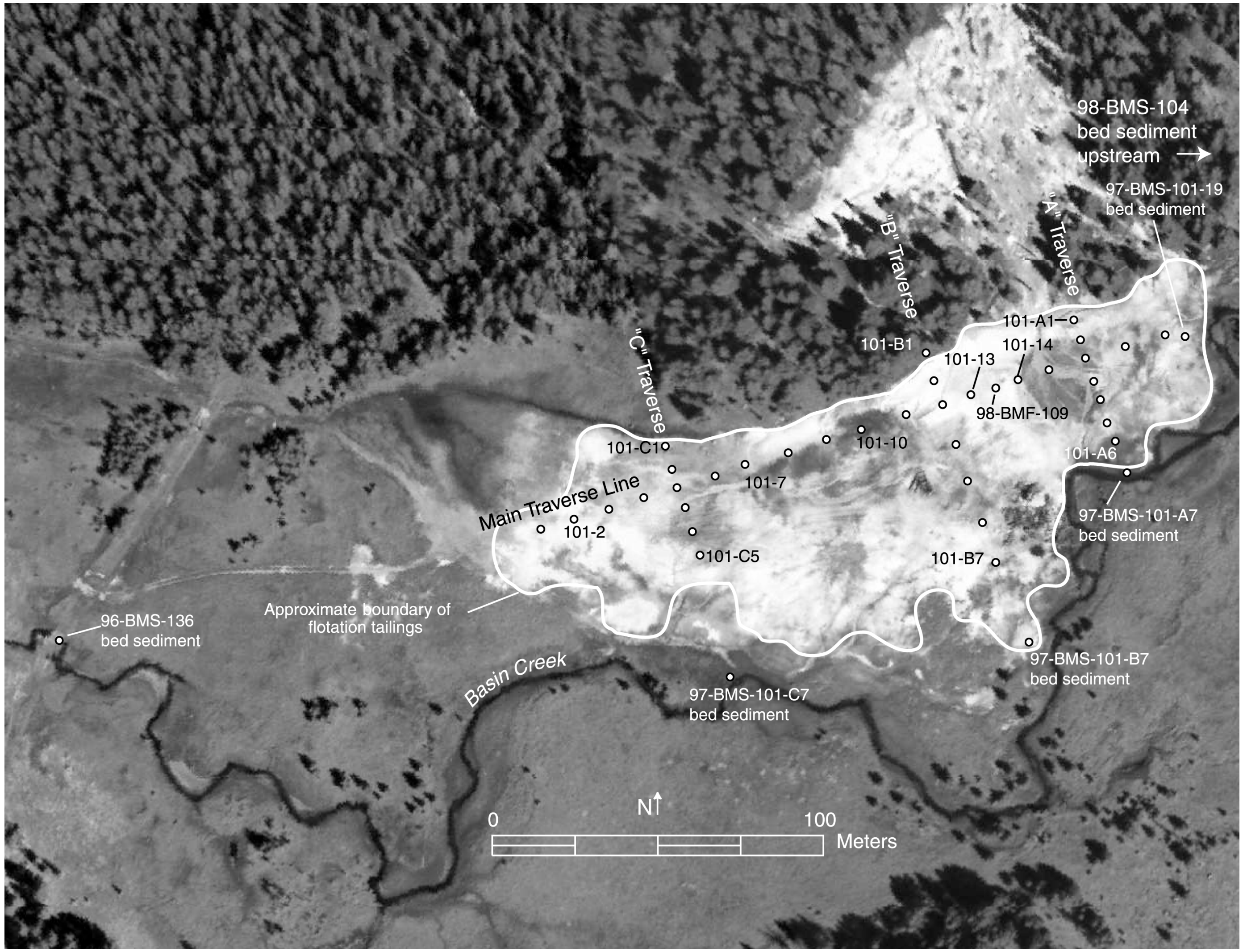


Figure 4. Site map for flotation-mill tailings cores and bed sediments at or near the Buckeye tailings area, Buckeye meadow, upper Basin Creek, Montana. Aerial photo mosaic. Image data provided by the U.S. Forest Service. (from Fey and others, 1999)

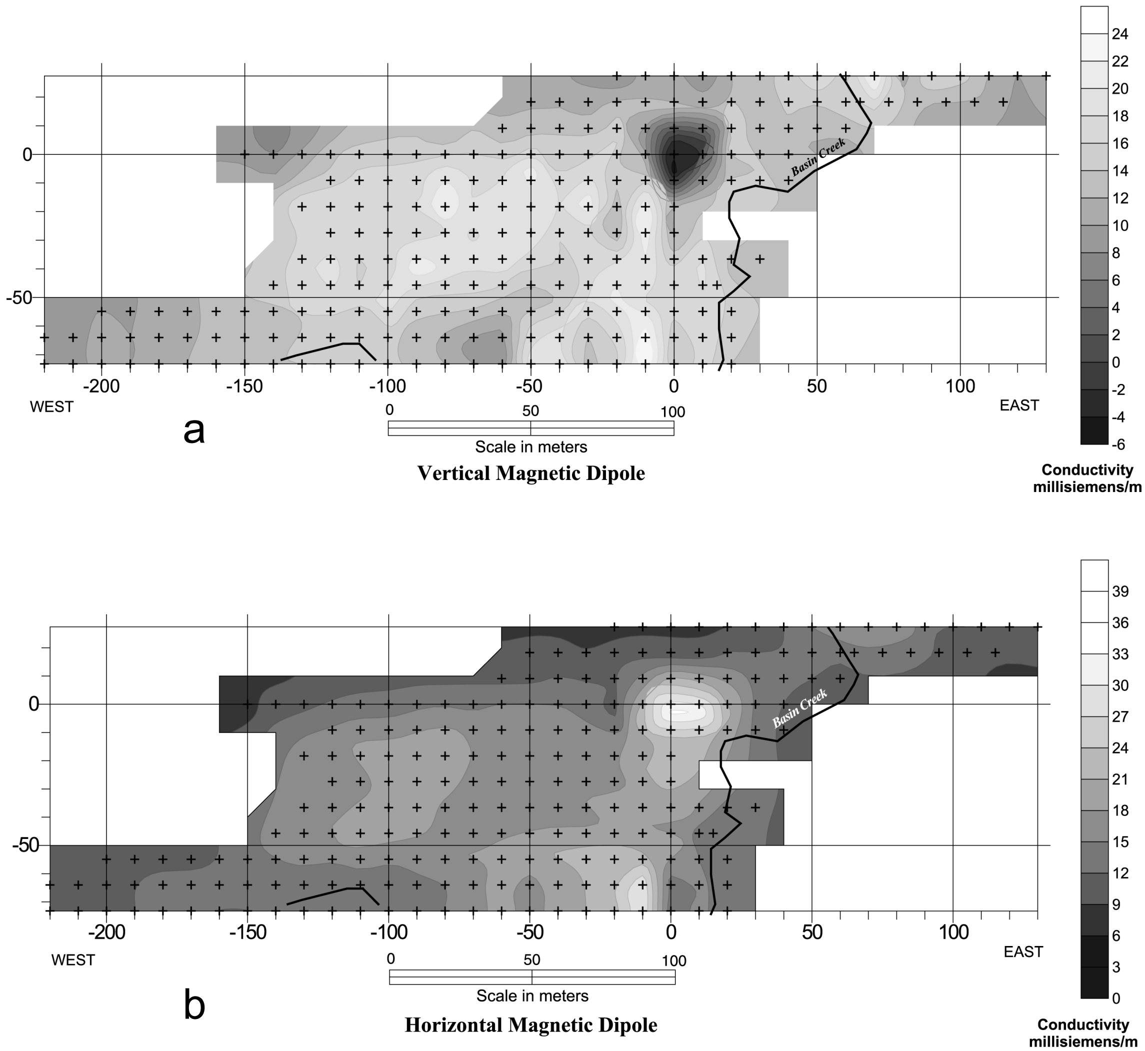


Figure 5. EM-34 Electromagnetic survey contour maps (a – vertical magnetic dipole; b – horizontal magnetic dipole)

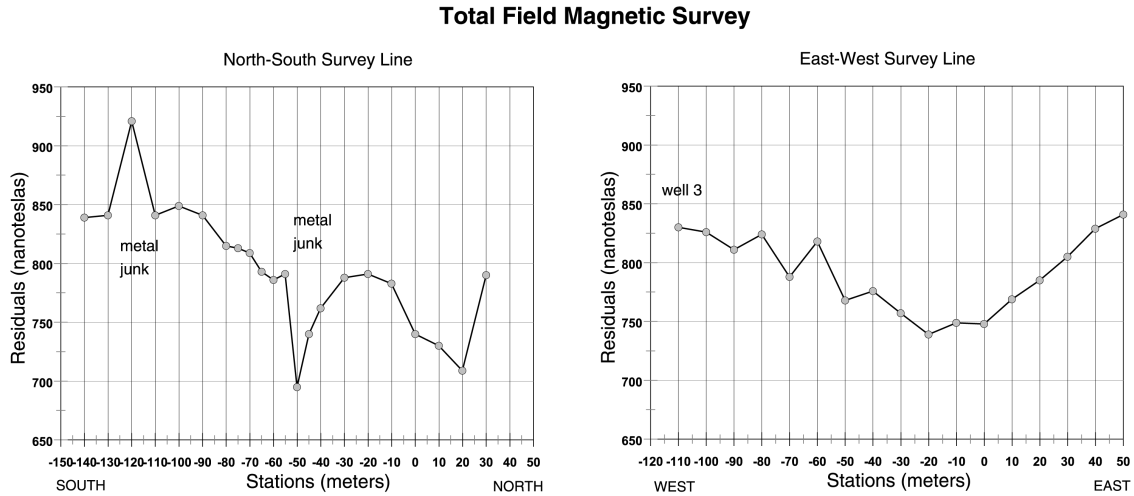


Figure 6. Graphs of total field magnetic surveys (see Figure 3 for location of survey lines)

The exploration trench, dug near the conductivity anomaly, encountered several layers of oxidized and unoxidized sulfides (Figure 7) a few centimeters thick. Laboratory measurements of the core sample (98-BMF-109) from the trench show that the conductivity is on the order of 1000 millisiemens/m (unpublished data, USGS petrophysics lab). It is likely that the high conductivity anomaly near the grid origin is the result of these sulfide layers and/or high dissolved solids also shown in the core analysis. The negative conductivity response seen in the EM34 VMD data may be the result of the heterogeneous layering of the tailings deposits near the grid origin. Another possible explanation is that the conductivity values, indicated from the core analysis, are high enough to allow for the low induction number approximation to breakdown. At high conductivity values, the approximation of the linear relationship between instrumental response and terrain conductivity becomes invalid (McNeill, 1980).

The EM31 HMD (figure 8) and VMD (figure 9) contour maps show the same high conductivity anomaly seen in the EM34 contour maps. The EM31 and EM34 VMD data show higher conductivity than the HMD data, indicating increased conductivity with depth.

The EM maps show a conductive anomaly interpreted as a plume of conductive material extending to the southwest toward the stream. This plume, in terms of depth, position and conductivity, correlates well with the potentiometric surface and direction of ground water flow, and water quality data from the monitoring wells in and around the tailings. Core and bed-sediment samples also show that the highest levels of metals are downstream and in the direction of ground water movement indicated by the electromagnetic data (Fey and others, 1999). The expanded areal coverage of the EM31 survey also indicates areas of high conductivity in the northeast part of the survey area, below the Enterprise claim. This anomaly correlates well with the water analysis from test well #1 (Figure 2), which is also below the Enterprise tailings and waste rock. Water from test well #1 (BTMW-1) had a pH of 3.4, and relatively high concentrations of dissolved Al, Cd, Cu, Pb, Mn, and Zn. The dissolved lead concentration of 36 μg/L is the highest of any of the wells sampled (M.R. Cannon, 2000, unpublished data). There was also a surficial seep (observed in July of 1999) of red colored water in the area of the conductivity high.

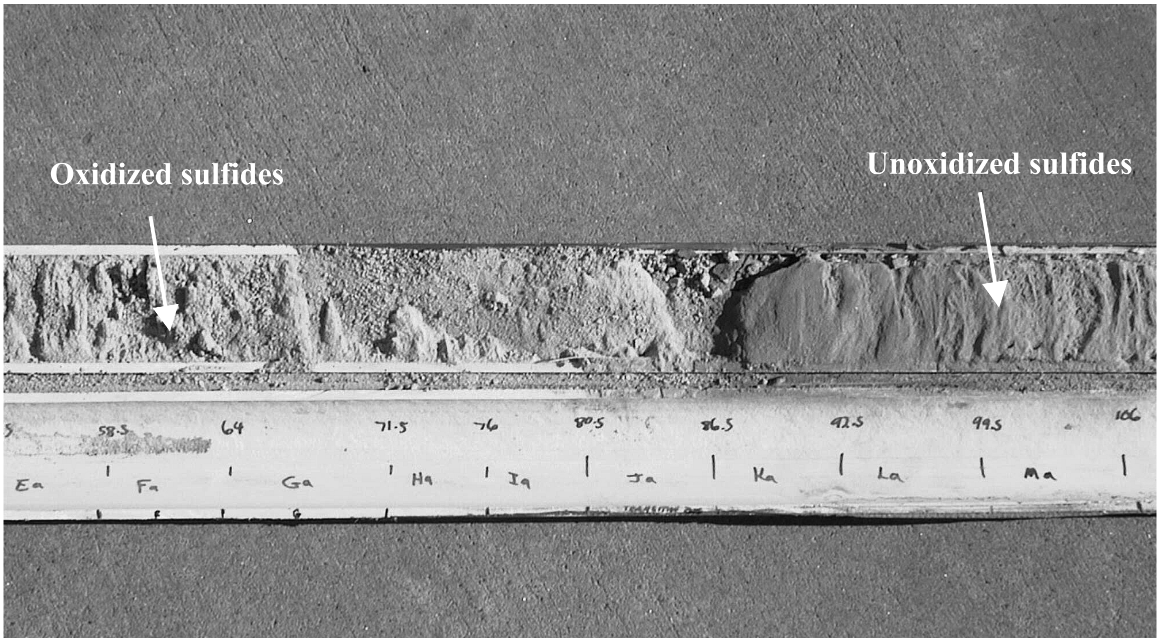


Figure 7. **Core section (98-BMF-102) from the bottom of the exploration trench near the EM survey grid origin (scale shown in centimeters)**

Another area of relatively high conductivity can be seen in the EM31 VMD contour map (Figure 9) (and to a lesser extent in the HMD map (Figure 8)) southwest of the Buckeye tailings in an area of wet meadows. There is no well data for this area, but the conductivity could be the result of high dissolved solids deposited during high stream flow conditions, or anomalous clay concentration in the meadow soils.

Subsurface conductivity as interpreted from the DC soundings is shown in contoured form in a cross-section (Figure10). Sounding DCS1 and DCS3 (Figure 3) were not used in this interpretation because they had marked effects from lateral heterogeneities. For each sounding, the estimated subsurface conductivity was assumed to be located at the mid-point of the interpreted subsurface layer. The layer thickness increases at an approximately logarithmic rate since the resolution decreases at a similar rate. Consequently, the depth estimates of conductivity increase logarithmically. The estimate of the conductivity of the last layer should be taken as relatively resistive or conductive since the soundings did not asymptote to a constant value at large electrode spacings.

The conductive anomaly in the center of the section (Figure 10) is interpreted to be a plume of high dissolved solids. The plume shows up a little deeper than suggested from drilling and trenching. This may be due to some downward migration of a few meters. The relatively high-interpreted subsurface conductivity at DCS06 is an unknown source but the nearby shallow well #9 (BTMW-9) did have high dissolved solids at a somewhat shallower depth.

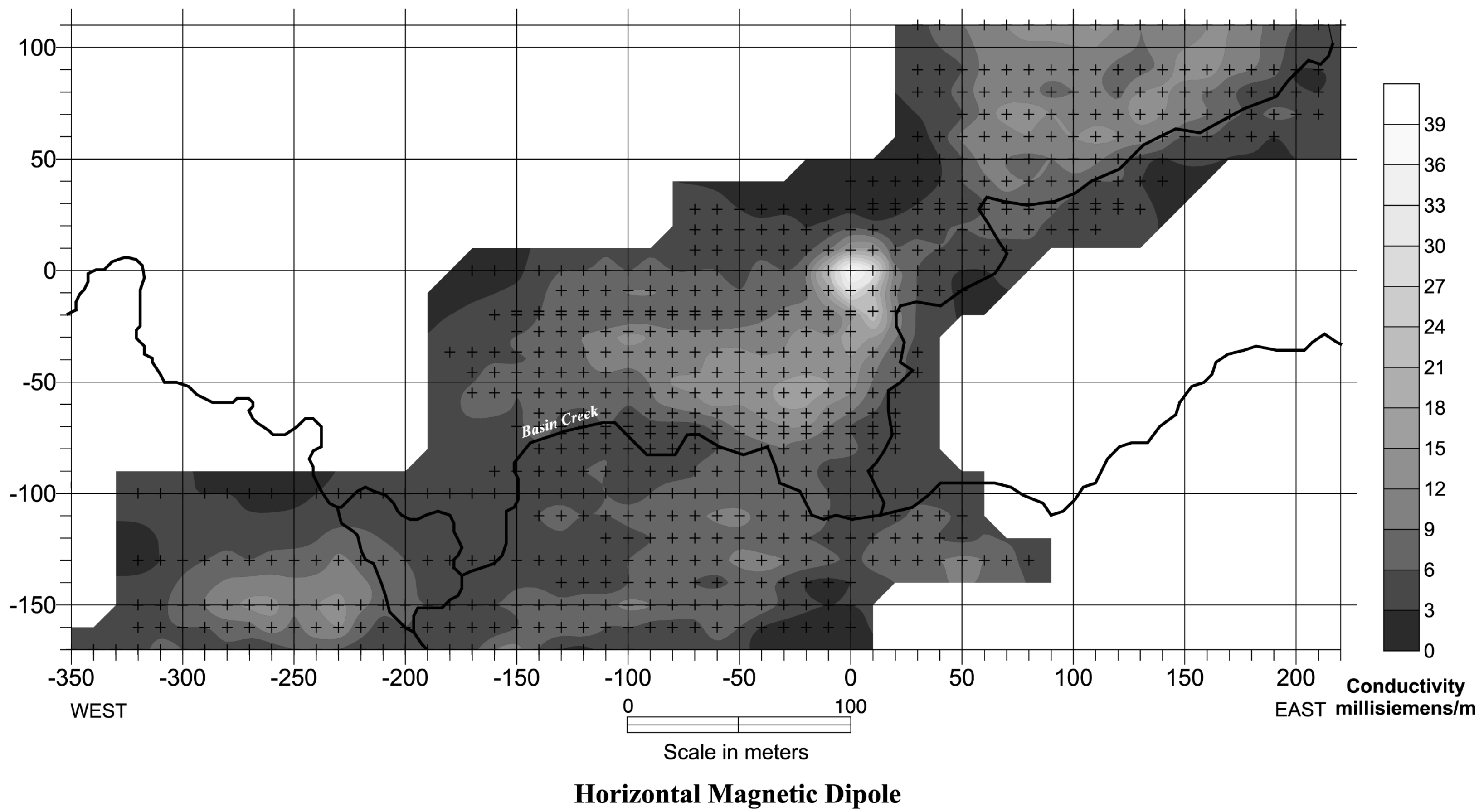
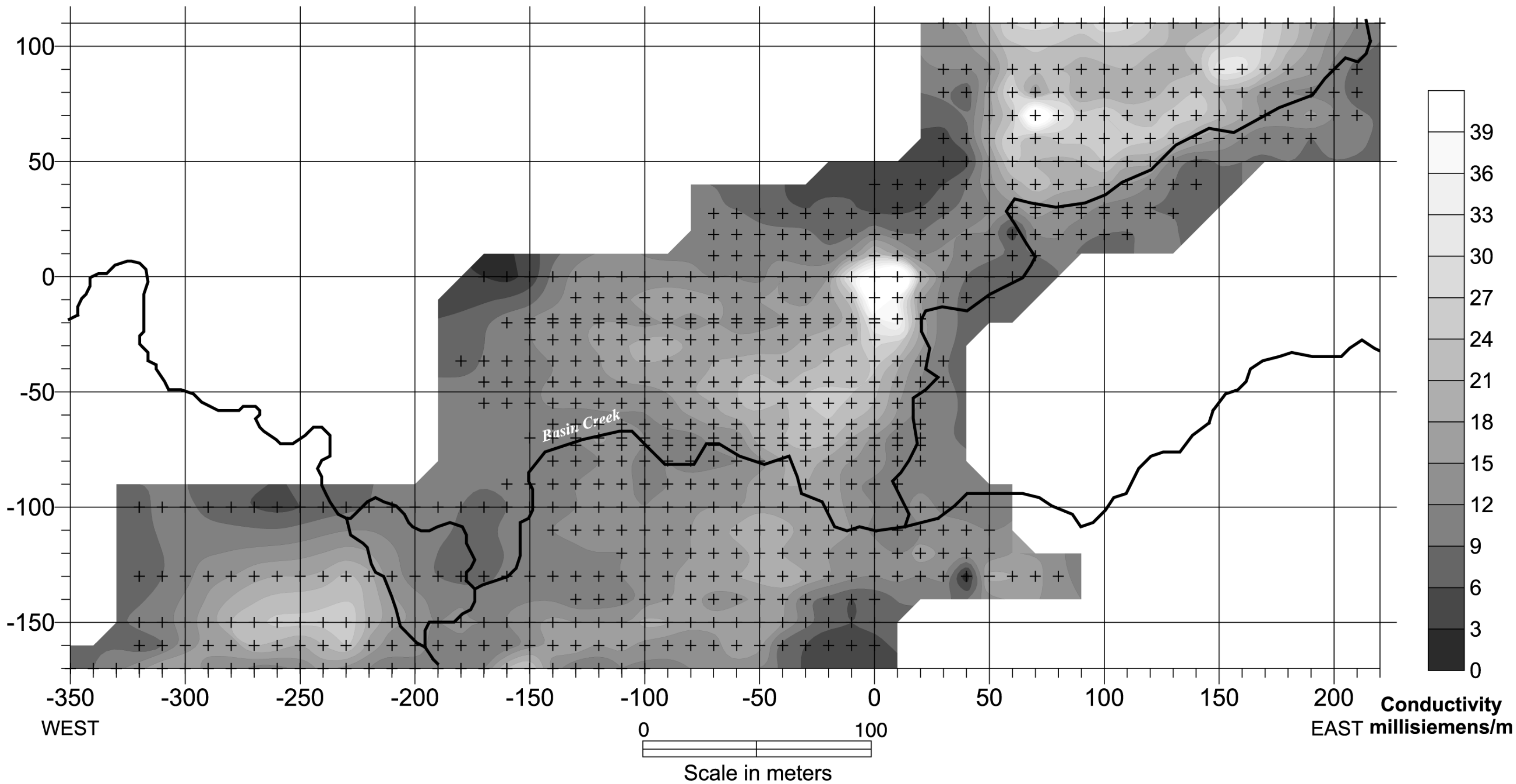


Figure 8. **EM-31 Electromagnetic survey contour map**



Vertical Magnetic Dipole

Figure 9. **EM-31 Electromagnetic survey contour map**

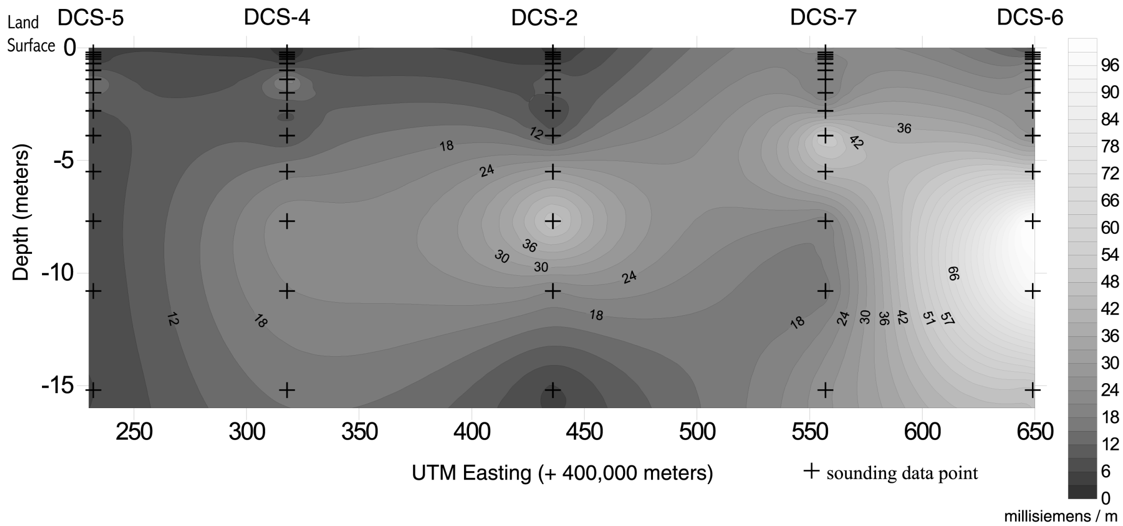


Figure 10. **Subsurface cross-section of DC soundings (depth is plotted with a vertical exaggeration factor of ten)**

The sounding done on a nearby granite outcrop to the north of the mine (DCS8) showed the shallow conductivity is on the order of 5 millisiemens. None of the interpreted subsurface conductivities are this low except perhaps for DCS2 (Figure 10). Consequently, granite underlying the mine tailings, with similar electrical properties as the outcropping area, may be more than 30 meters deep. It is likely that the granite in the stream valley is more weathered and has a higher volume of water than the outcrop area. It is also possible that the underlying granite aquifer has fractures that contain clays and/or high dissolved solids.

Specific conductance measured from water samples taken from the test wells is shown in contour form in figure 11. Data from well 5 was not included, since it is adjacent to well 4 and drilled to a shallower depth (Table 1). In general, the map shows a conductive plume, extending to the southwest, similar to that of the EM contour maps. Relative limitations to the map are the limited number of data points (test wells), and that water samples were not taken at the same potentiometric or stratigraphic level in each well.

Sampling of ground water and surface water indicates that the highest metal loading to Basin Creek occurs during spring run-off and other high flow conditions. Highest measured flows were recorded in May of 1997 and 1998, and lowest flows were recorded in September of 1999. Historical stream flow records for the Boulder River indicate May and June account for 63 percent of mean annual discharge, and August through March accounts for less than 5 percent of discharge. Discharge patterns for Basin Creek are likely similar to those for the Boulder River.

The geochemical analysis concludes that As, Cd, Cu, Pb, and Zn contamination persists to a depth of about 30 cm below the tailings. Analysis of the bed-sediment samples indicates that forty to sixty percent of the previously mentioned trace elements are present in leachable phases, and include settled colloids and hydrous amorphous iron, and manganese hydroxide coatings on stream-bed sediments (Fey and others, 1999).

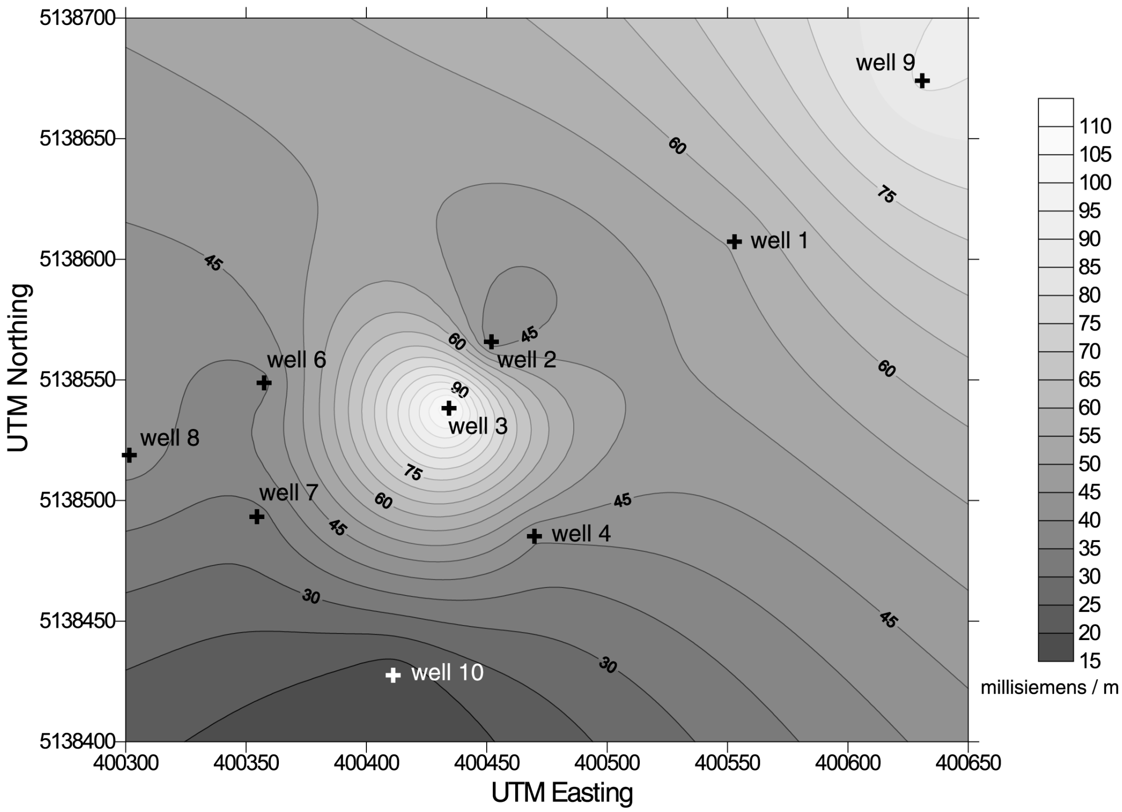


Figure 11 **Contour map of specific conductance measured from test well water samples**

To a large degree, the methods used in this study produced results that were well correlated. Each of the data sets yields information about the characteristics of the mine tailings and related metals, at different spatial and quantitative scales. When used in combination, these methods provide a more comprehensive characterization of the Buckeye tailings and the associated subsurface areas of high dissolved solids in ground water. The results provide important considerations for remediation efforts in terms of direction of movement, depth, and extent of metal contamination at the site. Conductive areas, which were previously uninvestigated, and may contribute metal loading to Basin Creek, were also identified. Outflow areas for the contaminated ground water should be considered in the remedial action proposed for the Buckeye site.

LITERATURE CITED

Briggs, P.H., 1996, Forty elements by inductively coupled-plasma atomic emission spectrometry, *in* Arbogast, B.F., ed., Analytical methods manual for the Mineral Resources Program, U.S. Geological Survey Open-File Report 96-525, p. 77-94.

Buxton, H.T., Nimick, D.A., von Guerard, P., Church, S.E., Frazier, A., Gray, J.R., Lipin, B.R., Marsh, S.P., Woodward, D., Kimball, B., Finger, S., Ischinger, L., Fordham, J.C., Power, M.S., Bunck, C., and Jones, J.W., 1997, A science-based Watershed strategy to support effective remediation of abandoned mine lands: *in* Fourth International Conference on Acid Rock Drainage Proceedings, v. IV, Vancouver, B.C. Canada, May 31-June 5, 1997, p. 1869-1880.

Crock, J.G., Lichte, F.E., and Briggs, 1983, Determination of elements in National Bureau of Standards geologic reference materials SRM 278 obsidian and SRM 688 basalt by inductively coupled plasma-atomic emission spectroscopy: *Geostandards Newslette*r, v. 7, p. 335-340.

Farag, A.M., Woodward, D.F., Skaar, Don, and Brumbaugh, W.G., 1999, Characterizing the aquatic health in the Boulder River watershed, Montana, USGS WRIR 4018A, p. 55-58.

Fey, D.L., Church, S.E., and Finney, C.J., 1997, Analytical results for 35 mine-waste tailings cores and six bed-sediment samples, and an estimate of the volume of contaminated material at Buckeye meadow on upper Basin Creek, northern Jefferson County, Montana: U.S. Geological Survey Open-File Report 99-537.

INTERPEX, 1993, RESIX-IP v 2.0 Users Manual, Interpex Limited, Golden Colorado, 150p.

Metesh, J., Lonn, J., Duaime, T., and Wintergerst, R., 1994, Abandoned-inactive mines program Deer Lodge National Forest, Volume I - Basin Creek Drainage: Montana Bureau of Mines and Geology Open-File Report 321, 131 p.

McNeill, J.D., 1980, Electromagnetic Terrain Conductivity Measurement at Low Induction Numbers, Technical Note TN-6, Geonics Limited, Ontario, Canada.

O'Neill J.M., Lund, K., Sole, T.C., Van Gosen, B.S., Desborough, G., and Dewitt, E., 2000, Geologic framework of the Boulder abandoned mine lands study area, Powell, Jefferson, and Lewis and Clark Counties, Montana: U.S. Geological Survey Open-File Report 00-xxx.

Ruppel, E.T., 1963, Geology of the Basin quadrangle, Jefferson, Lewis and Clark, and Powell Counties, Montana: U.S. Geological Survey Bulletin 1151, 121 p., 7 plates.

Smith, B.D. and Sole, T.C., 2000, Schlumberger DC Resistivity Soundings in the Boulder Watershed, Jefferson and Lewis and Clark Counties, Montana: U.S. Geological Survey Open-File Report 00-110.

Telford, W. M., L. P. Geldart, and R. E. Sheriff, 1990, Applied Geophysics, 2nd ed., Cambridge University Press, 875p.