THE USE OF AIRBORNE MAGNETIC AND EM CONDUCTIVITY SURVEYS TO LOCATE GROUNDWATER FLOW PATHS AT THE SULPHUR BANK MERCURY MINE SUPERFUND SITE[1]

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Abstract Airborne magnetic and electromagnetic (EM) conductivity surveys were conducted at the Sulphur Bank Mercury Mine Superfund Site near Clearlake, California to identify potential pathways for groundwater flow. The total field magnetic survey identified four fault zones that are potential conduits for mercury-contaminated, groundwater flow out of the flooded pit of the abandoned Sulphur Bank Mercury Mine. The location of the four fault zones was corroborated by the EM conductivity survey, which also provided evidence that the fault zones contained highly conductive water, either from deep, geothermal origin or from meteoric water made acidic by weathering of sulfide minerals and oxidation of H_2S-bearing gases. This information was used to locate groundwater-monitoring wells and to provide assurance that all potential avenues for groundwater leaving the site were identified.

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Introduction

The Sulphur Bank Mercury Mine (SBMM) is an abandoned open-pit and underground mine on the eastern shore of the Oaks Arm of Clear Lake (Fig. 1), a large, freshwater lake located about 80 miles north of San Francisco. In 1986, the State of California posted an advisory against the consumption of fish from Clear Lake because of mercury (Hg) contamination. Sulphur Bank Mercury Mine's location on the shore of Clear Lake makes it the most likely source for the Hg contamination. Additional evidence is the temporal coincidence of surface mining at SBMM with the sharp increase in the Hg content of dated sediment cores taken from Clear Lake (Sims and White, 1981). During mining operations, Hg-containing waste rock and tailings from on-site ore processing were disposed in piles on the mine site, along the Clear Lake shoreline, and directly into Clear Lake (US EPA, 1994). SBMM was proposed for inclusion on

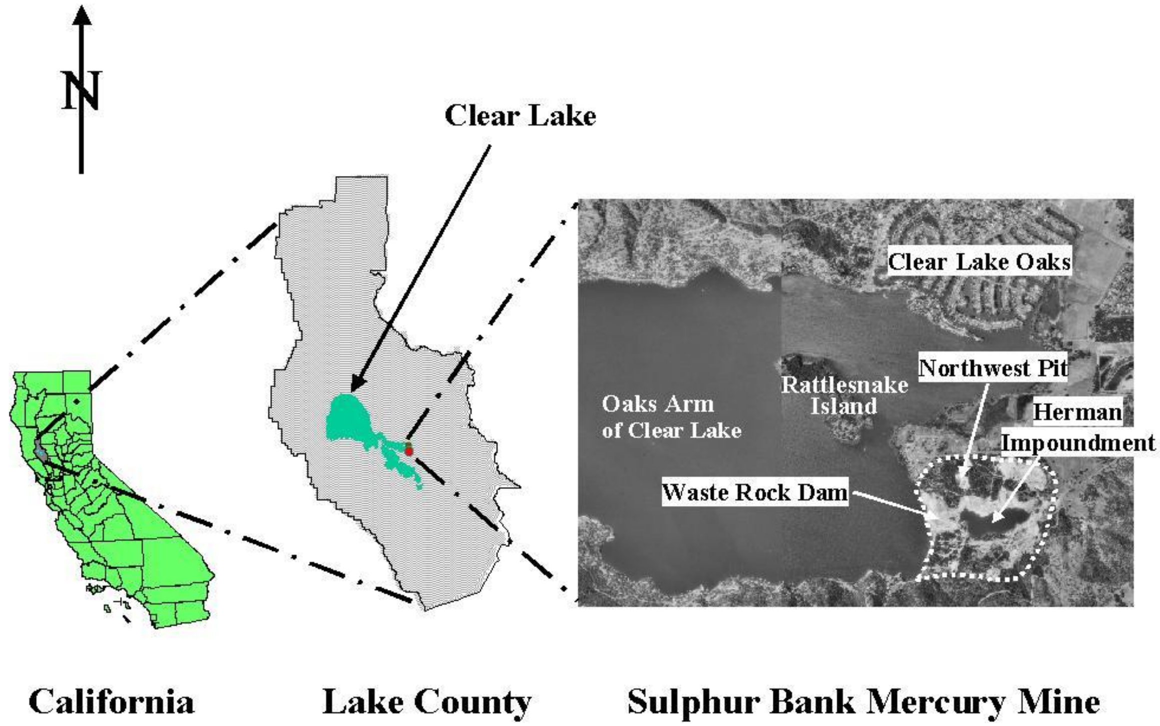

Figure 1. Location map for Sulphur Bank Mercury Mine

the National Priority List in 1988 and became a superfund site in 1991 (US EPA, 1994). Two remedial actions have been performed since superfund designation: regrading and vegetation of mine waste piles along the shoreline of Clear Lake to decrease erosion, and the construction of a surface runoff diversion system to reduce the amount of water contacting mine waste (USEPA, 1994). A Remedial Investigation/Feasibility Study (RI/FS) that fully characterizes the SBMM site and proposes remedial actions was published in December 2001. The U.S. EPA, National Risk Management Laboratory funded the geophysical reconnaissance described in this paper to augment the RI/FS process.

This paper contains the results of an airborne geophysical reconnaissance of the Oaks Arm of Clear Lake (including the SBMM Superfund Site), that was conducted to identify geologic structures and conductive groundwater plumes that may be responsible for Hg flux into the lake. Airborne geophysical results were supplemented with results from airborne multispectral imaging, a limited ground-based geophysical survey, and site information provided by Tetra

Tech EM, Inc., which included down-hole geophysical logs, a site hydrologic model, and a site geologic map.

Site Description

The Sulphur Bank Mercury Mine comprises approximately 49 hectares (120 acres) of disturbed ground, including piles of low-grade ore, waste rock or tailings and a flooded open-pit now known as the Herman Impoundment (Fig. 1). Herman Impoundment covers approximately 9.3 hectares (23 acres) and is about 33-m (100-ft) deep. A smaller pit (Northwest Pit, Fig.1) is located about 175 meters (575 ft) northwest of Herman Impoundment. Most of the waste rock excavated from the open pits was disposed in an elevated area between Herman Impoundment and Clear Lake (Waste Rock Dam, Fig. 1).

Mining History

SBMM was initially mined for sulfur during 1865-68. From 1899 until 1918, mercury ore was intermittently mined at the site using underground methods. Most of the mercury ore was mined from open pits between 1922 and the mine's final closure in 1957 (White and Roberson, 1982).

Geologic Setting

The Sulphur Bank Mercury Mine is located in the southern part of the Northern Coast Ranges of California. The predominant bedrock in the mine area is graywacke and argillite of the Jurassic to Eocene Franciscan Complex that is overlain by Quaternary andesitic lava from vents northeast of the study area. Other lava sources could be vents directly northwest of Herman Impoundment on Rattlesnake Island (Hearn et. al., 1995). The flow is part of the Clear Lake Volcanics, a sequence of volcanic flows and domes that range in composition from rhyolite to basalt. The Franciscan Complex in the southern part of the study area consists of a thick sequence of metamorphosed sandstone, conglomerate, argillite, basalt, amphibolite, and serpentinite. Unconsolidated Quaternary lake sediments overlie Franciscan bedrock in areas adjacent to Clear Lake but underlie the andesite flow (White and Roberson, 1962).

Thermal modeling indicates that a shallow (4 to 5-km depth) body of cooling magma underlies the SBMM and is responsible for the strong geothermal activity in the immediate area

(Stimac et. al., 2001). The Sulphur Bank Mine Stock is one part of a complex of magma bodies underlying Clear Lake volcanic field west and south of SBMM (Isherwood, 1975; Stimac et. al., 2001).

Problem Definition

The water level elevation in Herman Impoundment, the flooded open-pit of the SBMM, is about 3.96 m (13 ft) higher than the level of Clear Lake. Groundwater would be expected to flow downgradient from Herman Impoundment through the 200-m wide dam that separates the two water bodies and into Clear Lake. One goal of the RI/FS is to identify groundwater flow paths through the dam.

The dam is predominantly composed of waste rock from the open pit. When the waste rock was dumped, the coarser materials rolled to the bottom of the pile, and a segregation of particle sizes occurred. The particle-size heterogeneity that is typical of mine waste dumps results in a pseudokarst hydrology where zones of high permeability are separated both vertically and laterally by areas of much lower permeability. The erratic distribution of permeable zones is a function of dump history and design, as well as the physical characteristics of the waste rock material.

The acidic, metal-containing water of Herman Impoundment is highly conductive and contrasts sharply with the more resistive andesite, which is the predominant rock type at SBMM. Altered andesite also comprises most of the material in the waste rock dam. Because of this contrast, the flow pathway(s) for Herman Impoundment water through the waste rock dam are expected to be readily apparent in electromagnetic (EM) conductivity surveys.

Methods

Geophysical Surveys

Airborne, multiple-frequency EM conductivity surveys and total field magnetic surveys were flown over a 12.3 km^2 (4.75 sq. mile) area of the Oaks Arm of Clear Lake. Fugro Airborne Surveys performed these surveys August 9-16, 2000 using proprietary Dighem^{V} and Dighem^{VRES} multi-coil, multi-frequency EM systems, as well as a high-sensitivity cesium magnetometer. The Dighem^{V} EM system contains two vertical coaxial coil pairs and three horizontal coplanar coil pairs (Fig. 2). The vertical coaxial coil pairs are especially useful for detecting narrow conductors such as faults or man-made objects such as pipelines or electrical cables. The three horizontal coplanar coil pairs are used for detecting horizontal conductors such as aquifers or conductive strata in layered earth. The Dighem^{VRES} contains five horizontal coplanar coil pairs (Fig. 2) with a frequency spread of 380 to 90,000 Hz. This system is optimized to define conductive properties of the earth's layering in the top 100 m (Fugro Airborne Surveys, 2000). Magnetic data were acquired using a cesium magnetometer to determine differences in the earth's magnetic field, which reflect differences in the local abundance of magnetic minerals. Magnetic data are especially useful for locating faults and geological contacts. The survey was conducted from a helicopter platform with the EM sensor about 30 m (100 ft) above ground level and a line spacing of 50 m. The survey was first flown with the Dighem^{V} EM "bird" and a cesium magnetometer and then repeated with the Dighem^{VRES} EM "bird". The airborne surveys were conducted August 9-17, 2000.

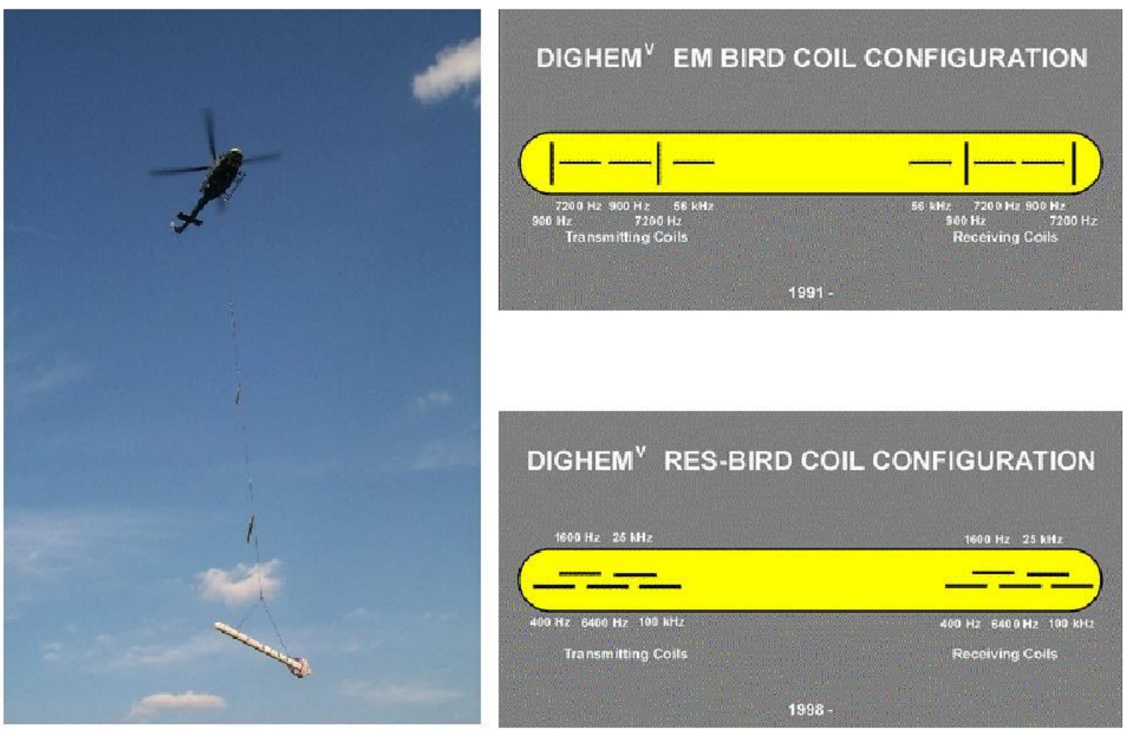

Figure 2. Coil Configuration for the Dighem^{V} and Dighem ^{VRES} birds.

Airborne EM conductivity data were acquired at eight frequencies using a horizontal coplanar coil configuration (380 Hz, 900 Hz, 1400 Hz, 6200 Hz, 7200 Hz, 25 kHz, 56 kHz, and 102 kHz) and two frequencies using a vertical coaxial coil orientation (900 Hz and 5500 Hz). Although data acquired using the vertical coaxial coil orientation were useful for identifying line conductors such as pipelines and submarine electrical cables, the horizontal coplanar coil orientation was better suited for identifying hydrologic features at SBMM. Data acquired at frequencies of 56 kHz, 7200 Hz, and 1400 Hz using a horizontal coplanar coil orientation are presented in this paper, and represent ground conductivity from the near-surface to depths of at least 30 m (100 ft).

A follow-up ground-based geophysical survey was conducted on October 16-18, 2000 by DOE's National Energy Technology Laboratory (NETL). The ground survey was conducted on a portion of the waste rock dam that exhibited anomalous conductivity in airborne surveys. The Geonics EM34-3XL used for ground-based electromagnetic surveys consisted of a transmitter and a receiver coil pair with an inter-coil spacing of either 20 m or 40 m. Different exploration depths were achieved by changing the orientation and inter-coil spacing of the transmitter and receiver coils. Measurements were acquired with the coil pairs in the horizontal dipole mode and in the vertical dipole mode. The vertical dipole mode is equivalent to the horizontal coplanar orientation used in airborne surveys. The exploration depth (δ) can be approximated using the coil orientation and separation (s).

For horizontal dipole $\delta \cong 0.75\ s$

For vertical dipole $\delta \cong 1.5\ s$

Therefore, the first approximation of exploration depth would be:

15 m for horizontal dipole, 20-m coil separation
30 m for horizontal dipole, 40-m coil separation
30 m for vertical dipole, 20-m coil separation, and
60 m for vertical dipole, 40-m coil separation.

<u>Project Goals</u>

Goals for the current study were: 1) to demonstrate the efficacy of geophysical techniques for characterizing environmental problems, 2) to determine the accuracy of geophysical information, its spatial correctness, and its relevance to site geology and hydrology, and 3) to provide new information to the RI/FS that will augment existing hydrologic and geologic information.

Results

Total Magnetic Field

Total field magnetic data collected from airborne surveys are shown in Figure 3. This information is especially useful for mapping the extent of a lava flow beneath Clear Lake (solid black line). Because the lava flow contains a higher concentration of magnetic minerals, it contrasts sharply with surrounding lake sediments. Faulting and associated rock alteration destroys the remnant magnetism of volcanic rocks. Therefore, faults can be interpreted from sub-linear, magnetic "lows" in areas underlain by the lava flow. Faults interpreted from a detailed analysis of the magnetic data are shown as dashed magenta lines in Figure 4. Names were given to faults identified in this study for the sake of convenience. No attempt was made to correlate these faults with faults identified by other investigators.

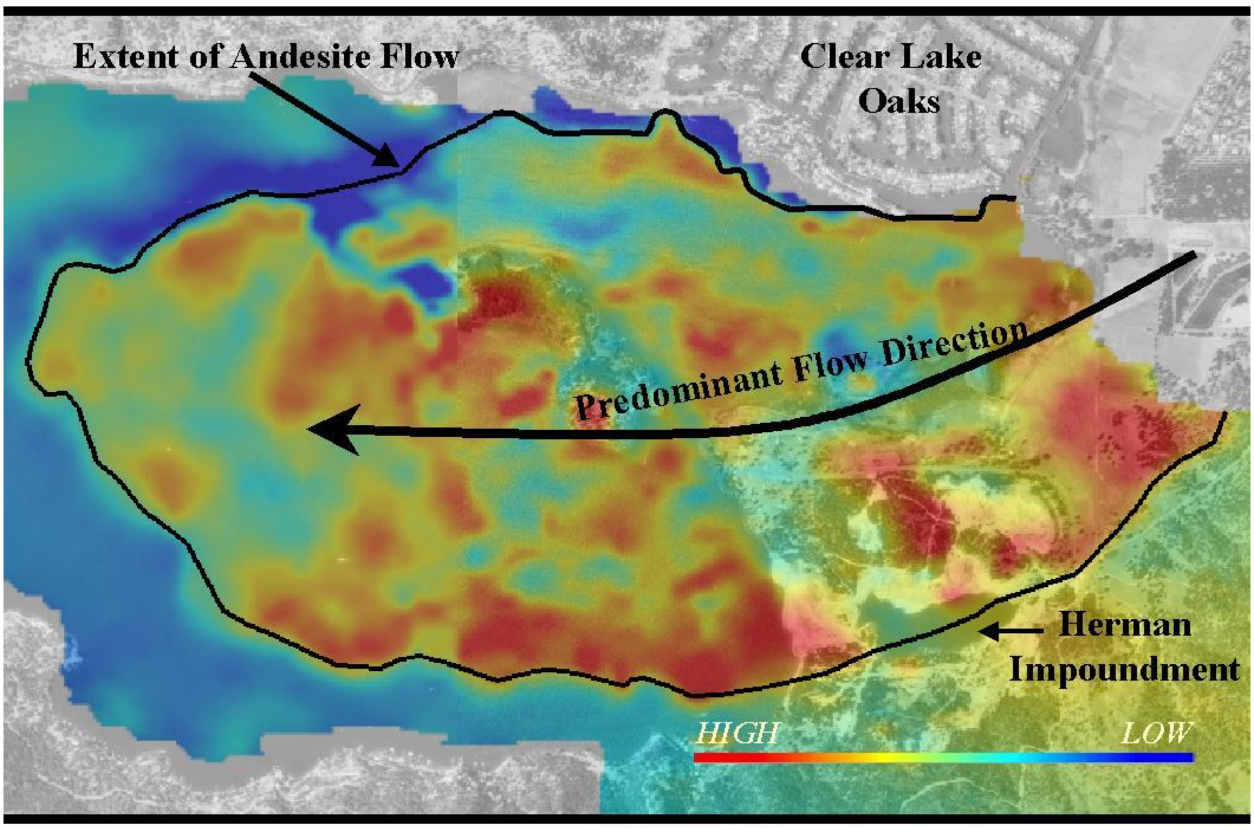

Figure 3. Airborne total field magnetic map of Oaks Arm of Clearlake

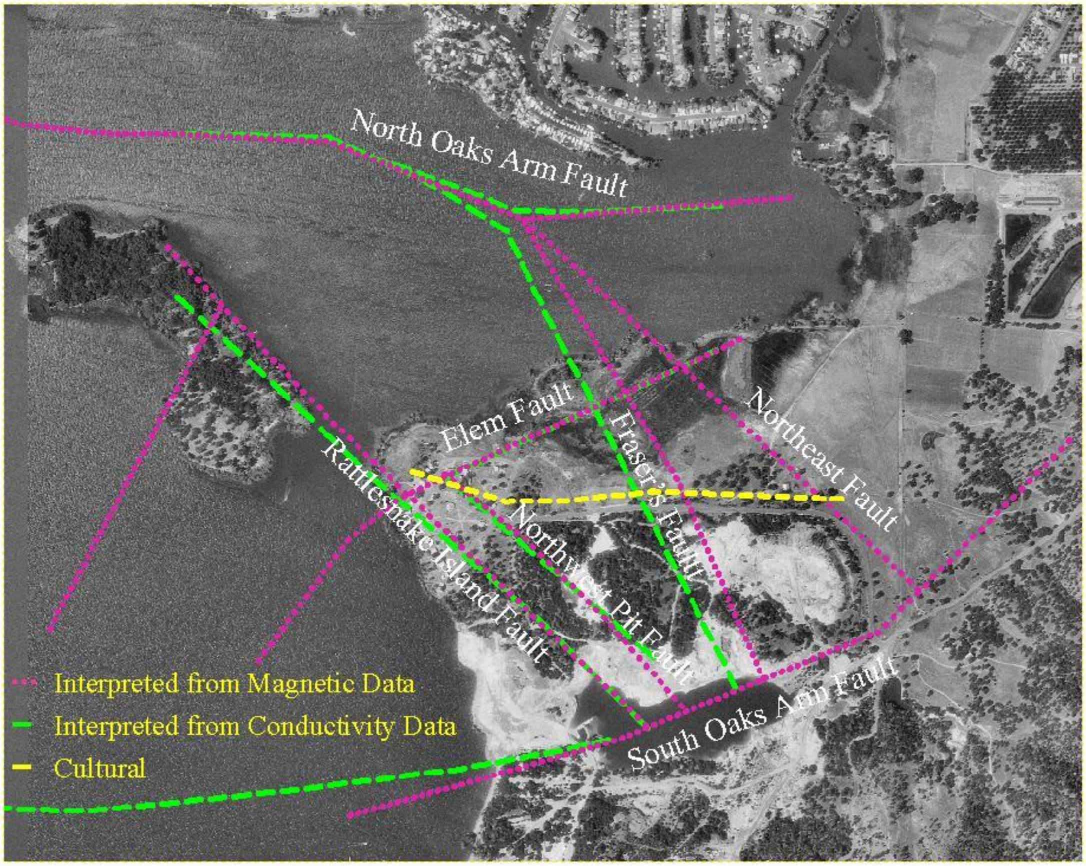

Figure 4. Fault map of Sulphur Bank Mercury Mine

Multiple-frequency EM Conductivity

Figure 5 is an airborne conductivity map acquired at a frequency of 56 kHz, the highest frequency data acquired at SBMM (data were also collected at 102 kHz but were not useable due to excessive swinging of the "bird"). At this frequency, the exploration depth ranges from 2.5 m (8 ft) in red areas to 33 m (110 ft) in blue areas. The water within Herman Impoundment is acidic and produced a strong conductive anomaly (A, Fig. 5). However, the conductive anomaly extends beyond the boundaries of the impoundment and into the bedrock north of the pit and into the waste rock dam (dump) west of the pit (B, Fig. 5). A conductive zone extends completely through the waste rock dam (C, Fig. 5). An area of anomalous conductivity also exists within Clear Lake with the highest values being measured near the shoreline (D, Fig. 5).

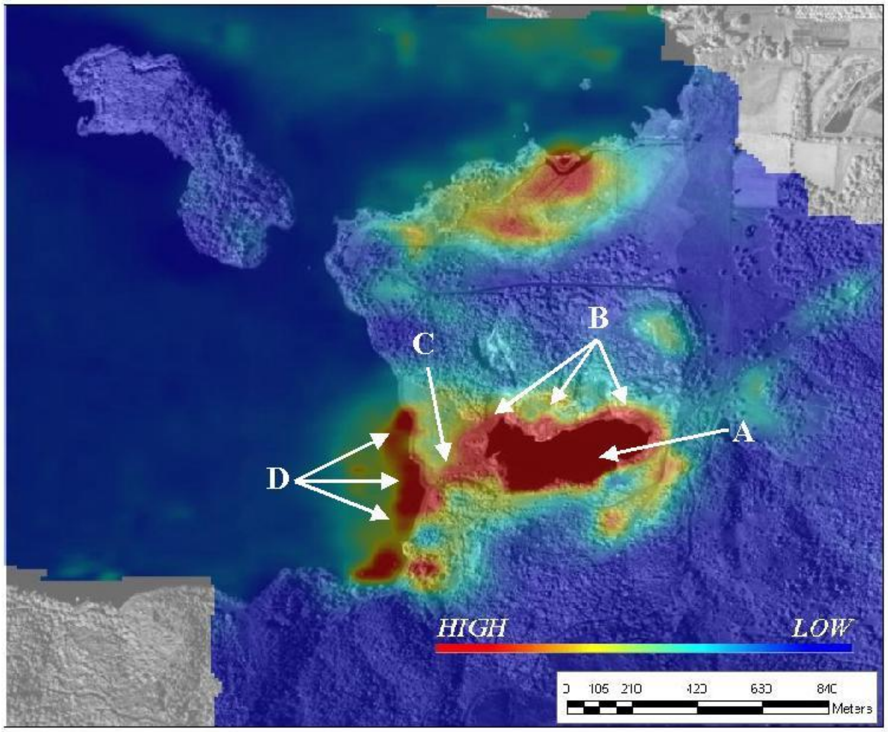

Figure 5. Apparent Conductivity Map Acquired Using a Horizontal Coplanar Coil Orientation at a Frequency of 56 kHz

Figure 6 is a map showing the location of shallow, conductive anomalies. Anomalies A, B, C, E, F, and G are thought to represent shallow, acidic groundwater plumes formed in situ by the weathering of sulfide minerals. Anomaly D is a wetland area where the anomalous conductivity may indicate the presence of clay minerals. However, the area also served as a settling basin for water pumped from the open pit during mining. Therefore, the anomalous conductivity also could indicate the presence of weathered metal sulfide minerals.

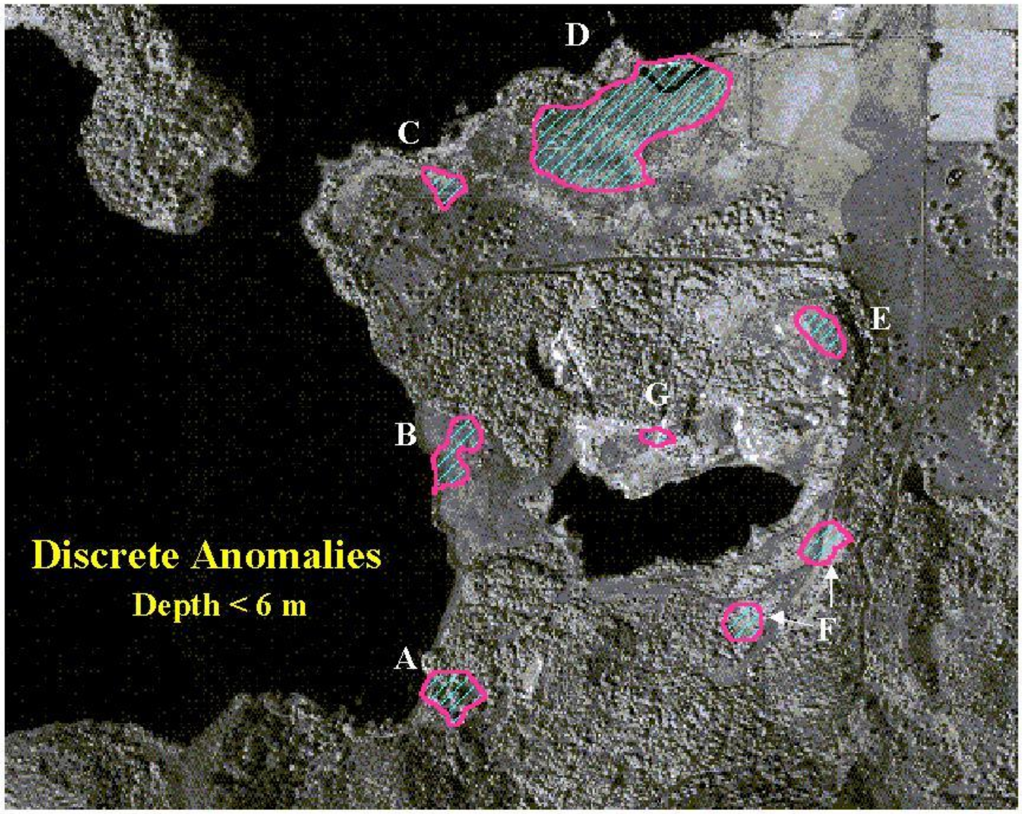

Figure 6. Location of shallow anomalies. SBMM anomaly not shown.

Figure 7 is an airborne conductivity map acquired with a horizontal coplanar coil orientation at a frequency of 7200 Hz. The exploration depth for this map ranges from 7 m (23 ft) in the conductive areas (red) to 94 m (308 ft) in the most resistive areas (blue). The 7200 Hz conductivity map has many of the same anomalies that were observed in the 56 kHz data. However, one difference is that the conductive anomalies in the 7200 Hz data are elongated and coincide with the primary faults in the SBMM area (shown in black, Fig. 7).

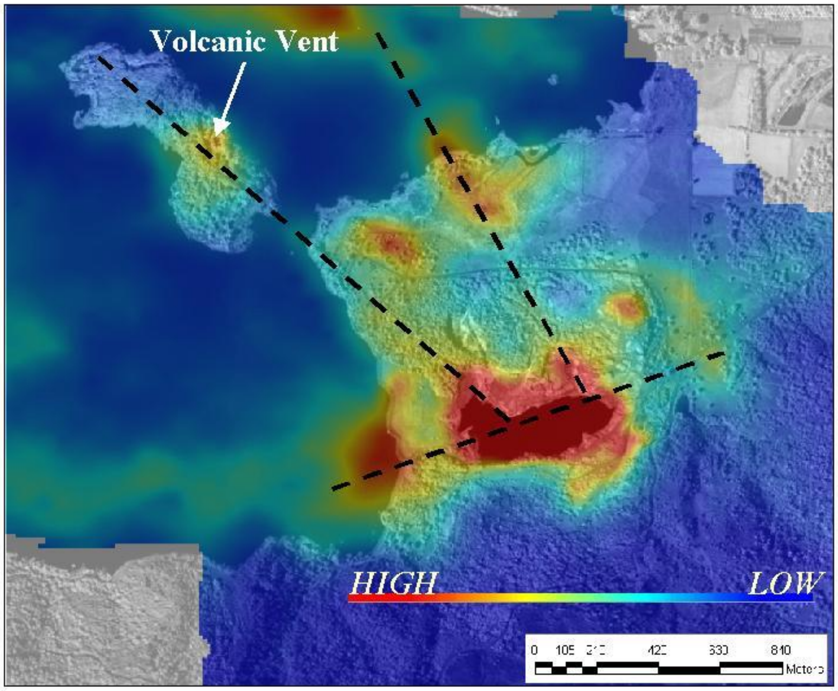

Figure 7. Airborne Conductivity Map of SBMM acquired using a Horizontal Coplanar Coil Orientation and a Frequency of 7200 Hz

Figure 8 is an airborne conductivity map acquired with a horizontal coplanar coil orientation at a frequency of 1400 Hz. The exploration depth range for this map is from 15 m (50 ft) to 200 m (650 ft), depending on ground conductivity. The alignment of conductive anomalies with faults (dashed black lines) is more pronounced with increasing exploration depth.

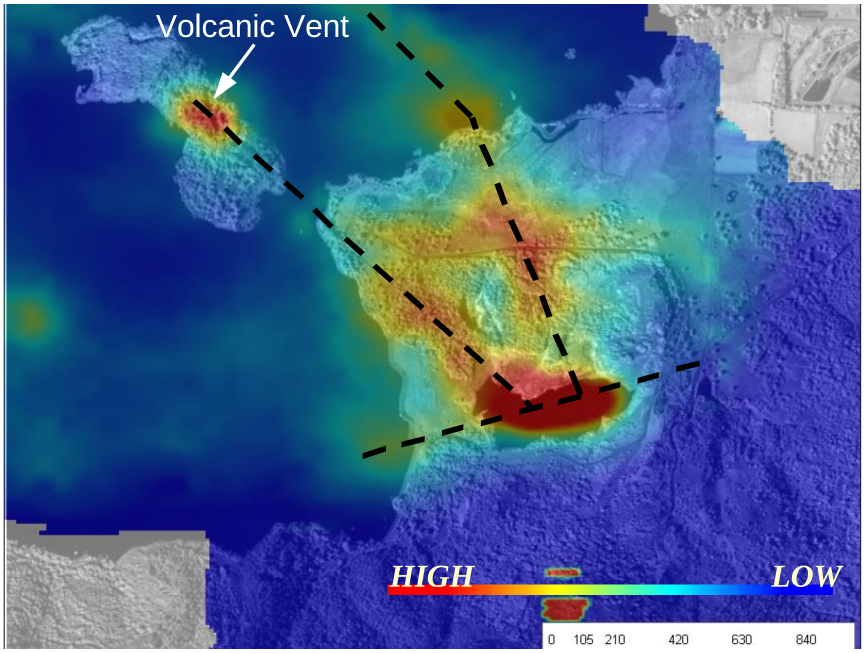

Figure 8. Airborne Conductivity Map of SBMM acquired using a Horizontal Coplanar Coil Orientation and a Frequency of 1400 Hz

Ground Surveys

A ground EM conductivity survey was conducted on an anomalous area of the waste rock dam that was identified in airborne surveys. The purpose of the ground survey was to corroborate the airborne survey and to better define the conductive anomaly that extends across the waste rock dam between Herman Impoundment and Clear Lake. Figure 9 is a conductivity map from the ground EM34-3XL survey conducted with horizontal coplanar coil orientation (vertical dipole in Geonics terminology) and a 40-m inter-coil separation. The map of the ground survey is overlain on an airborne conductivity map acquired using a horizontal coplanar coil orientation and a frequency of 6200 Hz. The exploration depth for both the ground survey and the airborne survey is about 60 m (197 ft), depending on ground conductivity. Whereas airborne conductivity maps show a band of conductive ground trending east northeastward across the waste rock dam, the more-detailed ground survey shows that the conductive band follows a more serpentine path through the waste rock dam (Fig. 9). The more circuitous pathway probably indicates the location of discontinuous, permeable zones that are a function of the dump's construction history.

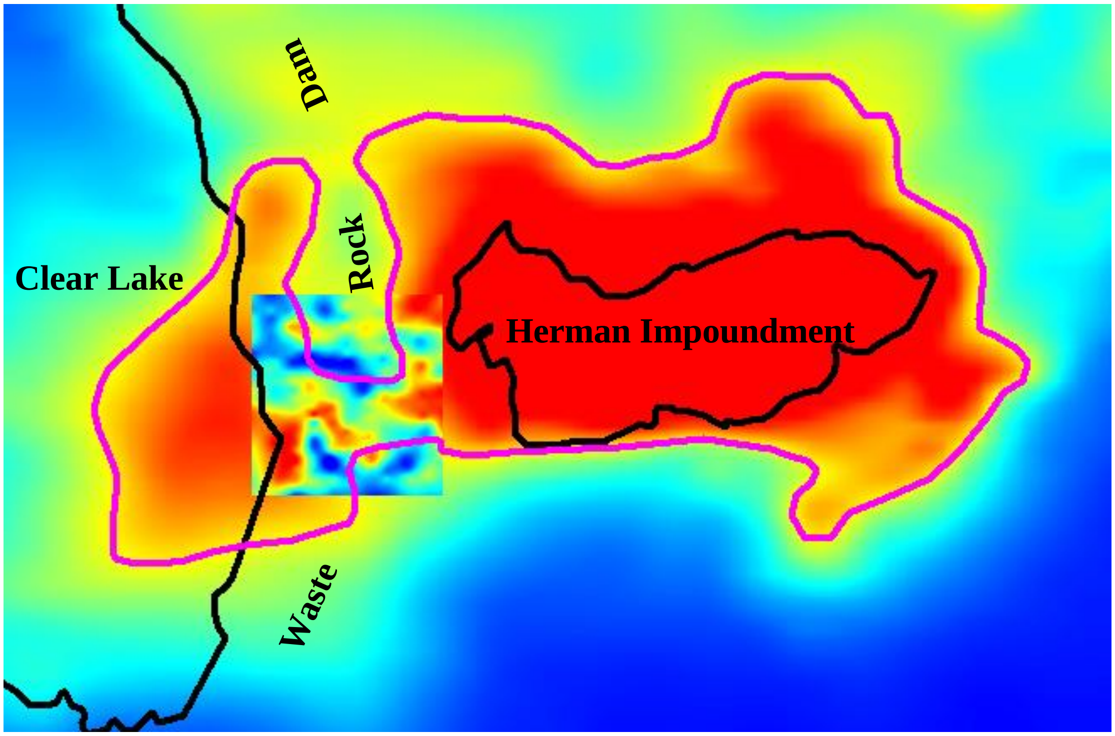

Figure 9. EM34-3XL Survey with 40-m Intercoil Separation (Rectanglar Inset) Superimposed on Airborne Conductivity Survey Acquired at 7200 Hz

Discussion

Faults

Airborne magnetic and EM conductivity data were useful for determining the location of significant faults and fracture zones in the vicinity of SBMM. Faulting and hydrothermal alteration destroy remanent magnetism. Therefore, fault zones within the andesite flow and underlying Franciscan bedrock appear as magnetic "lows". Zones of rock alteration, sulfide mineralization, or conductive groundwater in faulted areas are depicted as EM conductivity "highs". In Figure 4, faults interpreted from magnetic "lows" and EM conductivity "highs" are shown as dashed magenta lines and dashed green lines, respectively. In most cases, the fault locations interpreted from magnetic data correspond well with fault indications from EM conductivity data. One notable exception is the Fraser's Fault where the fault location based on magnetic data is about 50 m east of the location based on EM conductivity data. Geologic mapping of bedrock exposures on the north wall of Herman Pit validates the locations for the Rattlesnake Island Fault and the Northwest Pit Fault (interpreted from magnetic and EM conductivity data) and suggests that the location of the Fraser's fault based on EM conductivity data is correct. Moreover, two groundwater-monitoring wells drilled in the Rattlesnake Island Fault Zone northeast of Herman Impoundment encountered fractured rock and clays indicative of fault gouge (Engle, 2001). These findings corroborate the fault interpretation based on geophysical data. Magnetic data, but not conductivity data, indicate the existence and location of the Northeast Fault. The Northeast Fault is probably not a conduit for conductive, hydrothermal water and has therefore undergone little wall-rock alteration. This information is important to the RI/FS because some faults may represent conduits for groundwater flow either toward or away from Herman Impoundment. Note that fault names are to be used only within the context of this paper.

Waste Rock Dam

Accurate locations for the groundwater pathways through the waste rock dam are important for the interdiction of Hg flux into Clear Lake. The most probable location for groundwater flow is visible in the airborne EM conductivity maps of all frequencies (Figs 5, 7, and 8) as the anomalous conductivity band that extends across the waste rock dam. The ground conductivity survey confirms and more accurately defines the band of anomalous conductivity (Fig. 9). The location of the conductivity anomaly is coincident with the location of the South Oaks Arm Fault (Fig. 4) and, possibly, a pre-mining stream channel (only anecdotal evidence). Both features are suggestive of fractured bedrock that would be expected to provide sub-linear zones of permeability and hydraulic conductivity. Groundwater flow paths through the dump material that overlies bedrock are a function of porous zones, which are an artifact of the dump's construction. Currently, there are no groundwater monitoring wells within the anomaly and the EM conductivity data and its interpretation cannot be confirmed.

Near-Surface Conductive Anomalies

Shallow, conductive anomalies were identified in EM conductivity maps collected at a frequency of 56 kHz (Figs. 6 and 6). These anomalies are thought to represent local concentrations of sulfidic ore, tailings, or waste rock that are weathering to produce conductive groundwater plumes. Anomaly locations from airborne geophysics are currently being used to direct soil and groundwater investigations at the SBMM Superfund Site.

Summary

Geophysical surveys were able to locate faults and potential groundwater flowpaths at Sulphur Bank Mercury Mine because contrast was optimal for the magnetic and electromagnetic conductivity techniques employed. The area was underlain by an andesitic lava flow that was highly magnetic and resistive. Against this background, the less magnetic and less resistive (more conductive) fault zones were easily discernable. Geophysical surveys detected four potential flowpaths for groundwater that had not been accurately located by a detailed hydrologic investigation. However, without drill hole confirmation, geophysics cannot determine the permeability of fault zones or the direction of groundwater flow.

When used as an early reconnaissance technique in areas with optimal contrast and minimal cultural interference, geophysical surveys can reduce the cost of hydrologic investigations by more effectively targeting groundwater-monitoring wells. In such cases, better information is obtained from a fewer number of wells, but ones that are ideally located.

Acknowledgements

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