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CONTROLLED SOURCE AUDIO-FREQUENCY MAGNETOTELLURIC SURVEYS OF PORPHYRY SULFIDE DEPOSITS AND PROSPECTS IN THE CORDILLERA OF THE UNITED STATES

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ABSTRACT

During the years 1978 to 1981, Zonge Engineering and AMAX, in a joint venture, continued the development of a commercially available controlled source audio-frequency magnetotelluric (CSAMT) technique. During the course of the development, CSAMT surveys were conducted over a number of known porphyry sulfide deposits and prospects in the western U.S. CSAMT surveys proved to be an extremely effective technique for defining the horizontal limits and depth extent of porphyry systems.

Known deposits surveyed included Mt. Emmons and Henderson in Colorado, and Pine Nut in Nevada. In CSAMT surveys, porphyry sulfide systems can be identified by steep to vertically bounded zones of low apparent resistivity (ρ_a). The vertical extent, or depth, of the system is determined by a 1-D interpretation of data in the center of the system.

The technique can be used to map the electrical stratigraphy, and dips ≥60° have been traced. The ability to map such steeply dipping horizons has applications both in engineering and exploration.

Low cost self-potential (SP) surveys were used to define the centers of the porphyry prospects prior to the CSAMT surveys in order to minimize the cost and maximize the effectiveness of the CSAMT surveys.

Of the prospects surveyed with CSAMT, two were explored by diamond core drilling. The first drill hole tested the Wolverine prospect on Mt. Emmons near Crested Butte, Colorado. Based on the CSAMT data, mineralization was predicted to lie 760 to 915 m below the surface. Ore grade mineralization (≥0.2 Wt% MoS_2) was first encountered at 747 m, and continued intermittently to about 850 m. Subsequent drilling showed the prospect to be subeconomic. However, the lateral definition provided by the CSAMT survey allowed AMAX to drill out the prospect with five holes, as compared to fifteen holes required to test the nearby, similar Redwell prospect. The savings realized on the drilling costs thus amounted to at least $1.5 million. The lateral boundaries defined by CSAMT were confirmed by competitor drilling outside the prospect. A second drill hole was used to test a prospect west of the Pine Nut deposit, Nevada. The bottom of the sulfides was predicted at 200 m. The base of the sulfides was found at 186 m. While neither prospect proved to be economic, the CSAMT surveys were an unquestionable success in defining the lateral and vertical extent of the systems, and minimizing the drilling costs.

Extremely low, directional resistivities, and an apparent resonance are possibly related to ferroelectric effects associated with known ferroelectric minerals in the sulfide systems surveyed. Disseminated sulfides in a porphyry system give a response which appears to be analogous with a ferroelectric ceramic. Within the sulfide system, ρ_a is probably the impedance of a ferroelectric ceramic at a given frequency and reflects the charge transfer characteristics of the medium rather than the ohmic resistance.

INTRODUCTION

The magnetotelluric method has been in use since the 1950's utilizing natural magnetic and electric fields as a source. An excellent collection of the basic papers on the subject can be found in Vozoff (1985). Limitations in the available frequency spectrum of natural sources, signal strengths which are dependent on solar activity and lightning discharges, and varying source distance and direction, place considerable limitations on the use of natural source magnetotellurics in exploration. To circumvent these problems, Goldstein (1971), and Goldstein and Strangway (1975), developed a controlled source audio-frequency magnetotelluric (CSAMT) method. In 1978, AMAX and Zonge Engineering entered into a joint project to continue development of a commercially available CSAMT technique. The joint project continued until October of 1981, when it was cancelled due to declining metal values. The development phase and experimental methods are described in Zonge and others (1985).

The results presented here emphasize the geologic interpretation of the surveys, with a minimum of survey data and methods of interpretation included. Survey data and interpretation techniques will be presented elsewhere in a subsequent paper.

All the sulfide systems surveyed had distinctly directional apparent resistivity (ρ_a) which we indicate by showing the high ρ_a and low ρ_a directions. We have no way of determining from the present data whether the high ρ_a line direction is a maximum or the low ρ_a line direction is a minimum. Also, when ore minerals are present in significant concentrations, we noticed a phenomena we have termed *resonance* because a log-log plot of ρ_a vs. frequency has the appearance of a series resonant tuned circuit. Such resonance effects appear to be characteristic of ore minerals and they are considered diagnostic. We have included a brief discussion of a possible ferroelectric mechanism for these phenomena.

Theory

The method of calculating ρ_a from measurements of the electric and magnetic fields, the Cagniard resistivity, is given by the relation:

$$\rho_a = [1/(2\pi f \mu_0)]\cdot[E/H]^2 \qquad (1)$$

where E and H are the measured tensor electric and magnetic fields, respectively, f is frequency in Hz, and μ_0 is the magnetic permeability of free space. Because it uses a plane wave controlled source whose direction is known, the CSAMT method has the advantage that only the E_y (the E field in the line direction) and the H_x (H field perpendicular to line direction) components of E and H must be measured in order to calculate the Cagniard resistivity. It should be emphasized that ρ_a has little relation to the ohmic resistance of the rock, as discussed by Spies and Eggers (1986), and in this paper. Within the sulfide system, ρ_a appears to be the impedance of a ferroelectric ceramic at a given frequency and reflects the charge transfer characteristics of a dielectric medium rather than simply the ohmic resistance.

In order to use a controlled source, it is necessary that the transmitter and receiver be sufficiently separated that the source field approximates a plane wave at the receiver, i.e. the receiver is located in the far field at all frequencies transmitted. It has been found in practice that the plane wave approximation is satisfied if the receiver and transmitter are separated by three or more skin depths (≥3δ). Skin depth (δ) is the distance from the source in some medium at which an electromagnetic wave is attenuated to 1/e of its original amplitude. Skin depth, in meters, is given by the relation:

$$\delta(m) \simeq 503(\rho/f)^{1/2} \qquad (2)$$

assuming the medium has the magnetic permeability of free space (μ_o) and ρ is ohmic resistivity of the medium in ohm-meters (Ω·m) given approximately by equation (1). The resistivity of the survey area must be estimated in order to establish δ at f_{min}. Because of the wide range of frequencies presently used, care must be taken that the 3δ relation is satisfied at the lowest frequency (f_{min}), i.e. the transmitter is $\geq 3\delta$ at f_{min}. Conversely, satisfying the far-field relation at the lowest frequency means that the signal will be greatly attenuated at high frequencies where the transmitter-receiver separation is many skin depths. In addition, at the higher frequencies the electric field measurement is contaminated by capacitive coupling between the receiver dipole wire and the earth. Capacitive coupling can be minimized by the techniques given in Zonge and Hughes (1985).

The effective depth of exploration is given by the magnetotelluric depth equation:

$$\text{Effective depth(m)} = \delta / \sqrt{2} = 356(\rho/f)^{1/2} \tag{3}$$

for a homogeneous earth. Layering and lateral effects reduce the effective depth. In general, however, lowering the frequency increases the depth of exploration. Hence, by measuring the apparent resistivity (ρ_a) at a series of progressively lower frequencies, a depth profile can be obtained for the earth beneath the reciever.

At each station frequencies are stepped in powers of two ($f = 2^n$) from the highest to the lowest. Power of two frequencies are used in order to facilitate stacking, averaging, and digital filtering in the GDP-12 receiver and data processor. The ρ_a is recorded at each frequency, and from this a parametric plot of frequency vs. ρ_a is made and contoured both in the field and later in the office after any required corrections to the data are applied. The layers can then be modeled by methods given by Constable and others (1987). The individual one-dimensional models are then plotted sequentially, in profile, from which the geologic interpretations presented below are made. Because the response of the earth is clearly not one-dimensional near a vertical resistivity boundary, considerable error can be expected for depth estimates in these areas.

Field layout

The general field layout is shown in Figures 1 and 2. The receiver and associated equipment are completely back-pack transportable, allowing for a great deal of flexibility in the location of receiver lines. The transmitter can be located at any site $\geq 3\delta$ at f_{min}. Occasionally a poor estimate of ρ_a required us to relocate the transmitter dipole closer to, or further away from, the receiver lines. The location of the transmitter was normally based on convenience of access, although the Henderson Mine survey required helicopter support for the transmitter site. The receiver lines were run within a 45° cone from the center of the transmitter, and normally within a 30° cone (Figure 1).

The initial survey at Mt. Emmons used a frequency range of 2 Hz to 2048 Hz. It was quickly realized that the low ρ_a found in association with sulfide deposits required lower frequencies, and subsequently the equipment was modified to allow a frequency range of 0.5 Hz to 4096 Hz. Capacitive coupling problems were evident at 4096 Hz, a problem not corrected until later (Zonge and Hughes, 1985), and the highest frequency used in the surveys presented here was 2048 Hz. Present (1987) CSAMT equipment has a frequency range from 0.125 Hz to 8192 Hz, allowing both deep and shallow exploration. Use of the entire frequency range at a single site would probably require two separate transmitter sites.

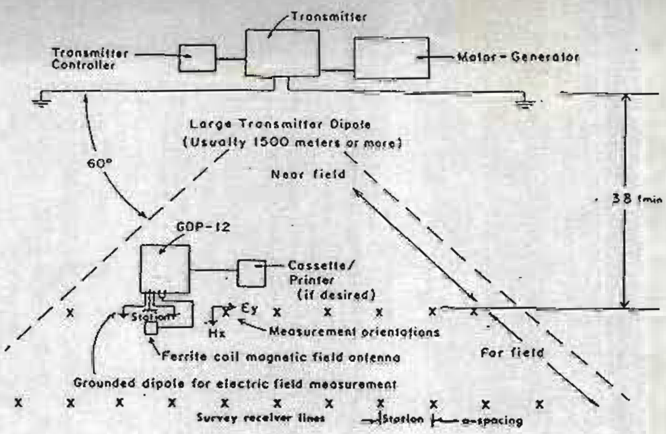

Figure 1. Explanation of standard CSAMT field set-up. Measurements can be made anywhere inside the cone delimited by the dotted lines. For far field (plane wave) measurements, the receiver lines should be no closer than 3δ to the transmitter dipole for the lowest frequency (f_{min}) used. Measurements can be made at separations < 3δ (near field) but interpretation is complicated and the interpretations are less reliable.

We were aware from the beginning that edge effects associated with electromagnetic (EM) coupling at the boundaries of the sulfide systems would be a severe problem. The CSAMT survey lines were always laid out to cross the mineralization boundary at a right angle. In order to do that, it is necessary to know where the center of mineralization is before running the CSAMT survey. In practice, the center of the mineralization was located with preliminary self-potential (SP) surveys (Corry, 1985). All of the surveys discussed here were targeted with SP surveys. The low cost SP surveys also allowed us to run CSAMT survey lines of minimum length, and optimally placed in areas of interest, thus minimizing the total cost.

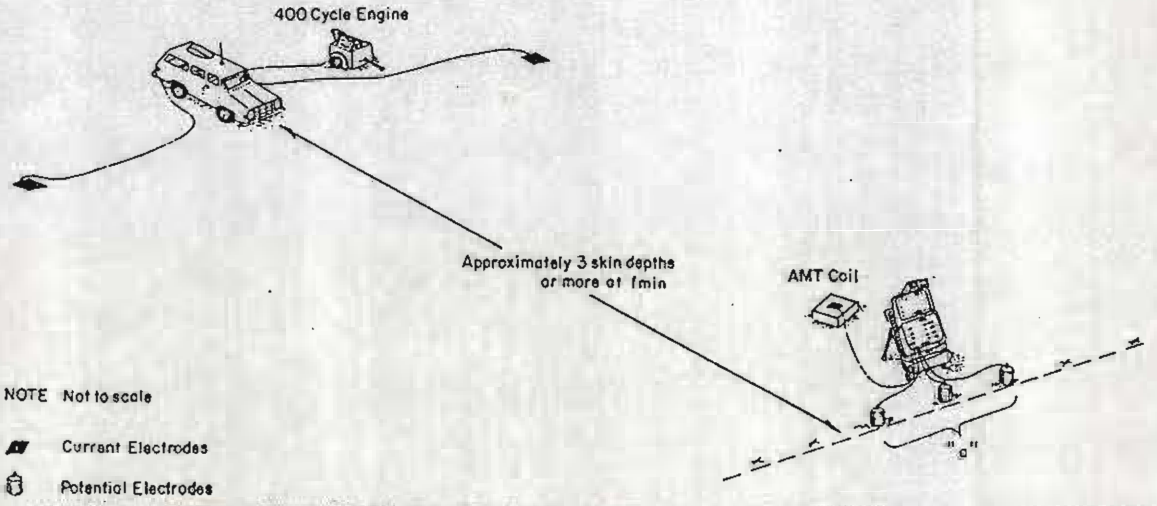

Figure 2. Pictorial representation of CSAMT field set-up. The lateral resolution is approximately one-half the receiver dipole size (a-spacing). Signal level decreases and survey time increases as the receiver dipole size is reduced. With only a few exceptions, all of the surveys presented here were run with a 122 m receiver dipole (a-spacing = 122 m). Signal level for a given receiver a-spacing can be increased by increasing the transmitter current or increasing the length of the transmitter dipole.

FIELD SURVEYS

Mt. Emmons, Colorado (38°53'N 107°03'W)

The initial survey of the project was run over the porphyry molybdenite deposit in Red Lady Basin at Mt. Emmons, Colorado. The Red Lady deposit is the third largest porphyry molybdenite deposit known and it was discovered shortly before the CSAMT project was begun. Since no development had occurred, cultural interference was minimal, and it made an ideal test site.

The line layout showing the relation of the CSAMT survey to the SP anomalies associated with the deposits on Mt. Emmons is shown on Figure 3. Our first CSAMT line was Red Lady 1 (Figure 4). Our geologic interpretation of the parametric plot (Figure 4) for Red Lady 1 is shown in Figure 5. Ore grade (≥0.2 Wt% MoS_2) mineralization extends from about station 2 to station 30 on this line as determined from drilling. Sulfide mineralization, in the form of a pyrite-pyrrhotite halo, extends to station 66.

In retrospect, the poor data quality and the lack of low frequency information make the interpretation shown in Figure 5 questionable when compared with later surveys, e.g. Red Cone. Nonetheless, the detail in depth determination and lateral extent exceeded that available from any other technique, e.g. magnetics, gravity, complex resistivity, and seismic reflection, used at this site. For comparison, the high-resolution (10 m shot point spacing) seismic survey over the Red Lady deposit did not show the ore body or underlying stock at all, though bedding in the sedimentary rocks was clearly definable in the seismic data.

The ore body is more clearly delineated in line Red Lady 2, as shown in Figure 6. From drilling, ore grade MoS_2 extends from between stations -16 and -12 to station +12. Pyrite and pyrrhotite haloes extend both northeast and southwest from the ore body. The low resistivity zone around the central stock corresponds to the quartz-sericite-pyrite (QSP) alteration.

The apparent resistivity for stations -4, 0, and +4 on line Red Lady 2 exhibits a feature which appears to be characteristic of ore minerals. When plotted on a log-log plot of frequency vs. ρ_a (Figure 7), the slope of the plot exceeds the theoretical maximum of 45° for a layered earth with a perfectly conducting basement, and shows a pronounced minimum resistivity at a frequency of 64 - 128 Hz. An equivalent electrical circuit would be a series resonant tuned circuit. We do not attribute this apparent resonance to 60 Hz power lines since there is very little culture in the vicinity of Mt. Emmons.

SP anomalies (Figure 3) on the ridge between Wolverine and Redwell Basins were investigated by line Daisy Mine 1 (Figure 8). The Wolverine prospect (Figure 8) was delineated by this line and line Daisy Mine 2 (Figure 9). Based on a preliminary version of Figure 9, possible ore grade mineralization was predicted to lie 760 to 915 m beneath the surface. Subsequent drilling near station 50 on line Daisy Mine 1 (Figure 8) encountered ore grade mineralization (≥0.2 Wt% MoS_2) at 747 m, and this mineralization continued intermittently to about 850 m.

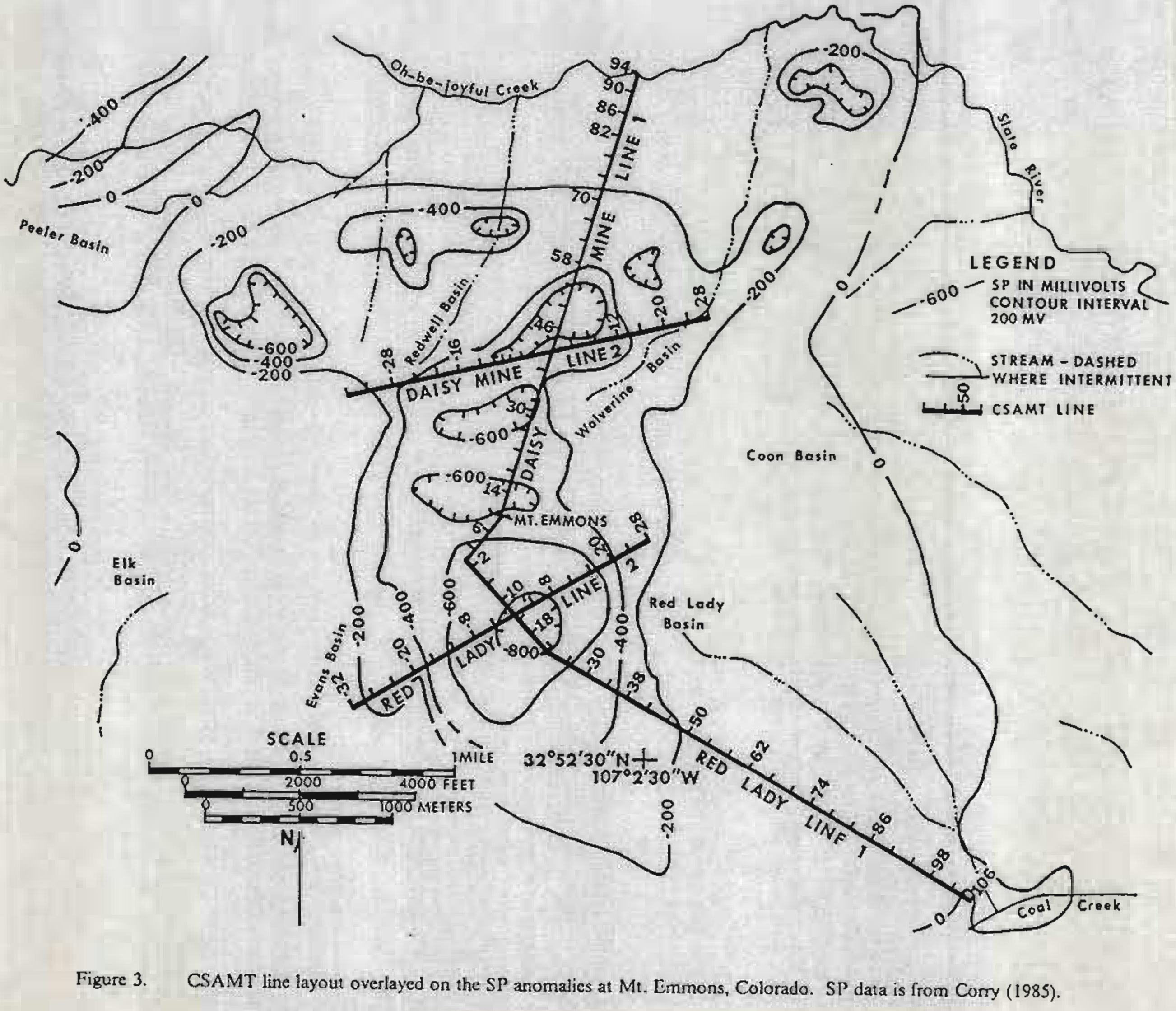

Figure 3. CSAMT line layout overlayed on the SP anomalies at Mt. Emmons, Colorado. SP data is from Corry (1985).

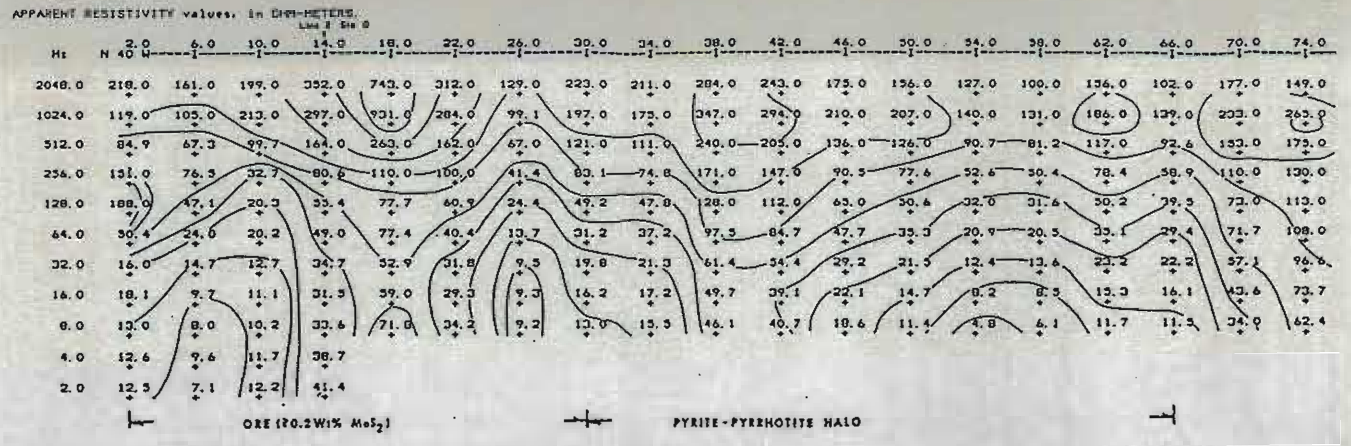

Figure 4. Parametric plot of frequency vs. ρ_a for a portion of line Red Lady 1. This is the high ρ_a direction. The ore zone (≥0.2 Wt% MoS_2) defined by drilling extends from station 2 to 30. The pyrite - pyrrhotite halo extends to station 66. For a graphic interpretation, each station is plotted on a log-log graph of ρ_a vs. frequency. Depths to layers with contrasting ρ_a are represented on such a plot as inflection points from which depths can be estimated. An average ρ_a for each layer is also estimated and from such 1-D plots the electrical stratigraphy can be deduced. The geologic interpretations presented here were done in this fashion. The initial models can then be refined by methods described in Constable and others (1987). We have not yet made such advanced interpretations. These plots are originally drawn and contoured in the field so that structures, boundaries, and low ρ_a are immediately apparent to the operator. Where necessary, the a-spacing can be reduced to better resolve a boundary, or other necessary changes can be made in the survey as it progresses, based on the field parametric plot.

While subsequent drilling showed the prospect to be subeconomic, the lateral and vertical definition provided by the CSAMT survey (Figures 8 and 9) allowed the prospect to be completely tested with 5 drill holes. Similar deposits, located nearby at the head of Redwell Basin, required 15 drill holes to define the system there. At a drilling cost of ~$130/m, the savings in drilling costs amounted to at least $1.5 million. The total cost of the CSAMT survey at Mt. Emmons was $23,634. Obviously, CSAMT surveys can be very cost effective. Competitor drilling north of station 16 on line Daisy Mine 2 encountered only barren rock.

A low resistivity zone on line Daisy Mine 1 (Figure 8) near the stock underlying the Slate River was not tested directly by drilling during the life of the project. Near Mt. Emmons, on line Daisy Mine 1 (Figure 8), the northern end of the QSP zone around the Red Lady deposit is evident. Possible resonance is seen at station 14, but lack of low frequency capabilities on this survey prevented definition.

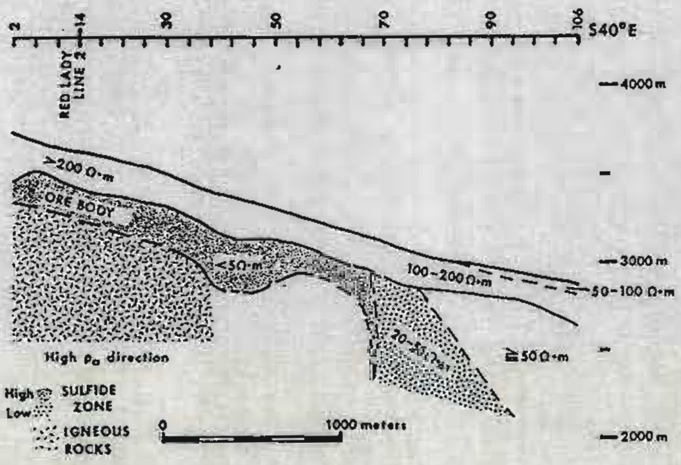

Figure 5. Geologic interpretation of line Red Lady 1. View is looking northeast. The parametric plot of the data on which this model is based is given in Figure 4. A 1-D scheme is used to make the interpretation as explained in Figure 4. The stock and ore body between stations 2 to 30 are known from drilling. The a-spacing for the survey was 122 m. The boundaries evident in the CSAMT survey are very close (generally within ±½a-spacing) of the boundaries defined by drilling. The ρ_a over the sulfides forming the ore body is much higher in this direction compared to line Red Lady 2 at the crossing point. This directional character of ρ_a is typical for all sulfide systems surveyed.

Henderson Mine, Red Mountain, Colorado (39°45'N 105°45'W)

The Henderson ore body lies approximately 1 km below the surface of Red Mountain. The limits of alteration are clearly defined on Figure 10 between stations -6 and +18. The ore body is associated with the crest of the stock. The QSP zone extends upward and laterally to the southwest from the stock. The available data do not suggest an extension of the QSP zone to the northeast. Data over the ore body for stations 2 to 10 are apparently affected by the air gap and rubble associated with the block caving operation. A glory hole formed beneath these stations within a month after the survey was completed.

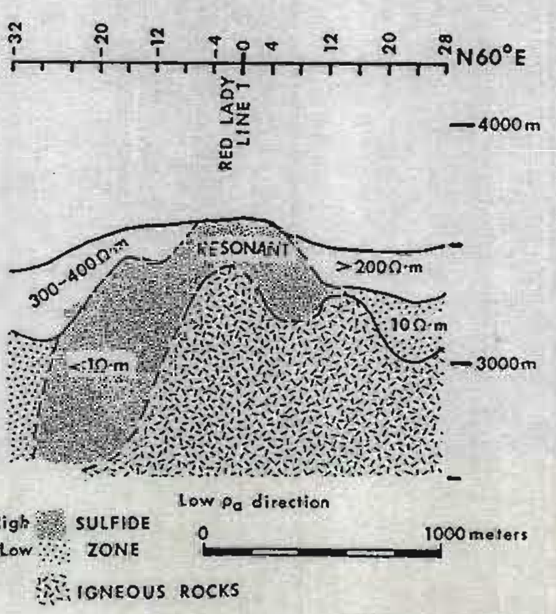

Figure 6. Geologic interpretation for line Red Lady 2 over the known molybdenite deposit in Red Lady Basin on Mt. Emmons, Colorado. View is looking northwest. The ore body extends from stations -16 to +12. Stations -4 to +4 show apparent resonance, with minimum impedance between 64 and 128 Hz. The percent contained sulfides is maximum (~8%) in this area. Note that ρ_a is much lower over the ore body in this direction. This directional character of ρ_a was found in all lines which crossed sulfide mineralization. Electrical basement is assumed to be igneous.

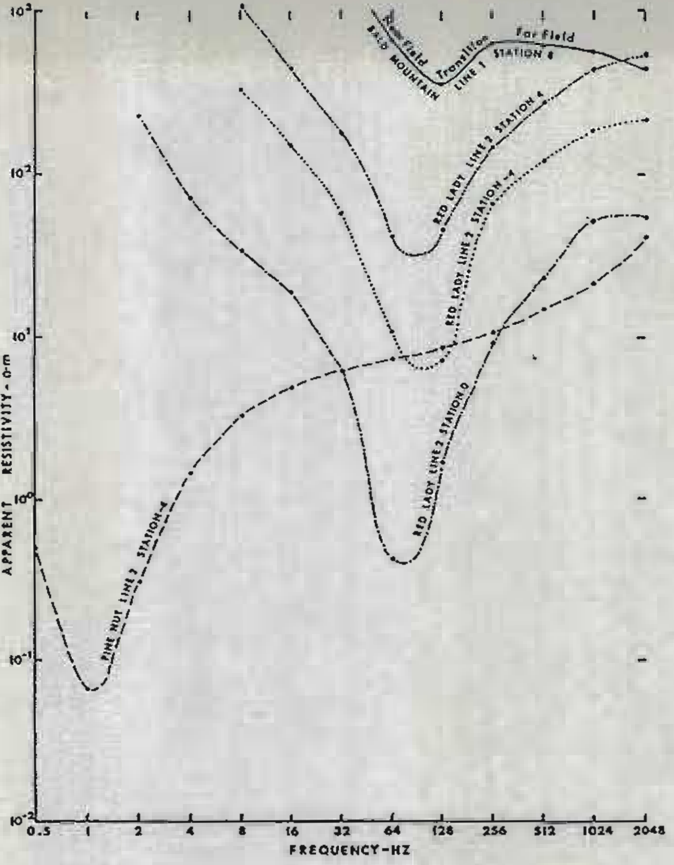

Figure 7. Log-log plot of frequency vs. ρ_a for stations -4, 0, and +4 on line Red Lady 2, and station -4 on line Pine Nut 2. All these stations show slopes greater than the theoretical maximum of 45° observed over a layered earth with a perfectly conducting basement. The notch extends over several frequencies with a minimum ρ_a between 64 and 128 Hz at Red Lady and 1 Hz at Pine Nut. An equivalent electrical circuit for such a curve is a series resonant tuned circuit. The resonance is attributed to ferroelectric effects associated with the ore minerals in the system. For comparison, the transition zone between far field and near field is plotted from station 8 of Bald Mountain line 1. No apparent similarity exists between the resonance and near field - far field transition effects. The Pine Nut and Bald Mountain surveys are discussed subsequently.

Extreme cultural interference is associated with the present mining operations, and the survey was limited to three days during a 4th of July shutdown of the mine. Consequently, no time was available to run a cross line.

The requirement for lower frequency data is evident. Again, time considerations prevented acquisition of such data. Previous resistivity and induced polarization (IP) surveys had suggested resistivities on the order of 10 kΩ-m and the transmitter location was calculated on that basis. As evident in Figure 10, the Cagniard resistivities are much lower, and an unacceptably low signal level at the higher frequencies was the result. Some production time was thus lost while the transmitter was relocated. Despite the logistical difficulties, the results of this survey gave us confidence in our ability to reliably detect deep ore bodies at a cost of $38,028.

Bald Mountain, Colorado (38°47′N 106°02′W)

Bald Mountain is a Tertiary volcano within the Rio Grande Rift southeast of Buena Vista, Colorado. Surface alteration, geochemistry, and an SP survey all suggested the possibility of economic mineralization in association with the feature. However, erosion of the feature has been minimal and a possible ore body could lie as deep as 2 km beneath the present surface.

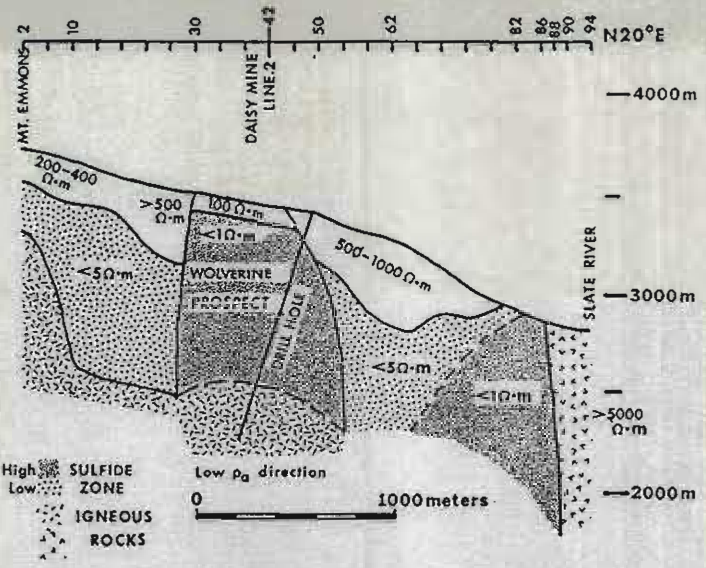

Figure 8. Geologic interpretation of line Daisy Mine 1 along the ridge between Redwell and Wolverine Basins on Mt. Emmons, Colorado. View is looking west-northwest. Based on a preliminary interpretation, the Wolverine prospect was initially drilled in the area shown. Ore grade (≥0.2 Wt% MoS_2) mineralization was encountered at a hole depth of 747 m, and the mineralization continued intermittently to about 850 m. Four additional holes (not shown) were then drilled to define the extent of mineralization. Electrical basement is assumed to be igneous rock. The sulfide zone south of Slate River was not tested by drilling. The intrusion at Slate River is capped by high resistivity hornfels and shale not resolved by the CSAMT survey.

With the confidence gained from the Henderson survey, the CSAMT technique provided an economical method of exploring the prospect without the expense of drilling a 2 km hole. Two lines were run across the center of the SP anomaly. Cross sections are shown in Figures 11 and 12. Both lines suggest sulfide mineralization essentially from the surface to a depth of ~500 m. On line 1 (Figure 11), sulfide mineralization extends from station -9 to 4. For line 2 (Figure 12), possible sulfide mineralization extends from station -3 to 4. The lines show the characteristic directional apparent resistivities associated with sulfide systems. However, the apparent resistivities are not as dramatically low as at Mt. Emmons, nor are resonance effects apparent. We thus consider it unlikely that sulfides in economic quantities are associated with this system.

There is no evidence in the CSAMT data for deeper mineralization in the volcanic complex. All the soundings clearly show electrical basement below 500 m. Hence, a deep drill hole is not justified. The cost of a single deep hole to test this system, as originally proposed, would have been at least $200,000, whereas the entire system was adequately mapped by the CSAMT survey for a cost of $18,820.

Red Cone, Colorado (39°32′N 105°49′W)

The Red Cone prospect lies on the southeast margin of the Montezuma mining district on the continental divide. Red Cone Peak is 3902 m high, with steep, rugged flanks. The prospect is about 5 km south of the Geneva Basin prospect, a sub-economic porphyry molybdenite prospect drilled out by AMAX. Both the Geneva Basin and the Red Cone prospects have definitive SP anomalies. Red Cone also shows strong surface alteration and distinctive geochemical anomalies.

The question at Red Cone is where to drill. The costs of drilling from the peak are obviously much higher than drilling a slant hole from Handcart Gulch. Water for drilling is available in Handcart Gulch (Figure 13) at an elevation of ~3400 m, while it would have to be pumped or trucked up to the peak. Thus, one of the principal objectives of the survey was to determine whether a slant, or angle hole from Handcart Gulch would reach the projected mineralization. The

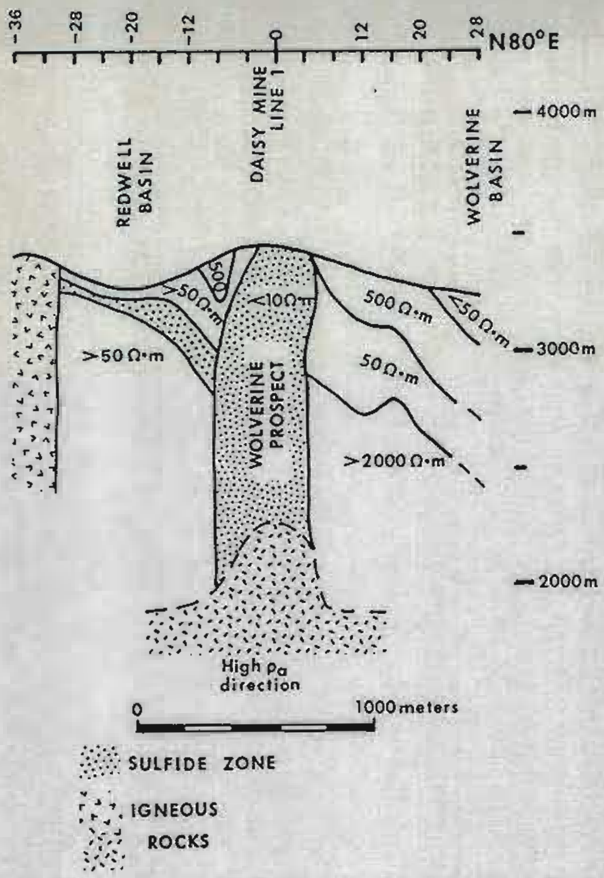

Figure 9. Geologic interpretation of line Daisy Mine 2 from Redwell Basin to Wolverine Basin on Mt. Emmons, Colorado. View is looking north-northwest. The boundaries of the Wolverine prospect were confirmed by drilling. Electrical basement is igneous rock.

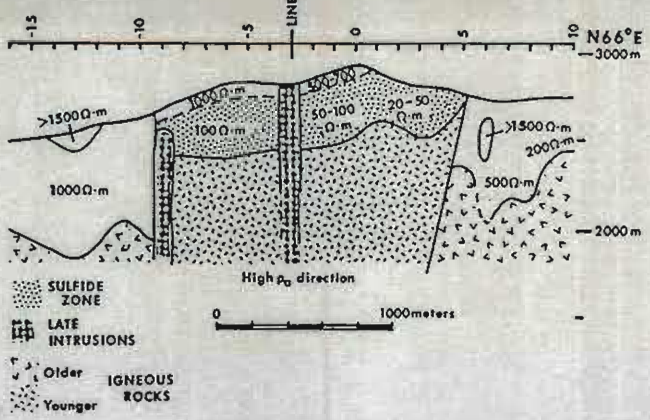

Figure 11. Geologic interpretation of line 1 across the volcanic complex at Bald Mountain southeast of Buena Vista, Colorado. View is looking north-northwest. Relatively high resistivities in the sulfide zone suggest that mineralization is not present in economic quantities. The late intrusions shown are based on likely geology. The anomalies from which the late intrusions are inferred could also be simply a small surface effect producing a static offset.

CSAMT survey shows that ore mineralization, if it exists, lies between stations -6 and 2 on line 1 (Figure 13) on line 1 and between stations -3 and 3 (Figure 14) on line 2. The base of the mineralization is at an elevation of ~3400 m. Hence, a slant hole from Handcart Gulch (~3400 m) would pass beneath the area of possible ore grade mineralization. To test the mineralization, the system must thus be drilled from the top of Red Cone. While directional low resistivities are found in association with the sulfide system, the resonance seen elsewhere is not found here. While the system has not yet been drilled, the survey objectives were met at a cost of $31,567.

Pine Nut, Nevada (38°47'N 119°32'W)

The Pine Nut molybdenite deposit is located just below the surface on Pine Nut Creek on the west flank of the Pine Nut Mountains just east of Lake Tahoe in Nevada. An extensive geophysical program,

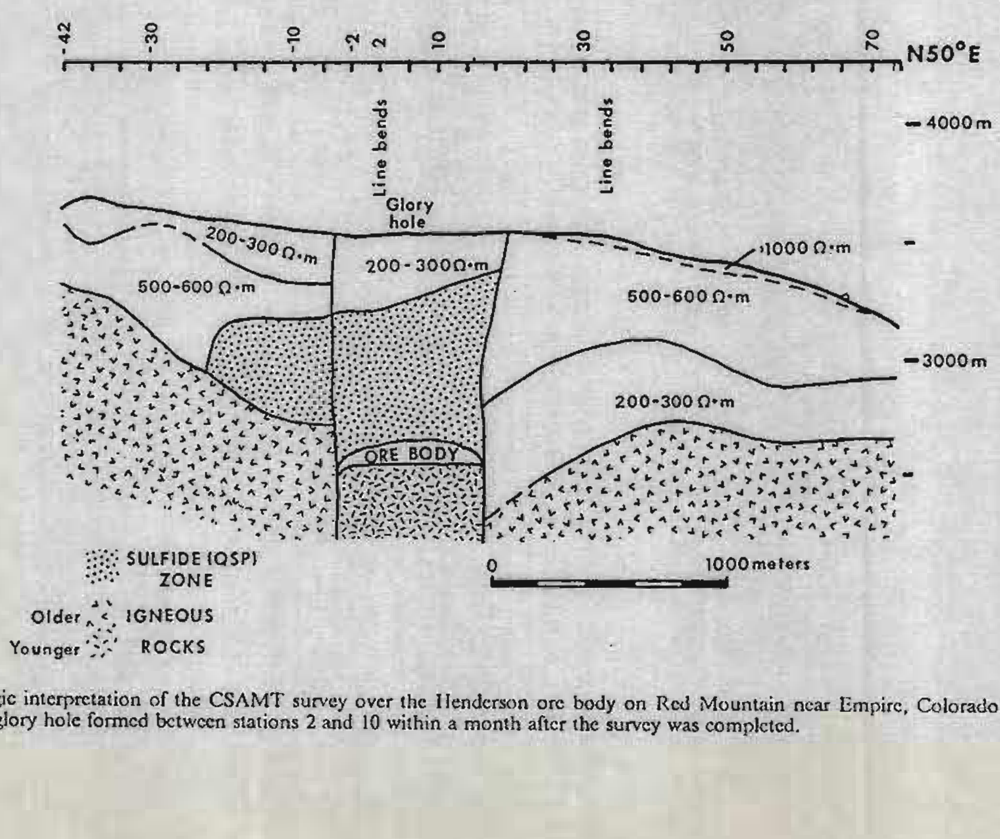

Figure 10. Geologic interpretation of the CSAMT survey over the Henderson ore body on Red Mountain near Empire, Colorado. View is looking northwest. A glory hole formed between stations 2 and 10 within a month after the survey was completed.

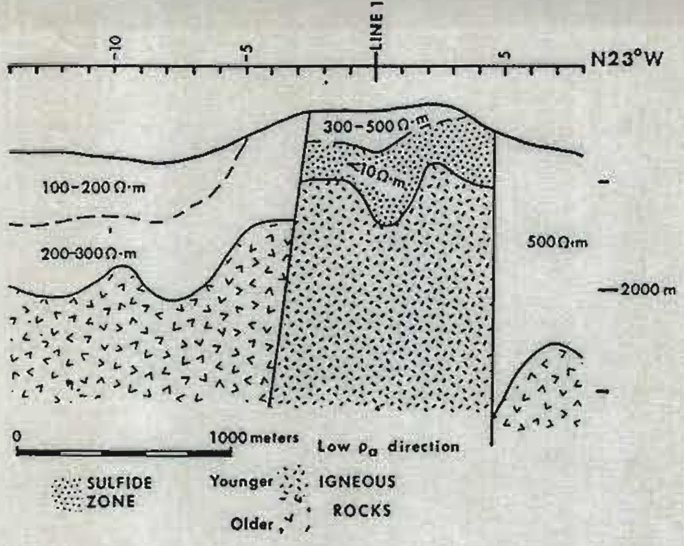

Figure 12. Geologic interpretation of line 2 across the Bald Mountain volcanic complex, Colorado. View is looking west-southwest. Even though the resistivities in the sulfide zone are considerably less than for line 1, they are still much higher than at Mt. Emmons. The late intrusion shown on Figure 11 at station -3 is not apparent on this line.

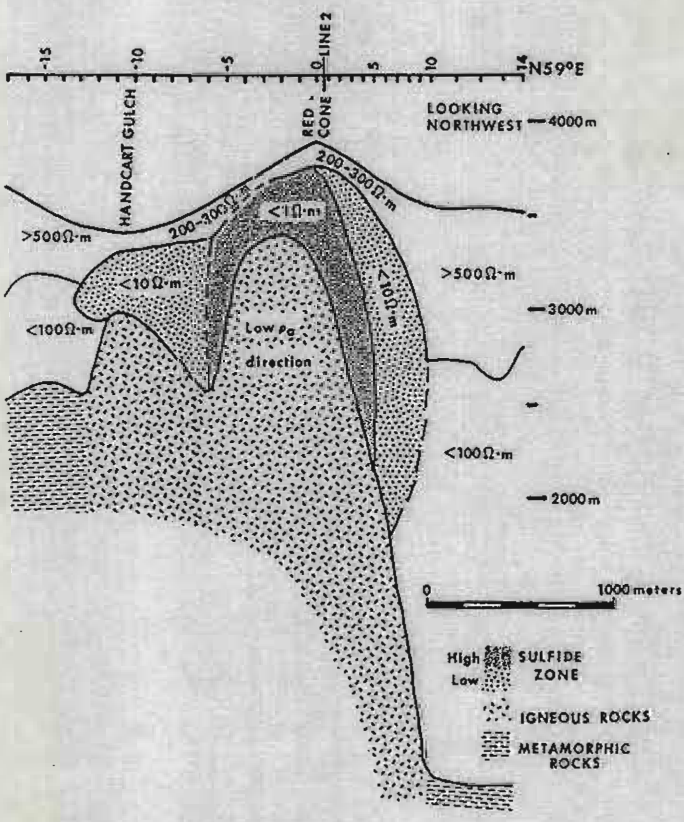

Figure 13. Geologic interpretation of line 1 across Red Cone Peak on the southeastern margin of the Montezuma mining district, Colorado. View is looking northwest. While the resistivity is very low in the sulfide zone, no resonant effects were noted. Electrical basement beneath the sulfides appears to be an elongate stock. Outside the stock the basement rocks are schist, gneiss, and migmatite.

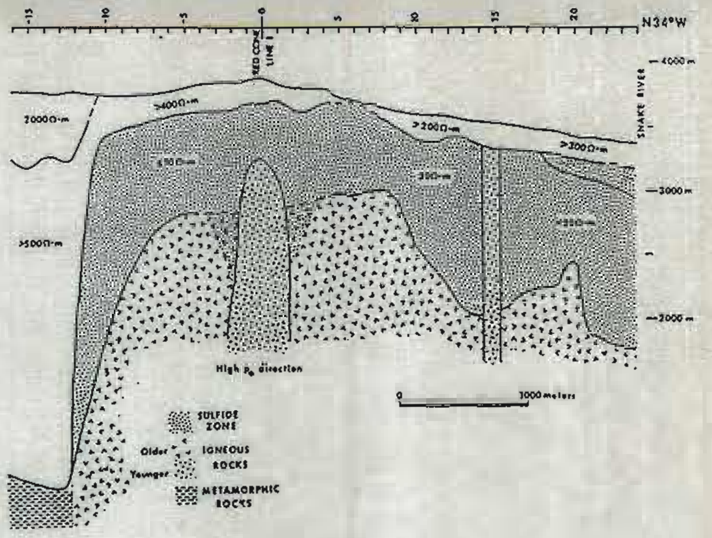

Figure 14. Geologic interpretation of line 2 at Red Cone, Colorado. View is looking southwest. Electrical basement beneath the sulfides is apparently an elongate stock. The dikes and stock apparently cut the metamorphic basement rocks. The dike mapped at station 15 could be due to small surface effects producing a static offset in the CSAMT data.

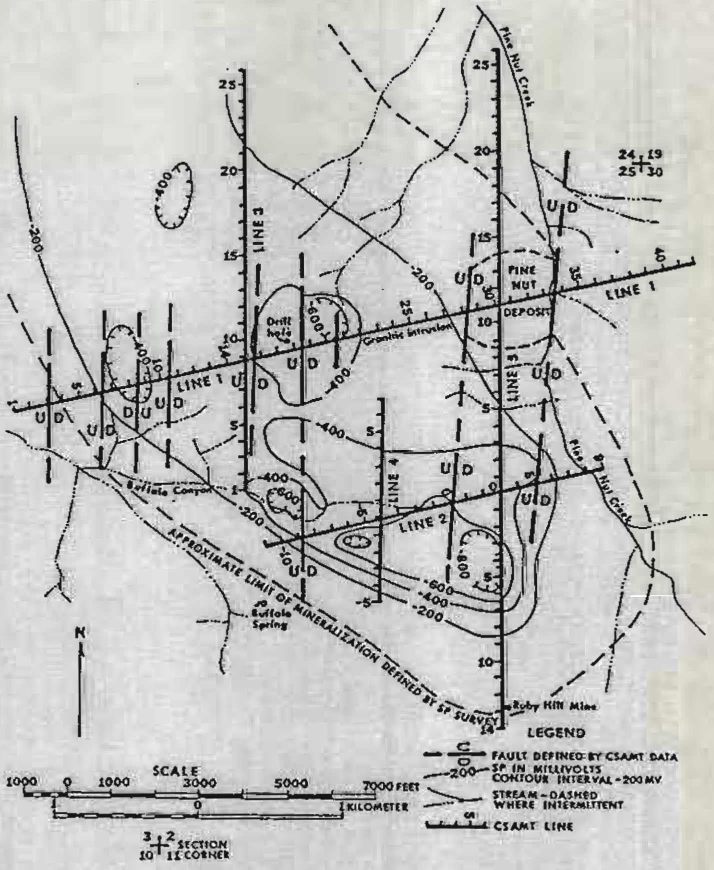

Figure 15. SP survey and line location for the CSAMT survey at the Pine Nut deposit, Nevada. North - south lines 3 and 5 parallel faulting and the interpretation of these lines is ambiguous outside the sulfide zones.

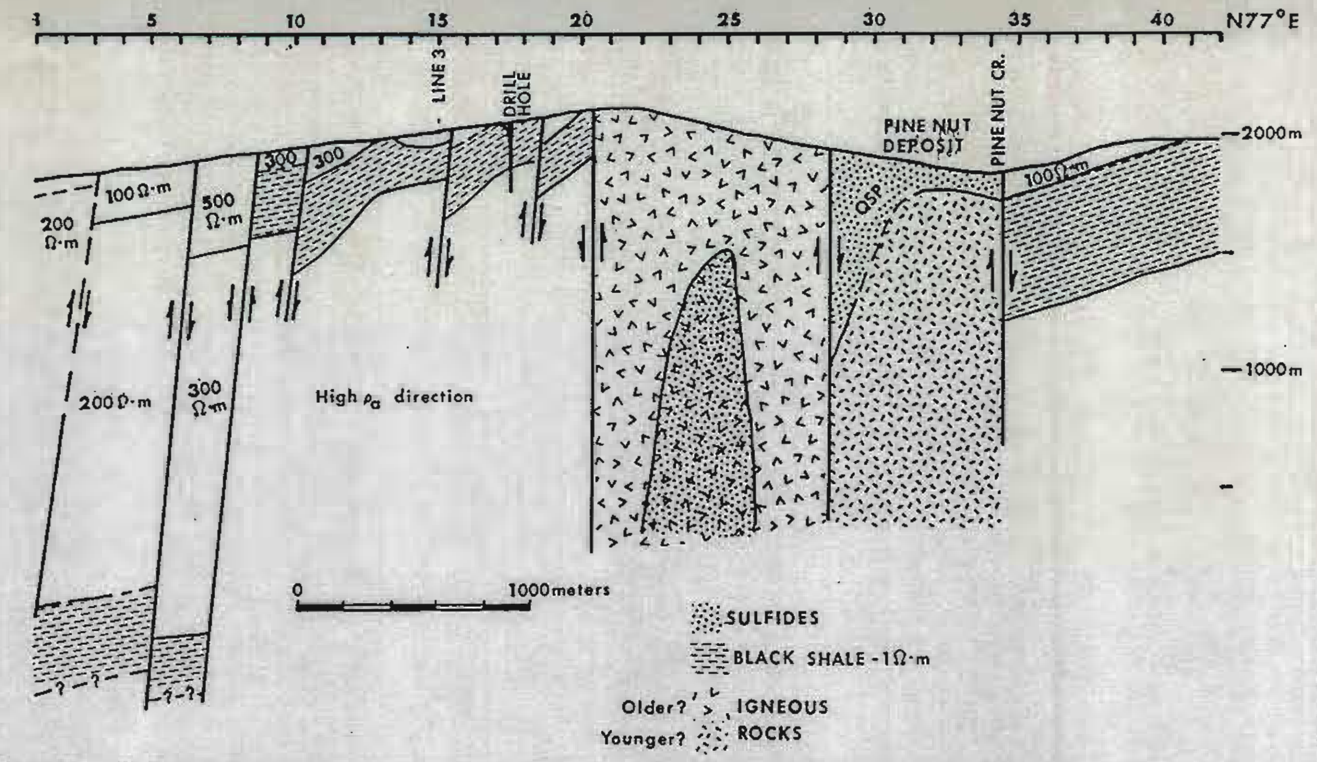

Figure 16. Geologic interpretation of line 1 across the Pine Nut porphyry molybdenite deposit at Pine Nut, Nevada. View is looking north. Geochemical, SP, and resistivity anomalies were tested as part of this project by a drill hole near station 18. The anomalies were found to be associated with black shale containing syngenetic (?) pyrite.

including remote sensing, gravity, magnetic, SP, IP, and CSAMT, was run over and around the deposit by AMAX, the U.S. Geological Survey, and Stanford University. The SP survey turned up several additional prospects in the vicinity of the known deposit. The SP data and CSAMT line locations are shown in Figure 15. The SP anomalies were also reflected by corresponding geochemical anomalies. The SP and geochemical anomalies were then followed up by a CSAMT survey, and finally with one drill hole before the project was cancelled.

Gravity surveys indicate a north-south trending batholithic intrusion along the west flank of the Pine Nut Mountains, and the known deposit is located on the west flank of the batholith.

The area surveyed is extensively faulted in a north-south direction as is evident on line 1 (Figure 16). Walker Lane lies immediately to the west of the survey area. Recent faulting is Basin-and-Range, down to the west, block faulting. Many of the faults, however, are down to the east and appear to be related to the intrusive activity.

The eastern margin of the known deposit is faulted down to the east between stations 34 and 35 as shown on line 1 (Figure 16). One of the survey objectives was to locate the down faulted portion of the deposit. However, the missing portion of the deposit is masked by a low resistivity (Figure 16) black shale with apparently syngenetic sulfides. The lowest frequency used in this area was 2 Hz. With lower frequency data it might be possible to delineate deeper horizons. However, the present data suggests that the missing section, if any, of the ore body is limited in area, and lies > 500 m beneath the surface. The ore grades in exposed sections of the ore body are such that it is very unlikely that such deep mineralization would be economic at that depth even if it were located.

The known deposit is delineated by erosional remnants of the QSP zone, as shown in Figure 16. The western flank of the QSP zone is cutoff between stations 28 and 29 on line 1 by what appears to be a later granitic intrusion. Between stations 22 and 26 (Figure 16), the intrusion is apparently altered, and beneath station 25 the alteration zone comes to within a few hundred meters of the surface. The apparent resistivities associated with this alteration are not as low as found with other targets in the area, nor as areally extensive. Hence, the alteration is probably not associated with ore grade mineralization.

Continuing west along line 1 (Figure 16), a series of reverse faults are found. The structure is readily followed due to the marker bed of black shale. The low resistivity, a large amplitude SP anomaly, and a geochemical anomaly in the vicinity of stations 16 to 20 (Figure 16) led to a drill test of the anomaly near station 18. From a preliminary interpretation, it was estimated that the base of the sulfides was 200 m below the surface; hence, the system could be tested by a relatively shallow drill hole. The anomalies proved to be associated with a black shale with syngenetic (?) sulfides instead of ore. The base of the shale was found at 186 m, very close to the predicted depth.

Line 2 (Figure 17) was run to investigate the large SP anomaly on the south side of Buffalo Canyon (Figure 15) north and east of Buffalo Spring. Low resistivities and the resonance we think are characteristic of ore minerals is found between station -8 and 0 on line 2 (Figure 17). Directional resistivity is also apparent. Line 4 (cross section not shown) was run north-south through the center of this anomaly and also shows low resistivities between stations -2 and 4. Both stations 2 and 4 on line 4 exhibit 3-D edge effects. The SP and CSAMT data strongly suggest the possibility of significant mineralization at a depth of ≤600 m. At the center of the anomaly, mineralization may be no more than 100 m beneath the surface but it has not been tested by drilling.

Continuing eastward on line 2 (Figure 17), a second sulfide system is found between stations 0 and 4 and on line 5 (cross section not shown) between stations -8 and 1. The SP and the CSAMT data suggest this is the principal sulfide system in the Pine Nut area. The depth of this system appears to be < 200 m, but the resistivities on line 5 are so low that even at 0.5 Hz we were unable to see through the sulfide system. Note that the high ρ_a - low ρ_a directional relationships between lines 2 and 4 and lines 2 and 5 are reversed between the east and the west anomalies on line 2. We cannot be certain that these anomalies are not due to the same black shale drilled on line 1, although we don't see resonance on line 1 in association with the black shales.

The north-south lines (Figure 15), lines 3, 4, and 5, are run close to the strike direction of the faults evident on line 1 (Figure 16). Because of this, the lines cross faults at low angles. Outside the sulfide

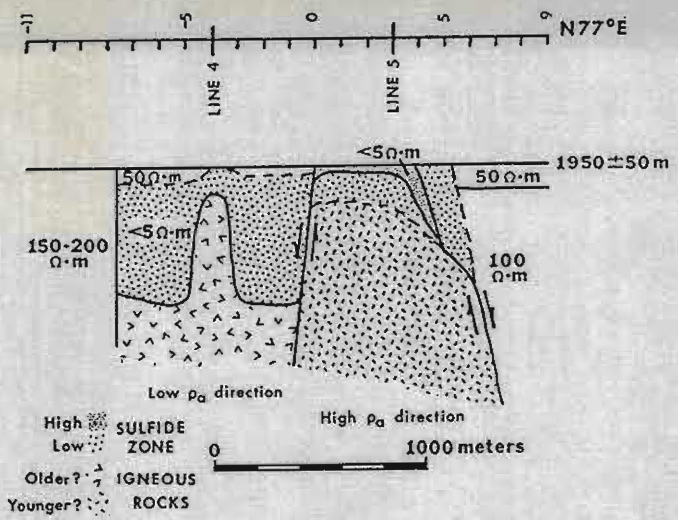

Figure 17. Geologic interpretation of line 2 at Pine Nut, Nevada. View is looking north. Note that the two different sulfide systems have different directions of high and low ρ_a.

systems the interpretation becomes very difficult and the results ambiguous due to 3-D edge effects.

From the SP and CSAMT surveys, three new prospects were found, and depth and lateral extent delineated, in the vicinity of the known Pine Nut deposit. While one prospect drilled proved to be black shale, the exploration objectives of the CSAMT survey were met at a cost of $43,993, comparable to the cost of a field season for a geologist.

FERROELECTRIC EFFECTS

The CSAMT surveys over sulfide systems produced several results we have been unable to account for on the basis of a simple resistive response from the sulfides. Since these results appear to be characteristic of sulfide systems explored in this work and; hence, are applicable to the exploration for ore minerals, we consider the possible mechanism here.

The observed effects include directional, extremely low ρ_a, commonly < 1 Ω·m between 1 and 100 Hz, and occasionally < 0.1 Ω·m at 1 to 2 Hz. It is possible that these responses could be due to current channeling in a 3-D anisotropic environment. However, we consider it more probable that these effects are due to rock properties associated with porphyry sulfide systems. We have been unable to model the observed data with a layered model even with very high resistivity contrasts. Two and three dimensional models do not provide satisfactory results either. Further, as shown in Figure 7, the slope of the log-log plot of ρ_a vs. f for stations in ore minerals in the low ρ_a direction exceeds the theoretical maximum of 45° observed over a layered earth with a perfectly conducting basement. The extremely sharp notch is suggestive a series resonant tuned circuit. We do not attribute this apparent resonance to 60 Hz power lines since there is very little culture in the vicinity of Mt. Emmons or the other prospects surveyed. At Mt. Emmons on line Red Lady 2, the resonant frequency is between 64 and 128 Hz, and on line Daisy Mine 1 we see an apparent resonance at 1 - 2 Hz. At the Pine Nut deposit in Nevada, a resonance at 1 Hz is observed. It is extremely unlikely that in these remote areas we are seeing cultural interference in the electric or magnetic magnetic fields at 1 to 2 Hz. Further, we only see the apparent resonance in one direction, e.g. line Red Lady 2 bearing N60°E (Figures 6) is resonant at station 0 where it crosses line Red Lady 1, but line Red Lady 1 (bearing S40°E) is not resonant at station 14.

The only natural materials we are aware of which might explain the directional ρ_a, the extremely low values of ρ_a observed, and the resonant response, are ferroelectrics (crystalline solids that exhibit spontaneous electric polarization analogous to ferromagnetic materials). The question then arises whether the ore minerals in the systems we were surveying are ferroelectrics. Pyrrhotite ($Fe_{1-x}S$), which occurs in significant quantities at Mt. Emmons, is a known ferroelectric at ordinary temperatures for $x \leq 0.04$ (van den Berg and others, 1969; van den Berg, 1970, 1972). Bieniulis and others (1987) have recently demonstrated ferroelectricity in natural samples of chalcocite. Corry (1984) has identified twenty ore or related minerals which are known ferroelectrics. Sixty-three other ore minerals, including molybdenite, chalcopyrite, arsenopyrite, etc., were found to be isostructural, i.e. they have the same space group, with known ferroelectrics and; hence, are probably also ferroelectrics. At least sixty additional ore minerals could be ferroelectrics based on their crystal structure, electrical, and optical properties. Thus, ferroelectricity appears to be a common property of ore minerals. Since ferroelectrics tend to dominate the electrical response of any system containing them, it would be surprising if ferroelectric effects were not apparent when making electrical measurements of sulfide deposits.

In a porphyry sulfide system, the sulfides are disseminated through the country rock. Thus, the electrical response of the system probably approximates that of a ferroelectric ceramic. ρ_a within the sulfide system is then the impedance of the ferroelectric ceramic at a given frequency and reflects the charge transfer characteristics of the medium rather than the ohmic resistance. The observed directional resistivity is probably related to the polarization direction of the ferroelectric sulfides. Ferroelectric ceramics virtually always polarize in some preferred direction when cooled through their Curie temperature. The factors controlling the poling direction in sulfide systems have not yet been established. The mechanism for the observed resonance has not been determined, but it may be related to Alfvén or induction (Fridkin, 1980) waves commonly observed in ferroelectric semiconductors.

CONCLUSIONS

The CSAMT technique has proven to be a fast and extremely effective method of delineating in detail the depth and lateral extent of sulfide mineralization provided the CSAMT survey is preceded by an SP survey with which to target it.

The ability of the CSAMT technique to map complex structure is evident in a number of instances, e.g. line 1 at Pine Nut (Figure 16). Applications of the CSAMT technique have thus been extended to engineering and hydrology studies. The technique has considerably higher lateral and depth resolution than was previously available with electrical methods in these applications. Resolution in favorable areas with current (1987) techniques is comparable with seismic reflection data. With steeply dipping horizons, or in structurally complex areas, CSAMT surveys may surpass resolution obtainable from seismic reflection methods.

The extremely low, directional resistivities, and the resonance are possibly related to ferroelectric effects associated with known ferroelectric minerals in the sulfide systems surveyed. The disseminated sulfides in a porphyry system give a response which appears to be analogous with a ferroelectric ceramic. ρ_a within the sulfide system thus appears to be the impedance of a ferroelectric ceramic at a given frequency and reflects the charge transfer characteristics of the medium rather than the ohmic resistance.

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