Case Histories of Controlled-Source Audio-Frequency Surveys

POS 1.4

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SUMMARY

Sulfide systems can be identified in controlled source audio-frequency magnetotelluric (CSAMT) surveys by steep to vertically bounded zones of low apparent resistivity (ρ_a) that provide definitive horizontal resolution of the lateral extent of the sulfides. The method proved most effective if low cost, preliminary self-potential (SP) surveys were used to define the centers of the sulfide systems prior to the CSAMT surveys. The technique can also be used to map the electrical stratigraphy, and dips ≥60° have been traced. The ability to map subsurface structure and stratigraphy also has applications in oil exploration, engineering, and hydrology.

INTRODUCTION

The magnetotelluric method has been used since the 1950's with natural magnetic and electric fields as a source. An excellent collection of the basic papers on the subject can be found in Vozoff (1985). To circumvent the problems of using natural sources in exploration, 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 CSAMT technique that became commercially available in 1981. The development phase and experimental methods are described in Zonge et al. (1985).

Results presented here emphasize the geologic interpretation of the surveys. All the sulfide systems surveyed had distinctly directional apparent resistivity (ρ_a). 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. A possible ferroelectric mechanism for these phenomena is described in Corry et al. (1987).

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 and H_x 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 Corry et al. (1987).

At each station, frequencies are stepped in powers of two ($f = 2^n$) from the highest to the lowest. ρ_a is recorded at each frequency. A parametric plot of frequency vs. ρ_a is then constructed and contoured. Each station is modeled one dimensionally assuming a laterally homogeneous layered earth. Methods for such modelling are given by Constable et al. (1987), among others. The individual one-dimensional models are then plotted sequentially, in profile, from which the geologic interpretations are made.

Field Layout

The general field layout is shown in Figure 1. The transmitter can be located at any site ≥3δ at f_{min}, where δ is the skin depth. Present (1988) CSAMT equipment has a frequency range from 0.125 Hz to 8192 Hz, allowing both deep and shallow exploration.

Lateral resolution is primarily determined by the E_y field dipole length. In our surveys, the maximum dipole length used was 125 m, and the minimum was 15 m. We were aware from the beginning that edge effects associated with electromagnetic (EM) coupling at the boundaries of sulfide systems would be a severe problem. The CSAMT survey lines were laid out to cross the mineralization boundary at a right angle whenever possible. In practice, the center of the porphyry sulfide deposits were located with SP surveys (Corry, 1985) for all AMAX surveys. Low cost preliminary SP surveys also allow the CSAMT survey lines to be of minimum length and optimally placed in areas of interest, thus minimizing total cost.

FIELD SURVEYS

Porphyry Sulfides

<u>Mt. Emmons, Colorado (38°53'N 107°03'W).</u> One of the initial surveys explored the porphyry molybdenite deposit in Red Lady Basin at Mt. Emmons, Colorado. 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 2. Ore grade (≥0.2 Wt% MoS_2) mineralization extends from about station 2 to station 30 on line Red Lady 1, as determined from drilling. Sulfide mineralization, in the form of a pyrite-pyrrhotite halo, extends to station 66.

The detail of the CSAMT survey in depth determination and lateral extent of the sulfides exceeded that available from any other technique, e.g., magnetics, gravity, complex resistivity, and seismic reflection, used at this site. For comparison, the 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 also clearly delineated in line Red Lady 2 between stations −16 and −12 to + 12, and this correlates well with ore boundaries defined by drilling. Pyrite and pyrrhotite haloes extend both northeast and southwest from the ore body.

SP anomalies (Figure 2) on the ridge between Wolverine and Redwell Basins were investigated by line Daisy Mine 1. The Wolverine prospect (Figure 3) was delineated by this line and line Daisy Mine 2. Based on a preliminary version of Figure 3, 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 3) encountered ore grade mineralization (≥0.2 Wt% MoS_2) at 747 m, and this mineralization continued intermittently to about 850 m. While subsequent drilling showed the prospect to be sub-economic, the lateral and vertical definition provided by the CSAMT survey (Figure 3) allowed the prospect to be completely tested with 5 drill holes. Competitor drilling north of station 16 on line Daisy Mine 2 encountered only barren rock. A similar deposit at the head of Redwell Basin explored before the CSAMT survey required 15 drill holes to define the mineralization.

<u>Henderson Mine, Red Mountain, Colorado (39°45'N 105°45'W).</u> The Henderson ore body lies approximately 1 km below the surface of Red Mountain. The limits of alteration are clearly defined 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.

<u>Red Cone, Colorado (39°32'N 105°49'W).</u> 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. Drilling costs from the peak are obviously much higher than drilling a slant hole from Handcart Gulch. Water for drilling is available in Handcart Gulch 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 CSAMT survey shows the base of the mineralization at an elevation of ~3400 m between stations −6 and + 2 on line 1 (Figure 4) and between stations −3 and + 3 on line 2. Hence, a slant hole from Handcart Gulch would pass beneath the area of possible ore grade mineralization. To test the mineralization the system must be drilled from the top of Red Cone.

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, Nevada. An extensive geophysical program, including remote sensing, gravity, magnetic, SP, IP, and CSAMT, was run over and around the deposit. The SP data and CSAMT line locations are shown in Figure 5. The SP anomalies were found to have 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.

The area surveyed is extensively faulted in a north-south direction as is evident on line 1 (Figure 6). 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 earlier 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 6). 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 black shale with apparently syngenetic sulfides. 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. Known ore grades in the deposit make it very unlikely that such deep mineralization would be economic even if it were located.

The known deposit is delineated by erosional remnants of the quartz-sericite-pyrite (QSP) zone, as shown in Figure 6. 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 6), 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 economic mineralization.

Continuing west along line 1 (Figure 6), 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 6) 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 was run to investigate the large SP anomaly on the south side of Buffalo Canyon (Figure 5) north and east of Buffalo Spring. Low resistivities and the resonance we think are characteristic of ore grade mineralization is found between station −8 and 0 on line 2. Directional resistivity is also apparent. Line 4 was run north-south through the center of this anomaly and also shows low resistivities between stations −2 and 4. 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.

Continuing eastward on line 2, a second sulfide system is found between stations 0 and 4 and on line 5 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. 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.

Massive Sulfide

A newly discovered massive sulfide deposit in the northern U.S. was explored with both an IP and a CSAMT survey in an effort to delineate the size and extent of the ore body. The IP survey is a standard dipole-dipole frequency domain/resistivity survey. The a-spacing for the IP survey was 61 m, and measurements were made down to n = 7. A pseudosection of the IP survey shows the "pantsleg" or "chevron" geometric effects typical of dipole-dipole surveys. A shallow conductor is suggested between stations 2 and 3. The conductor might be more accurately located in the IP survey by decreasing the a-spacing, but that would also decrease the depth of investigation, with the ore body then possibly beneath the depth of investigation.

A CSAMT survey was run over the same line as the IP survey and has been plotted at the same horizontal scale. A strong conductor is located between stations 2.00 and 2.25. The conductor is vertical to possibly a steep south dip. The phase difference data suggest the conductor does not extend to depth. The E_y dipole size was 15 m, and measurements were made at intervals of 30 m (50% coverage) on the south end of the line. Measurements were made every 15 m (100% coverage) in the target area and on the north end of the line. Since CSAMT data are not subject to the geometric effects seen in the dipole-dipole array used for the IP survey, the interpretation of the location and attitude of the ore body is relatively straightforward. The shorter dipole spacing of the CSAMT survey also provides better than a factor of four improvement in the lateral resolution. The lateral resolution could be further improved by simply shortening the E_y dipole, so long as adequate signal levels were attainable. No change in the transmitter dipole is necessary, and the change in the E_y dipole has no effect on the depth of investigation of the survey.

Hydrocarbon Reservoir

Four CSAMT lines were run across the Union Island gas field, California in an effort to determine whether alteration effects due to vertically migrating hydrocarbons were detectable in that environment. No electrically anomalous areas were detected that correlated with known production limits of the field. However, a repeatable low resistivity feature does correlate with the Stockton Arch fault that bounds the field on the eastern, updip side. The Stockton Arch fault is buried deeper than the depth of investigation of the CASMT survey, and there is no geological or geophysical evidence of the fault in the upper strata. The low resistivity area is evident on all four lines and does not appear to be related to any known surface features or culture. Phase difference data indicate that this is not a near-surface, static offset effect, but a bonafide change in resistivity below 50 m. One interpretation is that hydrocarbons are traveling along the Stockton Arch and then migrating vertically through the overlying, undifferentiated non-marine strata above the fault. Thus, the CSAMT survey appears to delineate alteration along the surface projection of the top of the fault. Additional lines are planned over nearby non-productive segments of the same fault to test our interpretation.

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. If the CSAMT survey is preceded by an SP survey with which to target it, the technique can be a very cost-effective method for detail surveying of sulfide systems.

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 6). Applications of the CSAMT technique have thus been extended to oil exploration, 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 (1988) techniques is comparable with seismic reflection data. With steeply dipping horizons, or in structurally complex areas, the resolution of CSAMT surveys may surpass seismic reflection methods.

ACKNOWLEDGEMENTS

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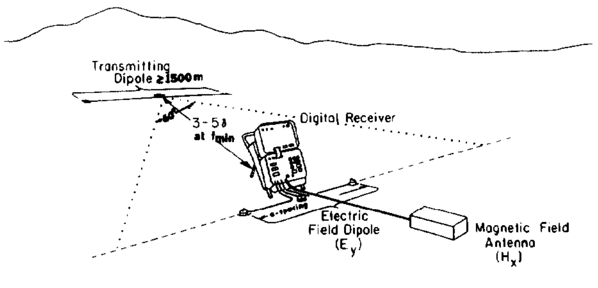

$$\text{Cagniard Resistivity (ohm-meters)} = \frac{1}{5f}\left|\frac{E_y}{H_x}\right|^2$$

FIG. 1. Pictorial representation of CSAMT field setup. Measurements can be made anywhere inside cone delimited by dotted lines. Lateral resolution is approximately one-half receiver dipole size (a-spacing).

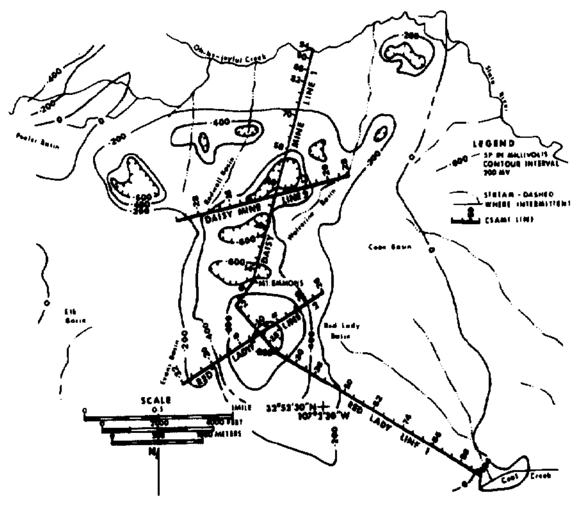

FIG. 2. CSAMT line layout overlayed on SP anomalies at Mt. Emmons, Colorado. SP data from Corry (1985).

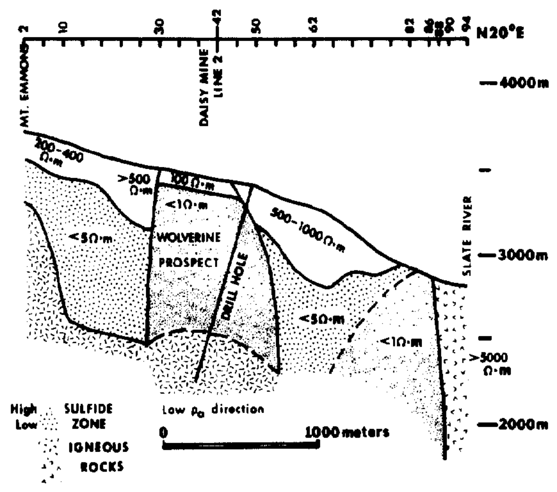

FIG. 3. Geologic interpretation of line Daisy mine 1 along the ridge between Redwell and Wolverine basins on Mt. Emmons, Colorado. View is looking west-northwest.

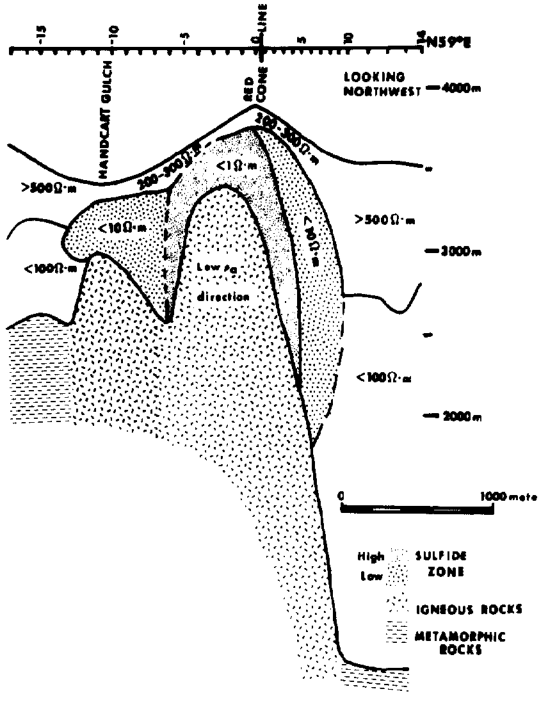

FIG. 4. Geologic interpretation of line 1 across Red Cone Peak on southeastern margin of Montezuma mining district, Colorado.

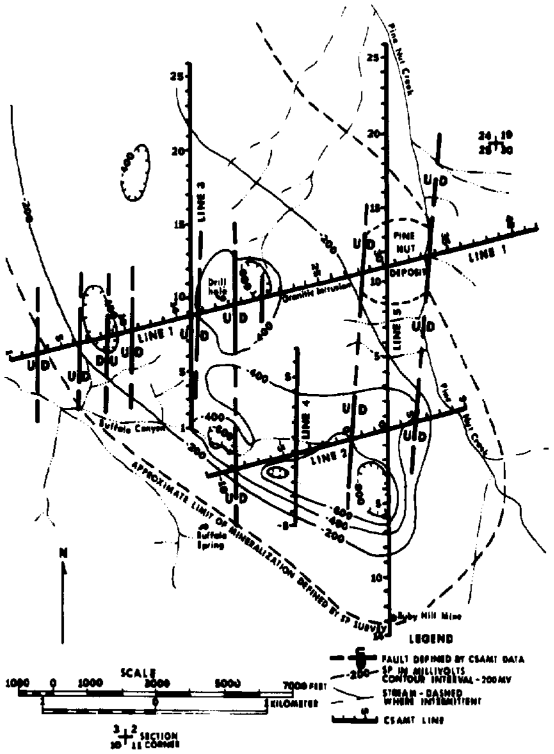

FIG. 5. SP survey and line location for CSAMT survey at Pine Nut deposit, Nevada.

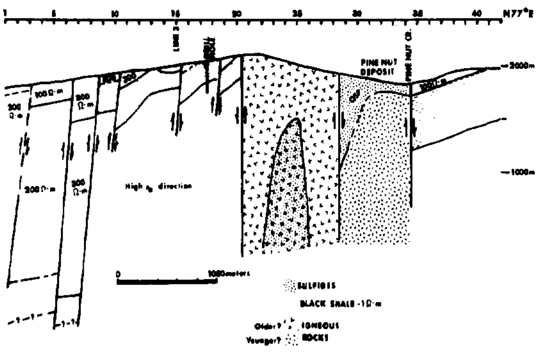

FIG. 6. Geologic interpretation of line 1 across Pine Nut porphyry molybdenite deposit in Pine Nut Mountains, Neveda. View is looking north.