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GEOLOGICAL SURVEY

Geophysical investigations in the Dhahar-Al Hajrah region, Wadi Malahah quadrangle, southwestern Saudi Arabia

by

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

1/ U.S. Geological Survey, Saudi Arabian Mission

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GEOPHYSICAL INVESTIGATIONS IN THE DHAHAR-AL HAJRAH REGION, WADI MALAHAH QUADRANGLE, SOUTHWESTERN SAUDI ARABIA

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ABSTRACT

Crone electromagnetic, self-potential, and induced polarization surveys were conducted in the Dhahar-Al Hajrah region, southwestern Saudi Arabia, in support of geological and geochemical exploration for volcanogenic sulfide deposits. Although a previous, airborne electromagnetic survey found no anomalies in the vicinity of the ancient mines in the region, surface indications of anomalous copper and zinc at both Dhahar and Al Hajrah are abundant.

Reconnaissance Crone electromagnetic traverses across the Dhahar prospect area delineated numerous conductive zones, but none had a dip-angle anomaly of more than 10°. Similar results were obtained at Al Hajrah.

With one or two encouraging exceptions, self-potential surveys at Al Hajrah showed only broad gradients and anomalies having amplitudes of less than 40 mV. Dipole-dipole induced polarization surveys at Al Hajrah delineated two nearly continuous polarizable zones having an aggregate strike length of almost 7 km. The two zones are symmetrically disposed on either side of a median aplitic dike and may lie on opposing limbs of a south-plunging antiform. Chargeabilities in the anomalous zones are weak to moderate but in most places are clearly associated with anomalous copper and (or) zinc concentrations found by surface sampling.

Ground electromagnetic traverses are recommended to determine the most conductive intervals of anomalous induced polarization effect in the anomalous zones; these conductive intervals should then be tested by drilling, where appropriate. Reconnaissance self-potential traverses are also recommended at Dhahar, and additional ground electromagnetic surveys are recommended across two airborne electromagnetic anomalies located immediately southeast of the Al Hajrah target.

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INTRODUCTION

The center of the Dhahar-Al Hajrah region is near lat 18°12' N., long 43°44' E., 200 km southeast of the city of Khamis Mushayt and 50 km from the eastern boundary of the Arabian Shield (fig. 1). The terrain is mountainous but of moderate to low relief, and the region has a mean elevation of about 1,900 m; vegetation is sparse to absent.

Between 1976 and 1978, a program of geologic, geochemical, and geophysical investigations, as well as the drilling of three exploratory holes, was conducted by the U.S. Geological Survey (USGS) to assess the economic potential of the region and, in particular, to evaluate copper-zinc deposits in the vicinity of ancient mine workings at both Dhahar (MODS 01360,01361) and Al Hajrah (MODS 02004). The geological and geochemical aspects of this work and a summary of the geophysical findings were presented by Smith (1980/1981). The purpose of the present report is to compile all geophysical data acquired to date and to discuss these data in the context of the geology and geochemistry.

The geophysical work consisted of an airborne electromagnetic (AEM) INPUT survey and ground surveys that utilized induced polarization (IP), self-potential (SP), and Crone electromagnetic (CEM) methods. The AEM and IP surveys and most of the SP surveys were made under contract to the Saudi Arabian Ministry of Petroleum and Mineral Resources and are described in reports by the Arabian Geophysical and Surveying Company (ARGAS) (1978) and Geoterrex Limited (1978). Some SP measurements and all CEM measurements were made by USGS personnel, and the CEM results are presented here for the first time.

The work on which this report is based has been conducted in accordance with an agreement between the USGS and the Saudi Arabian Ministry of Petroleum and Mineral Resources. The USGS field party chief was M. A. Bazzari, and he was assisted by C. W. Smith and M. Musa.

OUTLINE OF GEOLOGIC RELATIONS

The following summary of geologic relations in the Dhahar-Al Hajrah region was prepared by using the work of Smith (1980/1981), Greenwood (1980), and Greenwood and others (1982). Geological and geochemical maps (Smith, 1980/1981) have been composited with geophysical data on plates 3 and 4 of the present report; these plates will be discussed in a later section.

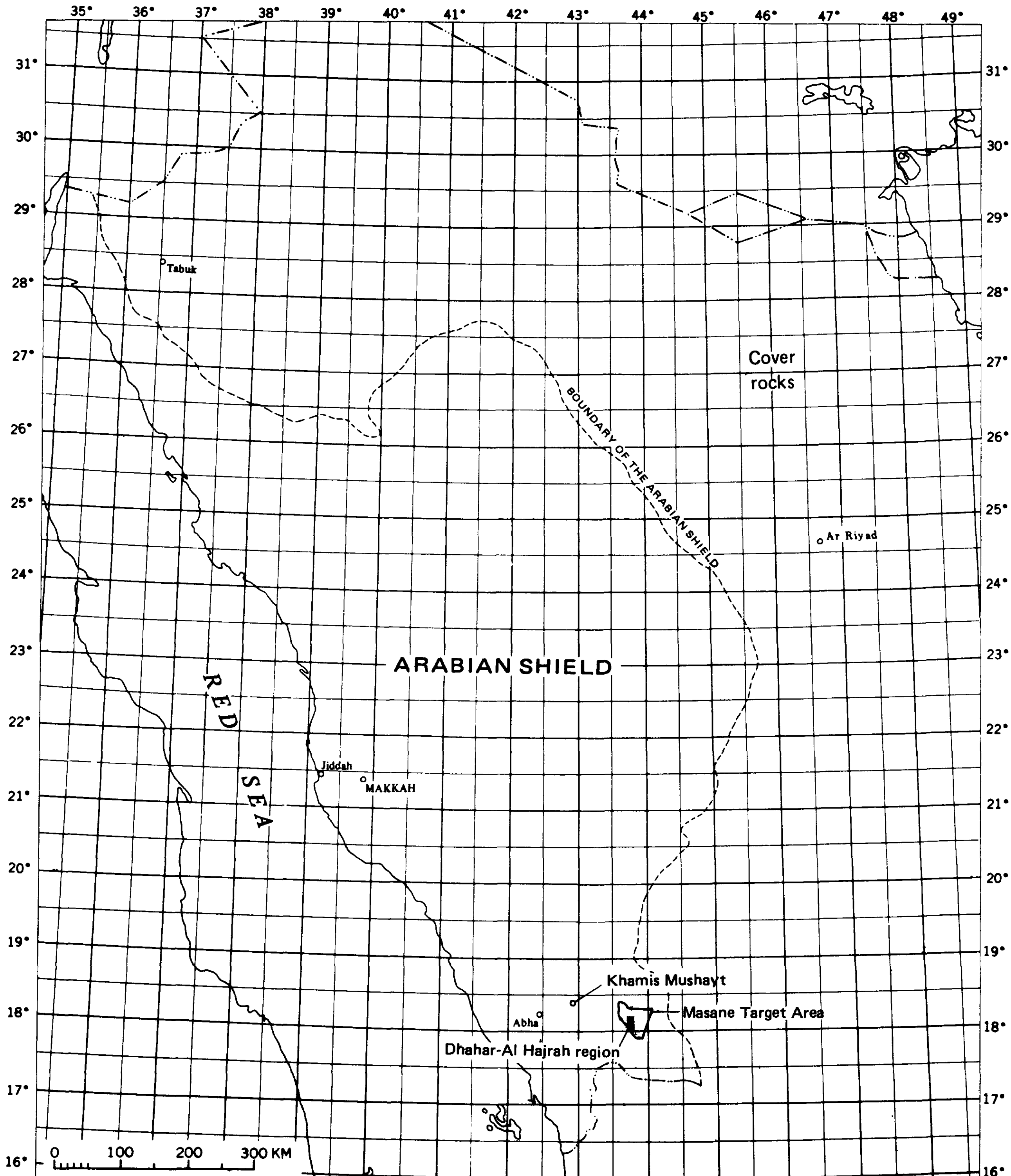

Figure 1.--Index map of western Saudi Arabia showing location of the Dhahar-Al Hajrah region.

The principal prospect areas of Dhahar and Al Hajrah are separated by only a few kilometers (fig. 2). They occur within a belt of tightly folded metasedimentary and metavolcanic rocks that abuts against plutonic intrusive rocks north of Dhahar and extends south 100 km or so to beyond the Yemen border. The structural grain within the Dhahar-Al Hajrah region is predominantly north-south, and fold axes plunge chiefly south. The stratigraphically lower part of the layered rock series in this region consists mainly of mafic flow rocks, tuffs, and breccias originally assigned to the Jiddah group by Greenwood (1980), whereas the upper part consists mainly of intermediate to silicic quartz-crystal tuffs and pyroclastic breccias (Smith, 1980/1981). The tuffs and breccias are believed by the present author to be predominantly ash-flow deposits but were considered by Greenwood (1980) to be of intrusive origin. Greenwood and others (1982) subsequently interpreted the entire layered series as being broadly equivalent to the Halaban group, a volcanic-arc assemblage that formed between 880 and 730 Ma ago. Quartz porphyry intrusive bodies were mapped by Smith (1980/1981) in both the Dhahar and Al Hajrah areas but are much more prevalent at Al Hajrah, where they occur as an irregular set of dikes that are probably offshoots of an adjacent quartz porphyry stock. The association of these dikes with intensely mineralized and hydrothermally altered zones may indicate a genetic relationship. Mafic dikes are present at Dhahar, but they clearly postdate mineralization and metamorphism and are possibly as young as Tertiary in age.

Ore minerals in the prospect areas are chiefly chalcopyrite and sphalerite and their oxidation products. At East Dhahar (fig. 2; MODS 01360), copper and zinc minerals are in a narrow zone of shearing and quartz-sericite-pyrite alteration that is interpreted to lie on the eastern limb of a north-plunging antiform. Half a kilometer to the west, at West Dhahar (MODS 01361), finely disseminated copper and zinc sulfides are associated with pyrite. The stratigraphic relationship between the two zones of workings at Dhahar has not been established. In the Al Hajrah area, the mineralized zone is extensive; it is about 3.5 km long by 2.5 km wide and coincides with a zone of pyritization, chloritization, and epidotization that includes lensoidal gossans. Copper is present in disseminated form and in stockworks; zinc is present in subordinate amounts. The structure of the Al Hajrah area as a whole is probably a south-plunging anticlinorium. The deposits at both Al Hajrah and Dhahar are believed by Smith (1980/1981) to be of volcanogenic origin.

No graphitic schists or other conductive formations were mapped that might interfere with electrical exploration in the region. Locally the silicic layered rocks have been extensively kaolinitized, probably as a result of leaching due

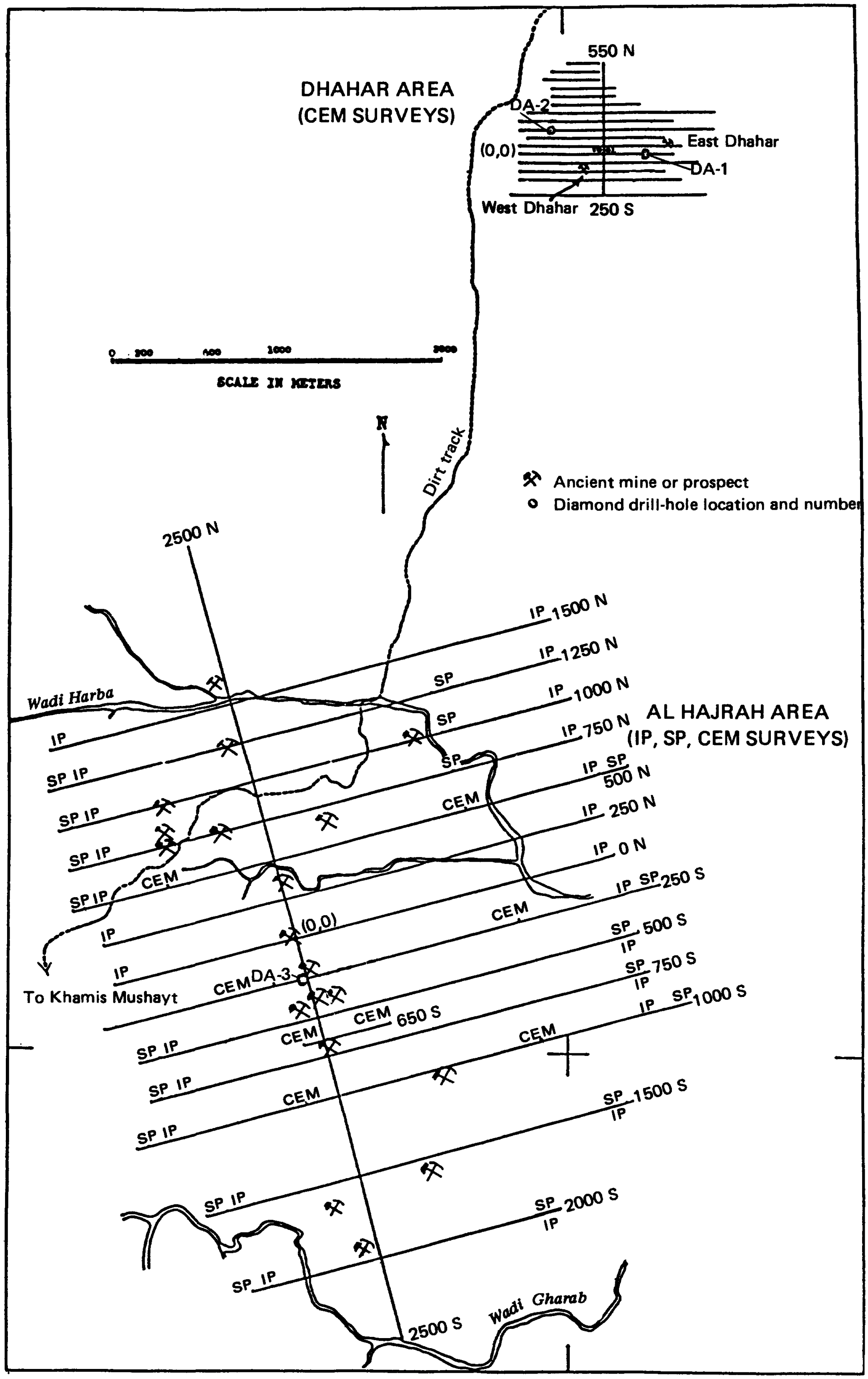

Figure 2.--Map showing location of ground geophysical traverses in the Dhahar-Al Hajrah region. Western and eastern limits of each type of traverse at Al Hajrah indicated by position of symbols: CEM, Crone electromagnetic (horizontal-shootback mode); IP, induced polarization (dipole-dipole, time-domain), SP, self-potential. Base map after Smith(1980/1981). Traverse lines drawn planimetrically using points (0,0) of Smith.

to breakdown of disseminated pyrite, and such kaolinized zones should behave as a strongly conductive overburden. The thickness of the oxidized zone in both areas, as determined from drill holes, is between 10 and 30 m. Below this zone there is almost no secondary enrichment.

Although geochemical analyses of rock-chip samples and samples from three drill cores show only very restricted anomalous copper and (or) zinc concentrations, Smith (1980/1981) considered the overall results of the work at Dhahar and Al Hajrah to be encouraging enough to warrant further investigations.

GEOPHYSICAL SURVEYS

Scope of work

The Dhahar-Al Hajrah region lies within the so-called "Masane Target Area" (fig. 1) of the 1977 airborne electromagnetic (AEM) INPUT survey of selected mineral belts on the Arabian Shield (Wynn and Blank, 1979). Although no AEM anomalies were delineated over either Dhahar or Al Hajrah, several were indicated in immediately adjacent terrain. In May 1977, soon after the preliminary results of the INPUT survey were received and during the period of Smith's fieldwork in the region, the region was visited briefly by M. E. Gettings (USGS) for the purpose of designing a reconnaissance ground geophysical exploration program that would take into consideration both the AEM results and Smith's findings. Gettings (written commun., 20 May 1977) recommended Crone electromagnetic (CEM) traverses of three of the most favorable AEM anomalies and of the Dhahar prospects and two induced polarization (IP) profiles across the large zone of disseminated copper and hydrothermal alteration at Al Hajrah.

In response to these recommendations, about 24 line-km of CEM traverses were made during October 1977 and January 1978 by a USGS field team. The IP program was expanded to 13 profiles totaling about 39 line-km and was conducted by ARGAS crews during December 1977 and April-May 1978. In addition, ARGAS determined elevations at 50-m intervals along each profile and at 250-m intervals along 4 km of base line at Al Hajrah. Self-potential measurements were made concurrently with the IP work, for the most part by a separate ARGAS survey team.

Figure 2 shows the location of all ground geophysical traverses at Dhahar and Al Hajrah (exclusive of the ground followup surveys of AEM anomalies). Each survey will be discussed in turn, and an overall evaluation, with recommendations for further work, will be given in the concluding section.

Airborne electromagnetic INPUT survey

Part of sheet 4 of both the airborne electromagnetic (AEM) conductor map and the aeromagnetic map of the Masane INPUT Target Area submitted by the survey contractor in his final report (Geoterrex, 1978) are reproduced as on plates 1 and 2, respectively. The area covered corresponds closely to the rectangular block of figure 2 and includes all of the Dhahar and Al Hajrah areas. The ground survey base line at each prospect area is shown for location purposes.

The AEM INPUT method has been described in detail elsewhere (Wynn and Blank, 1979). A terrain clearance of 120 m was used for the Masane survey, and flight traverse lines were nominally spaced 250 m apart. Because of the moderate relief (generally less than 50 m) in the Dhahar-Al Hajrah region these parameters were closely adhered to. The east-west traverse orientation is optimum for the northerly strike of the regional structure.

As can be seen by reference to plate 1 and figure 2, no AEM anomalies were detected at Dhahar and Al Hajrah within the areas subsequently covered by ground surveys. Because these ground survey areas included all of the zones of exposed hydrothermal alteration and mineralization at both prospects (Smith, 1980/1981), it may be concluded that any massive sulfide-bearing bodies have extremely limited strike length and (or) are below the range of detection. In view of the moderate to high surface resistivities measured in the region, the depth of penetration of the AEM signal is considered to have been sufficient to detect a moderately good conductor at a depth of 200 m or less.

Anomalies M-75 and M-76 (plate 1), which are directly east of the Dhahar area, were both placed in a "bedrock-poor" category because of the very high conductivities, as indicated by slow transient decay rates, and the large widths and strike extents of the anomalies (Geoterrex, 1978). The principal source of these anomalies is almost certainly formational graphitic material, as observed in the field by Gettings (written commun., 1977). Although the presence of sulfide conductors in the graphitic zone cannot be eliminated by using the AEM data alone, no surface indications of sulfide conductors were found during limited geological reconnaissance at anomaly M-76.

Anomalies M-72 and M-73, which are just east of the southern part of the Al Hajrah area, are quite different in character and were rated "bedrock-good" and "bedrock-fair", respectively. The transient decay rates are low, the anomalies are observed on all six channels on at least one line in each case, both anomalies are isolated and of relatively short wavelength, and one anomaly (M-72) is associated with an aeromagnetic anomaly (plate 2). All of these factors were considered by Geoterrex (1978) as favorable criteria for a sulfide origin. Gettings (written commun., 1977) noted pyrite at three locations but found no evidence of copper-mineralized rocks.

A weak 4-channel anomaly was recorded on line 92 near Wadi Gharab in the southern part of the Al Hajrah area. Although this anomaly (unlabeled) was not interpreted by the contractor (Geoterrex, 1978), its decay rate is low and Gettings (written commun., 1977) found it to be associated with a silicified zone that contains hematite (after pyrite), malachite, pyrite, and chalcopyrite. CEM traverses were recommended by Gettings and subsequently conducted across all three of these isolated anomalies (M-72, M-73, and the anomaly of line 92), but the results were inconclusive, as will be explained in the next section.

Aeromagnetic highs southwest of point (0,0) and north of point 2500 N on the Al Hajrah base line (plate 2) are most likely associated with intrusive quartz porphyry bodies. Because the quartz porphyry bodies appear to be intimately related to localization of the copper-mineralized rocks at Al Hajrah, a detailed aeromagnetic interpretation might prove useful; however, it was not attempted. An aeromagnetic dipole anomaly associated with anomaly M-72 (plate 2) has not been explained.

Crone electromagnetic surveys

Two Crone electromagnetic (CEM) systems were acquired by the USGS Geophysics Section shortly prior to deployment in the Dhahar-Al Hajrah region. The so-called "shootback" electromagnetic survey method, for which this equipment was specifically designed, was developed in 1957 and has become a standard geophysical technique in exploration for metallic sulfide-bearing bodies.

Two identical portable coils are used in CEM surveys. Each coil functions either as a transmitter or receiver, depending on the position of the function switch. In the horizontal-shootback mode of operation, the transmitting coil is held horizontally and the receiving coil is held vertically with the axes on the line of separation; normally this separation ranges from 50 to 150 m, depending on the depth of exploration desired. If no conductor is present, no magnetic flux will cut the receiving coil and the field-strength meter will indicate a null at zero dip angle of the receiving coil axis. If a conductor is present, the null will generally be obtained at some resultant (primary and secondary field) dip angle other than zero. After the reading has been made, the roles of transmitter and receiver are interchanged and the field procedures are such that the desired value is obtained as the algebraic sum of the two readings. The uncertainty in the determination of the null position for each reading is generally 1° or less. Because this system requires no hard-wire connection between coils and is relatively insensitive to coil separation and orientation errors, it can be employed rapidly and efficiently, particularly in rough terrain. The field strength at null can be recorded if an out-of-phase measurement is desired. Three frequencies are available (low=390 Hz, medium=1830 Hz, and high=5010 Hz), although normally only one frequency, selected on the basis of field tests but most commonly 1830 Hz, is used in reconnaissance surveys.

Experimental model response curves for curve matching are available if quantitative interpretation of the results is warranted. These include a very useful set developed by Lin (1969) that allows estimation of conductor width, depth, and dip for cases in which a dike model is appropriate. The conductivity thickness product (σt) can be estimated by comparing the amplitudes at different frequencies and using Lin's curves, which have been modified by Sadek (Sadek and Blank, 1982/1983) for use with the frequencies available in the USGS CEM system. Additional information about the conductor can also be obtained by operating the CEM equipment along the same traverse in the vertical-shootback or JEM mode (vertical transmitter position, coaxial coils) or in the coplanar vertical-loop or horizontal-loop modes.

For all of the CEM traverses at Dhahar and Al Hajrah, the equipment was operated in the horizontal-shootback mode at medium frequency. Although the CEM survey was thus strictly a reconnaissance survey, no conductors were found that warranted multifrequency, out-of-phase, or alternate mode measurements, in consideration of the objectives of the study.

Dhahar

Sixteen CEM traverses totaling 13 line-km were made along east-west lines laid out by tape and compass from stations surveyed by Smith(1980/1981) on the Dhahar base line. The coil spacing was 100 m, and the station increment was 50 m. Data are presented on figure 3 as profiles of resultant dip angle. Traverse lines and dip-angle plot points (centers of coil spread) have been plotted planimetrically with respect to Smith's base line, but no slope corrections have been made.

No dip-angle anomaly of more than 10° was detected in any traverse. The profiles reflect the presence of numerous

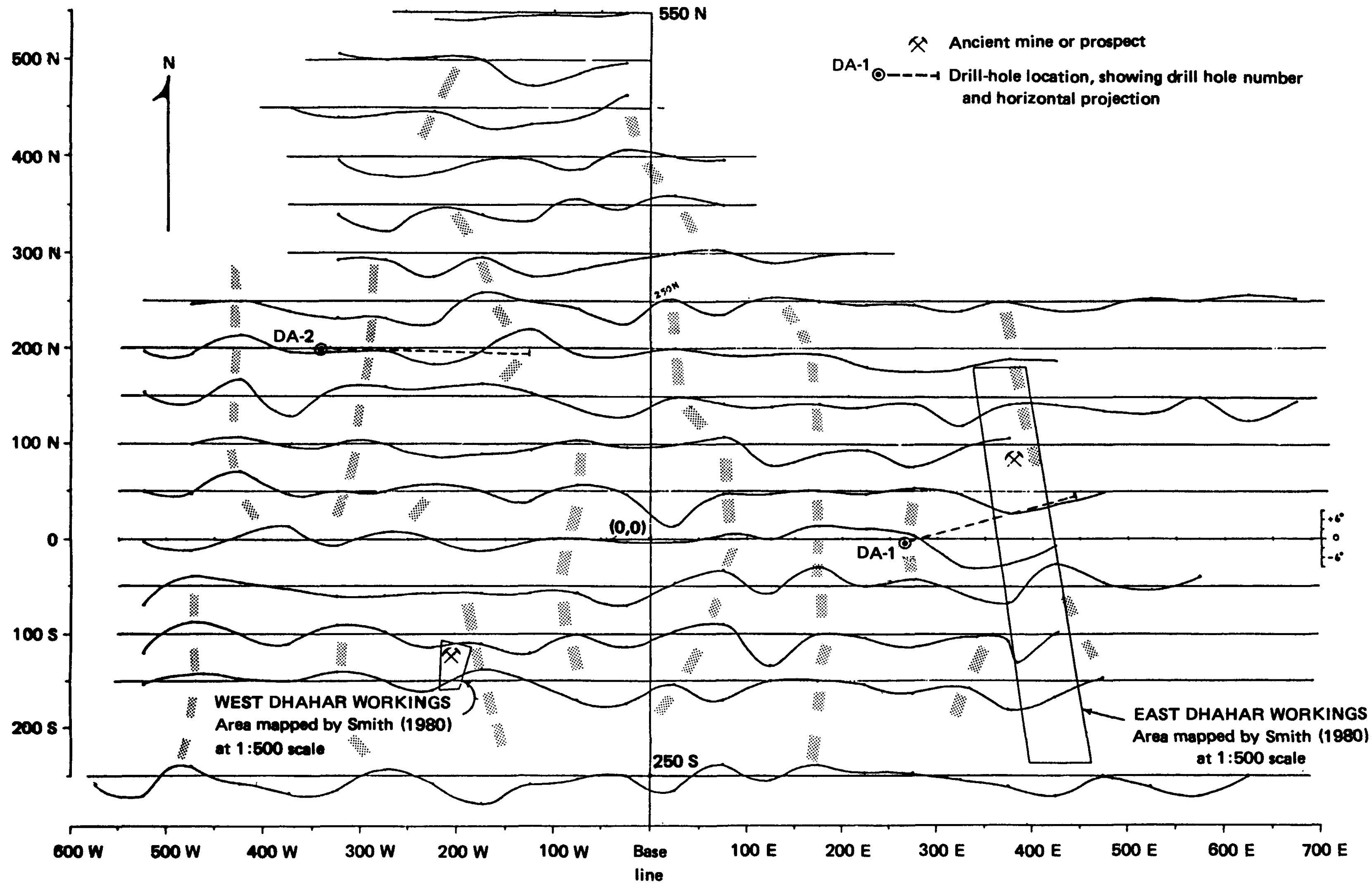

Figure 3.--Map showing Crone electromagnetic (CEM) anomalies in the Dhahar area, horizontal-shootback mode, medium frequency (1830 Hz), coil separation 100 m. Plot point is mid-position of coils. Base line surveyed by C. W. Smith; traverse and data points plotted planimetrically starting from point (0,0) of Smith (1980/1981) distance in meters. Dip-angle scale shown at line 0. CEM surveys by M. A. Bazzari and C. W. Smith in 1977 and 1978. Possible axes of continuous conductors indicated by dashes.

weakly conducting zones whose tops most generally lie approximately at the base of the oxidized zone at depths of 10-30 m. An anomaly centered at 25E, line 250N, is typical of the field results and is compared on figure 4 with model curves selected from a suite supplied by the CEM manufacturer (Crone, 1972). The field-response curve is drawn through only a few data points and may include the effects of more than one conductor. The model curves apply to steeply dipping dikes of varying thicknesses, infinite conductivity, and depths of 0.25 times the coil spacing (25 m for the coil spacing employed at Dhahar). If the dip-angle scale is adjusted, the field-response curve matches the narrow dike model curve reasonably well; the relative amplitudes of the central maximum and flanking minima agree with the relative amplitudes for the model. The absolute amplitudes of the field curve are lower than those of the model curve because of the much lower conductance of the real source. Because of the limitations of the field data, curve matching cannot be very diagnostic and the above results should not be misconstrued as definitive. In general, the CEM data at Dhahar are not suitable for a quantitative interpretation, which would require more detail, better resolution, and a delineation of the anomaly at more than one frequency. Examples of quantitative interpretations of CEM data over weakly conductive sources are contained in a report of geophysical exploration at Umm ar Rummf (Sadek and Blank, 1982/1983).

The strike continuity of the Dhahar CEM anomalies is problematical. Some possible conductor axes are indicated on figure 3, but the station increment and traverse spacing are evidently both too wide for the ambiguities of interpretation to be resolved. Dip-angle contours are shown on plate 3 and are subject to the same uncertainties. The contours are superimposed on the geologic map of Smith(1980/1981), together with the outline of areas of anomalous copper values determined by analysis of rock-chip samples. Because areas of anomalous zinc values are nearly identical, these are not shown. Both the East Dhahar (MODS 01360) and West Dhahar (MODS 01361) workings are associated with zones of anomalous CEM dip angle, though no more so than many other workings in the area of investigation. (Unfortunately coverage of East Dhahar is incomplete.) Probably because of the low conductivities, uncertain anomaly definition and speculative strike continuity, there is very little overall correlation between CEM results and mapped geology. A distinct northeast grain in the anomaly pattern interrupts many north-trending anomalies near the center of the contour map and suggests that conductivity distributions and the mafic dike set have a common structural control.

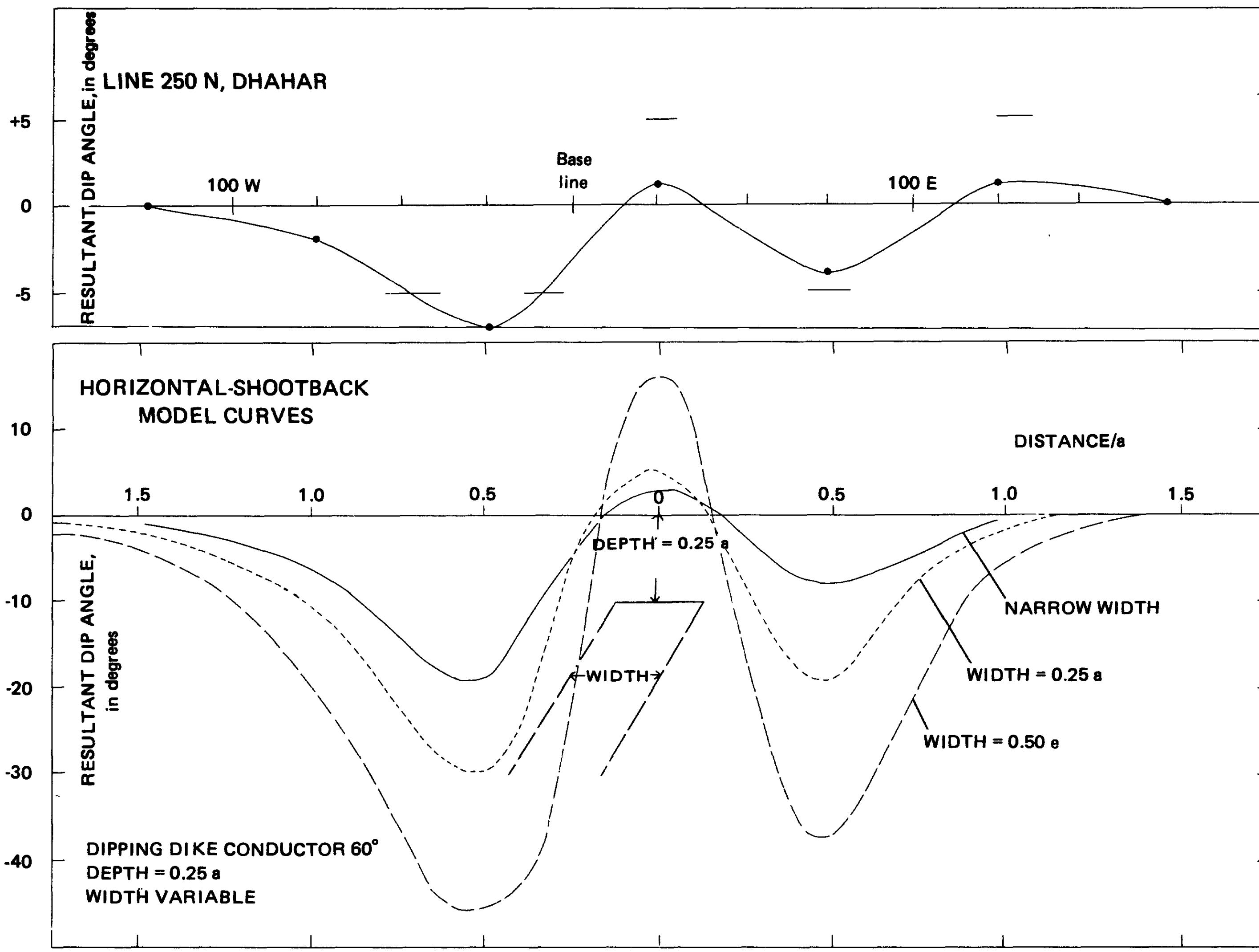

Figure 4.--Profiles showing comparison of Dhahar Crone electromagnetic (CEM) dip-angle anomaly with model response curves. Coil spacing (Dhahar) = 100 m; coil spacing = a (model curves); medium frequency (1830 Hz); horizontal-shootback mode. Model curves from Crone (1972).

Al Hajrah

Only four CEM traverses were made at Al Hajrah, for a total length of 6 km. Lines 500N, 250S, and 1000S were surveyed by using a 100-m coil separation; line 650S, a short intermediate line surveyed by tape and compass, was surveyed by using 50-m coil separation. The station increment on all four lines was 50 m.

The dip-angle profiles for Al Hajrah are plotted on a combined geological, geochemical, and geophysical map (plate 4). They are characterized by numerous low-amplitude fluctuations in dip-angle response; such fluctuations evidently reflect, as they did at Dhahar, the presence of numerous shallow sources having weak conductance. Profiles 250S and 1000S have many features in common that suggest a possible continuity of conducting zones that strike a few degrees east of north. The strongest response along both lines is just east of the base line; a pair of similar conductors was detected at 150E and 250E along line 250S and at 50E and 200E along line 1000S. Except for geochemical indications (plate 4), there is no surface evidence of mineralized rocks in the immediate vicinity of the CEM anomalies. The conductor at 150E, line 250S, coincides with an induced polarization anomaly, and an exploratory drill hole (DA-3) was drilled to the east beneath this line from the base line at an inclination of 45° (Smith, 1980/1981). At 150E, the vertical depth below surface of the drill hole was about 120 m and the core was essentially barren; however, this depth somewhat exceeds the depth of exploration of the CEM system in the configuration employed. Weaker anomalies near the eastern extremity of both lines also coincide with IP anomalies, as does the largest positive dip-angle response (+4°, line 500N, at the base line). The latter is associated with anomalous zinc values indicated by the geochemical survey.

A continuous zone of negative response along line 650S would seem to contradict the inference of conductor continuity between lines 250S and 1000S near the base line, but because this line was surveyed by using 50-m coil separation, significant penetration below the oxidized zone was probably not achieved and the response probably indicates conductive "overburden". The line was terminated before the negative anomaly form was adequately delineated.

Other Crone electromagnetic surveys

In conjunction with the surveys at Dhahar and Al Hajrah, reconnaissance CEM traverses were conducted across several additional targets in the general region. These include INPUT anomalies M-72 and M-73 (plate 1), the smaller anomaly observed along line 92 of the INPUT survey (plate 1), and the Masane copper deposit (MODS 00673) at Wadi Sadah, some 12 km southeast of Dhahar. The total traverse length was about 5 km.

Except for Wadi Sadah, no target produced a dip-angle response of more than 12°. Three of the four profiles at Wadi Sadah revealed high-amplitude anomalies indicative of high conductance, in agreement with TURAM electromagnetic results over this deposit (Hatim Khalady, Arabian Shield Development Company, oral commun., 1976).

These supplementary CEM traverses were conducted during an early period of familiarization and training with the equipment and the results are inconclusive. The AEM anomaly targets, in particular, are not considered to have been adequately tested.

Self-potential survey at Al Hajrah

A brief description of the self-potential (SP) method and its application at Al Hajrah was included in the contractor's report (ARGAS, 1978). Self-potential measurements were made by the ARGAS crew at 25-m intervals along 10 of the 13 cross lines and at 50-m intervals along the original base line, that is, from 2500S to 1500N, for a total coverage of about 33 line-km (fig. 2). An electronic millivoltmeter was used, and both "leap-frog" and fixed-electrode methods were employed.

Self-potential values on the base line became increasingly negative toward the north, and an SP low was incompletely delineated near the northern end of the base line. It was decided to extend the base line by tape and compass for an additional kilometer to the north to determine the anomaly closure. Station settings and SP measurements for the extension were made by the USGS.

The SP profile for the entire 5 km of base line was provided by the contractor (ARGAS, 1978), who used as an assumed datum the value zero millivolts at point (0,0). This profile is reproduced in the present report as figure 5 and shows that SP values are fairly constant on the northern extension and that negative closure is restricted to the segment between points (0,0) and 1500N. The low has a maximum amplitude of as much as 90 mV, but cross lines show a much weaker effect, and this low may result mostly from formational contrasts rather than from polarization of a massive sulfide deposit. On the other hand, because the low roughly coincides with induced polarization and geochemical anomalies (fig. 6 and later discussions), some contribution to the low by sul-

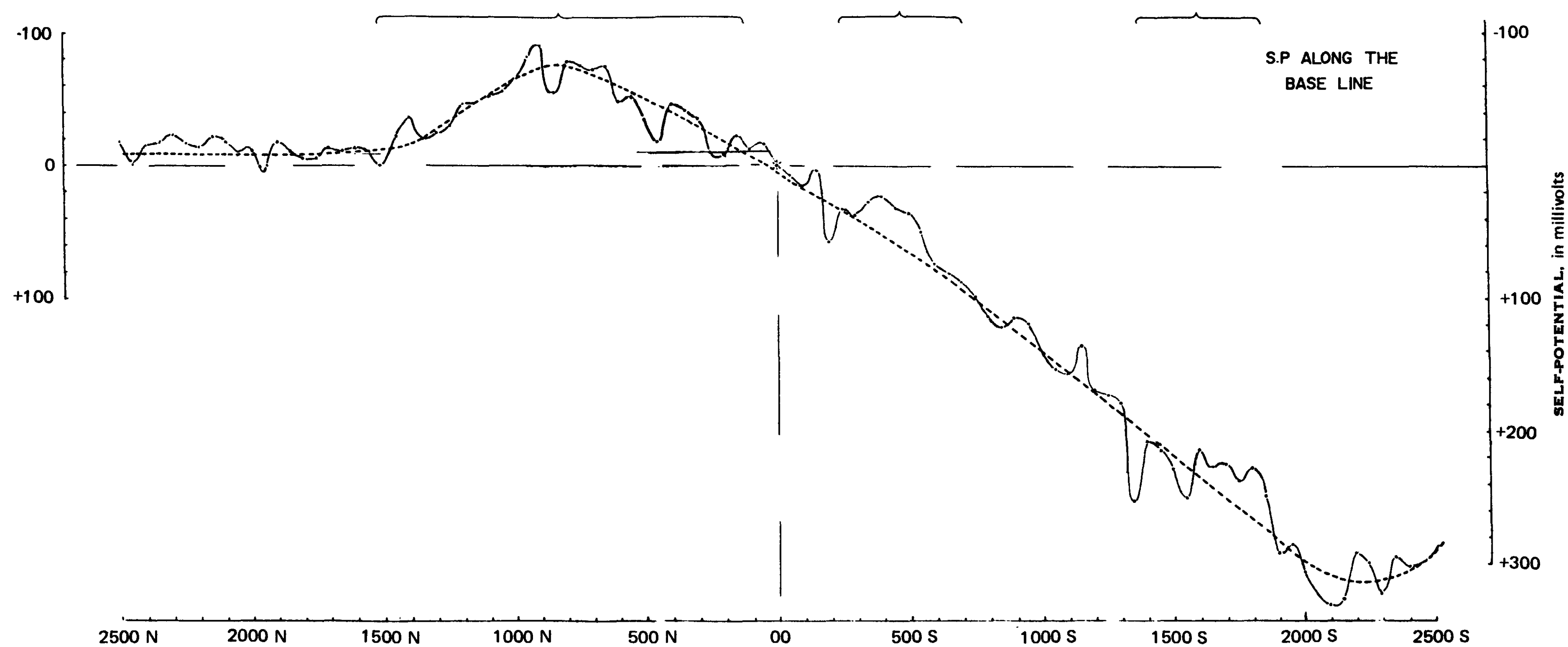

Figure 5.--Profiles showing self-potential (SP) anomalies along Al Hajrah base line (ARGAS, 1978). Brackets indicate SP lows having possible economic exploration significance. Distance in meters.

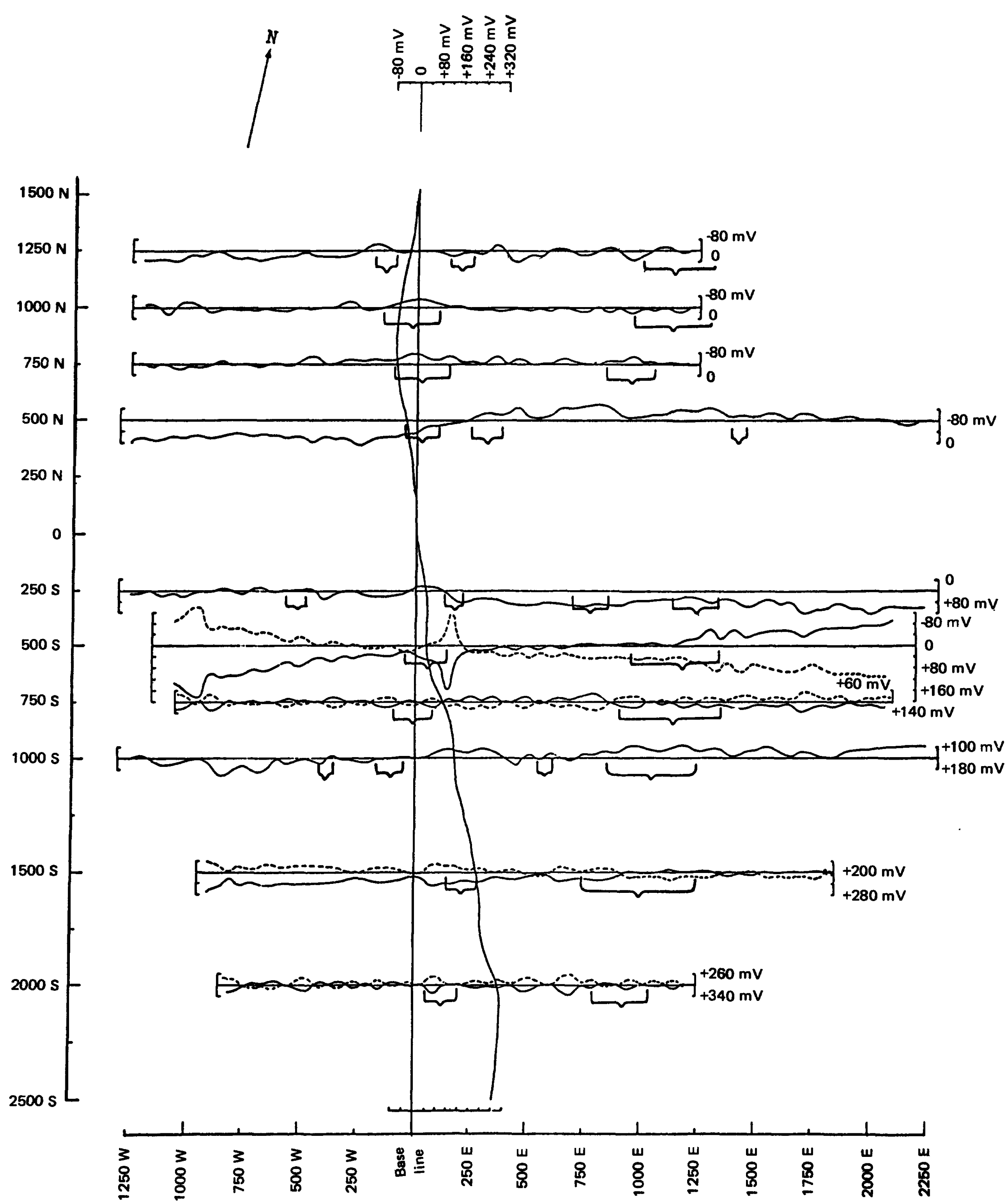

Figure 6.--Profiles showing self-potential (SP) anomalies along cross lines, Al Hajrah (after ARGAS, 1978). Self-potential in millivolts. Base-line SP is smoothed from readings at 50-m intervals (see figure 5). Lines 500S, 750S, 1500S, and 2000S may have sign error, and alternative versions are shown by dashed lines (see text). Horizontal datum line for each profile is plan position of profile, but note datum value changes between profiles. All values relative to assumed value of zero millivolts at point (0,0); distance in meters. All profiles surveyed by ARGAS in December 1977 and April-May 1978. Station interval 25 m along cross lines. Locations of induced polarization anomalies indicated by brackets (see plate 4).

fide concentrations seems likely.

The dashed line through the profile of figure 5 is identified by the contractor as a "probable...drift of the zero level" (ARGAS, 1978, p. 13). By this is meant simply that a smooth curve has been drawn through the data points; that is, anomalies having short spatial wavelengths have been smoothed out. The width of the envelope of typical short-wavelength anomalies is about 40 mV (20 mV north of 1500N), and the maximum amplitude of any excursion from the assumed mean is 60 mV, at point 1350S. Two lows, at 500S and 1700S, were cited by the contractor as being of possible economic interest. Although these lows persist through several data points, their amplitudes do not exceed that of the "noise" envelope and their significance is questionable. These two lows and the principal base line low between (0,0) and 1500N are indicated by brackets on figure 5.

The 10 cross-line profiles and the smoothed base-line profile are shown on figure 6, along with the locations of induced polarization anomalies (see also plates 4-6). Self-potential fluctuations along these profiles and along the base-line profile shown on figure 5 undoubtedly reflect to some extent the instability of the measurements. For test purposes, a segment along line 500S, from point (0-0) to 750W, was resurveyed after an interval of two days. Self-potential measurements on the second survey differed from those recorded on the first by as much as 20 mV.

Discrepancies of the magnitude observed can be generated by changes in electrode potential over the course of a few hours as a result of either dessication of pore fluids or electrofiltration in the immediate vicinity of the station. It is unfortunate, moreover, that the SP survey was conducted in two different stages separated by 4-5 months, probably under drastically different conditions of ground moisture, and also that most of the ARGAS work was done by the leap-frog method. (Of the 11 traverses, including that along the original base line, only the northern three (750N, 1000N, and 1250N) were surveyed by using the more accurate fixed-electrode method.) Crews as well as techniques were changed during the SP survey. Perhaps partly because of the lack of consistency in both data-recording and data-reduction procedures, there seems to have been some confusion in presentation of the profiles by the contractor. Profiles surveyed by using the fixed-electrode method were plotted as having a reversed sign in the ARGAS report (1978; later amended) because of an error in the drafting stage. Possibly the signs of the SP measurements on profiles 500S, 750S, 1500S, and 2000S were reversed during the reduction of data in the field, although this cannot be established from existing documentation.* Dashed lines on figure 6 show the four profiles with changed signs relative to readings where the lines crossed the base line (the reference station for each cross line). Possibly the most significant effect of the sign change is the conversion of two relatively large excursions on line 500S, at about 1200W and 150E, from highs to lows. The excursion at 150E is immediately east of an IP anomaly, and, with the proposed sign change, it is in better agreement with the low detected near 500S on the base line.

Except for the anomalies noted above, whose signs are in question, and the broad gradients attributable to formational effects, no anomalies having amplitudes significantly greater than the estimated reading uncertainties appear on any of the cross lines. In some places the SP profiles seem to mirror the topography, probably as a result of streaming potentials.

Correlation of anomalies between adjacent profiles is tenuous at best. It appears that self-potential method is not a very productive exploration tool at Al Hajrah and that, in order for the method to be of any real utility, the traverse spacing should be substantially less than 250 m. Great care should be exercised to ensure stable measurements.

Induced polarization survey at Al Hajrah

In accordance with recommendations made after initial reconnaissance in the region (Gettings, written commun., 1977), the principal focus of the geophysical work was the induced polarization (IP) survey at Al Hajrah. This survey was conducted by ARGAS under contract to the Directorate Gen-

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* The arguments for such a sign reversal are as follows.

1. For the earlier leap-frog profiles, the SP values were apparently measured as the difference between the potential at forward station and the potential at rear station; whereas for the later leap-frog profiles, the SP values were apparently measured as the difference between the potential at rear station minus the potential at forward station (relative to direction of advance); thus there was an unexplained change in recording procedures.

2. If the signs of the later leap-frog SP values are changed, then all base-line SP lows correspond to lows along cross lines, whereas if left unchanged, they correspond to highs along cross lines.

3. The overall correlation between adjacent traverse profiles is somewhat improved by changing the signs of the later leap-frog profiles.

eral of Mineral Resources; specifications and supervision were provided by the USGS. It resulted in the clear delineation of several significantly anomalous zones indicative of concentrated ions of disseminated sulfide minerals. The anomalous zones have not yet been systematically tested by drilling.

Principles and methodology of IP surveys are discussed in the contractor's final report (ARGAS, 1978); for further details, reference can be made to any standard textbook on geophysical exploration (for example, Telford and others, 1976). The IP surveys at Al Hajrah were conducted in the time domain by using a Scintrex 2.5-KVA IPC-7* transmitter and IPR-8 receiver set at 2-second timing. The transient decay voltage measured was the central slice in the three-slice mode, and the integration time was 520 milliseconds. The chargeability (M) obtained by using this method is approximately equivalent to five times the percent frequency effect.

The initial program called for three profiles to be surveyed by using 750-m intervals, a dipole length of 50 m, and five depths of exploration. The number of dipole lengths, n, separating the closest electrodes of current and potential dipoles, was varied to include integer steps between 1 and 5. Results of this survey phase were sufficiently encouraging to warrant additional profiles; however, because a greater depth capability was required, for subsequent work the dipole length was increased to 150 m and the maximum value of n was increased to 6.

The contractor has presented the dipole-dipole data as pseudosections of chargeability M, apparent resistivity ρ, and apparent metal conduction factor MF; each triad is on a separate sheet and its scale depends on the dipole length. Each sheet also contains the self-potential data if available and topographic profiles for the surveyed line. Plan positions of IP-effect anomalies were presented on a "comprehensive map" over the geological base of Smith(1980/1981). For convenience in comparing the IP data with other data, the geochemical and Crone electromagnetic results have been added to the ARGAS comprehensive map and presented as on plate 4 of the present report; pseudosections for chargeability and apparent resistivity are stacked at an approximately uniform scale on plates 5 and 6.

Note that on the pseudosections, the plot position corresponding to a depth of n=5 for a dipole length of 50 m

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* Specific mention of manufacturers or trade names in this report in no way constitutes an endorsement by the USGS and is for information purposes only.

(profiles 500N, 250S, and 1000S) is identical to that corresponding to a depth of n=1 for a dipole length of 150 m (the remaining profiles); thus, use of two different dipole lengths results in no apparent overlap in depth of coverage. In fact, the actual depth of exploration is much less than the depth implied by any of the pseudosections. If the depth of exploration is defined as that depth reached by 50 percent of the charging current in a uniform half-space, then the depth of exploration is less than 25 percent of the dipole separation or less than half the plotted depth for the corresponding dipole separation on the pseudosection. This depth of exploration amounts to 75 m at n=5 for the 50-m dipoles and a maximum depth of 262 m at n=6 for the 150-m dipoles.

A description of the pseudosection set for each profile forms the main body of the contractor's report (ARGAS, 1978), and further detail will not be added here.

Discussion of anomalies

Distinctly anomalous zones were delineated on all profiles, although the chargeability values in these zones are rather low, the maximum being about 40 mV/V or about four times background. The considerable strike continuity of most of the zones can be seen on stacked sections of IP effect (plate 5) and on the comprehensive map (plate 4), where the contractor's interpreted anomaly axes are indicated by dashed lines. The most extensive anomalous zone is in the southeastern part of the Al Hajrah area and has a strike length of more than 2 km. This zone is associated with pyritic alteration and anomalous zinc concentrations in outcrop samples, although there is very little surface evidence of copper-mineralized rocks. The anomalous zone still has a significant IP effect on the southernmost profile, but along that profile the source is apparently deeper. A weak conductor was detected by the two Crone electromagnetic traverses across the zone (lines 250S and 1000S). On the whole, however, apparent resistivities in all of the anomalous zones remain quite high, and apparent resistivities of less than 1,000 ohm-m are found only near the surface (plate 6). Little or no strike continuity is evident on the apparent resistivity pseudosections.

A weaker, four-profile anomalous zone, whose axis is delineated in the northeastern part of the area, may be a continuation of the zone described above, but, if so, the source is displaced westerly in the vicinity of Wadi Mahanit (plate 4). In support of the hypothesis of continuity, a small chargeability anomaly is on the pseudosection for line 500N (plate 5), below point 1050E. In fact, there is a remarkable similarity in the disposition of anomalous zones on either side of the large central aplite dike that crosses the Al Hajrah area from north to south, and the discrete anomaly axes indicated by the contractor on the western side of this dike may also represent a single continuous source with a westerly offset at Wadi Mahanit. Possibly disseminated sulfides are concentrated at essentially the same stratigraphic horizon and now appear on opposite sides of the antiform outlined by Smith (1980/1981).

At Wadi Harba, the northeastern anomalous zone is associated with minor zinc enhancement and an ancient copper prospect (100E, line 1000N). Again, the characteristics of the anomaly on successive pseudosections suggest a polarizable source that plunges south.

Although anomalous zones west of the central aplite dike generally show weaker IP effects than the southeastern zone, they are possibly of greater interest because the majority of the visible copper indications, such as malachite concentrations and ancient workings, as well as copper and zinc geochemical anomalies, are found in the western anomalous zones. Also several Crone electromagnetic anomalies are located over these zones, and the northwesternmost zone is associated with a negative self-potential anomaly along the base line and possibly two cross lines (1200N and 750N), as noted previously. The presence of an intricate system of quartz porphyry dikes in the central part of the map area is regarded by Smith(1980/1981) as an additional favorable factor because these dikes seem to be related to sulfide enrichment.

The source of the well-formed chargeability anomaly just east of the base line on line 250S, near the center of the western zonal system, was probed by diamond drill hole DA-3 (plate 4). The maximum copper content was well uphole from the projected source of the IP anomaly and was less than 0.3 percent. However, the relationship between IP effect and sulfide concentration was not really tested by this hole because the vertical depth of core beneath the IP anomaly was at least 50 m greater than the maximum depth of exploration for the dipole-dipole profile. In any case, the IP effect is relatively weak, being only about 10 mV/V above background, irregular, and of probable limited depth extent.

A quantitative interpretation of the IP anomalies has not been undertaken; most anomalies are complex and not amenable to modeling. Chargeability anomalies on profile 500N (plate 5) have the simplest forms. The western of two adjacent anomalies on this profile is centered at about 25W and agrees reasonably well in form but not in intensity with the theoretical IP response of a subvertical tabular source at shallow depth (fig. 7). The theoretical response was calculated in the frequency domain by Ludwig (1967) for a

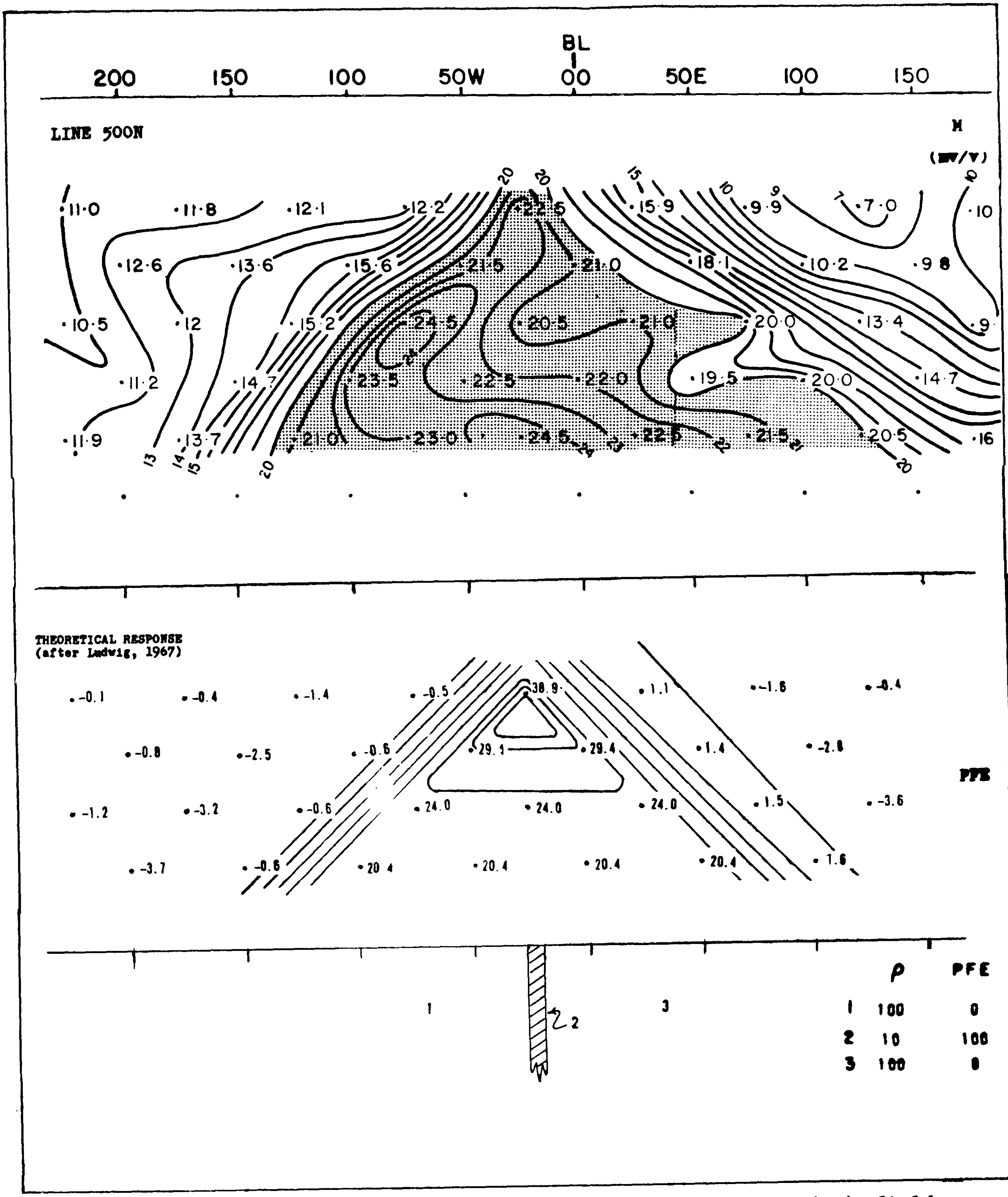

Figure 7.--Profiles showing comparison of induced polarization (IP) field anomaly (time domain) along line 500N, Al Hajrah, with theoretical response (frequency domain) of vertical tabular source. Dipole-dipole array, standard pseudosections. a = dipole length, t = thickness, ρ = resistivity (ohm-ft). Form of response is in general agreement, but intensity of response in field example is much weaker. M = PFE x 5; see text for explanation. Theoretical response pseudosection from Ludwig (1967).

strongly polarizable ideal body that is less resistive than the surrounding medium. Apparent resistivity (ρ) and IP-effect (PFE) contrasts in the model case are much greater than those at Al Hajrah.

The other anomaly of the pair on profile 500N is centered at about 500E and is similar to theoretical anomalies calculated for a more deeply buried subvertical tabular source.

SUMMARY AND CONCLUSIONS

Although several geophysical methods were employed in the Dhahar-Al Hajrah region, only the induced polarization surveys suceeded in locating specific targets for drilling. The airborne electromagnetic INPUT survey gave a strong preliminary indication that no major ground electromagnetic targets would be delineated, at least none having strike length in excess of 250 m, which was the flight-line spacing. The airborne electromagnetic response at Dhahar and Al Hajrah was flat although conditions were nearly optimum for airborne electromagnetic surveying: satisfactory maintenance of 120-m terrain clearance, moderately resistive surface rock, and absence of graphitic formations within the two principal areas of prospection. The accompanying aeromagnetic map shows a relatively smooth field in the vicinity of the prospects and suggests that ground magnetic surveys would prove of little direct aid to mineral exploration in the region.

Ground electromagnetic surveys confirmed the negative airborne electromagnetic results in both areas. At Dhahar, a tighter line spacing and closer recording intervals used with the Crone electromagnetic system would probably yield a more distinct pattern of low-amplitude anomalies that might prove useful in delineating structure and tracing out weak conductors; however, there is little chance of detecting significant zones of massive sulfides. There is perhaps a better chance at Al Hajrah because, although Crone electromagnetic coverage in that area was not nearly as extensive as at Dhahar, the response induced in one site was somewhat greater than any at Dhahar. A coil separation of 100 m appears to be the minimum to achieve adequate depth of exploration.

No measurements of self-potential were made at Dhahar, but at Al Hajrah this method yielded for the most part only very weak anomalies. In this type of terrain, self-potential surveys are almost useless without a very close control of secular drift and electrode polarization; otherwise, stable anomaly amplitudes may be exceeded by uncertainties in the residual potentials. "Leap-frog" methods do not provide the required accuracy. The only negative anomaly whose amplitude seems to be significantly greater than the uncertainties was between about 500N and 1250N on the base line. This anomaly coincides with a narrow zone of anomalous IP effect, with copper and zinc anomalies, and, on line 500N, with a weak Crone electromagnetic anomaly. The anomaly probably results mostly from formational effects but may result in part from spontaneous polarization of a low-grade massive-sulfide body. Better delineation of the anomaly is required to explore this possibility.

In contrast to the results of airborne electromagnetic, Crone electromagnetic, and self-potential surveys, induced polarization surveys at Al Hajrah were moderately successful and the results are encouraging. Most chargeability anomalies are well delineated, show systematic continuity along strike from profile to profile, and are associated with anomalous zinc and (or) copper values, as determined by the geochemical survey of Smith(1990/1991). Both the eastern and western zones of anomalous induced polarization effect are similar in several respects and may arise from a single mineralized horizon that has been antiformally folded and plunges south. Some indications of convergence of the two zones can be seen on pseudosections for the southernmost profiles.

The induced polarization effect in the anomalous zones at Al Hajrah is weak to moderate, and associated apparent resistivities are relatively high. Because the apparent resistivity variations do not seem to be nearly as systematic as those of induced polarization effect, careful consideration should be given to the apparent metal conduction factor pseudosections contained in the contractor's report (ARGAS, 1978).

The anomalous zone of strongest induced polarization effect, in the southeastern part of the Al Hajrah area, is a zone of intense pyritic alteration and moderately anomalous zinc values in rock-chip samples. Copper may be completely absent from this zone at the surface, but if pyrite and sphalerite are zoned peripherally to chalcopyrite, as has been suggested by Smith(1990/1991) then exploration of the induced polarization target at depth becomes especially attractive.

Although there is little hope of finding high-grade massive sulfide bodies associated with these induced polarization anomalies, they may represent zones of concentrated sulfide disseminations and the metal contents in some places may include copper and zinc of commercial grade. It is highly speculative as to whether or not the tonnages that can be proved will be adequate for exploitation, but the total area of disseminated base metals at Al Hajrah is so large that it must be considered to have hardly been tested. In view of the induced polarization results, further investigation would seem to be fully warranted. This recommendation agrees with the conclusion of Smith(1980/1981), which was arrived at principally on geological grounds.

RECOMMENDATIONS

The following additional work in the Dhahar-Al Hajrah region is recommended as a result of the foregoing surveys.

Dhahar

1. A reconnaissance self-potential survey of the Dhahar area should be made that uses widely spaced traverses in an attempt to detect a deeply buried massive-sulfide orebody.

2. If the results of (1) are favorable, a followup reconnaissance slingram electromagnetic survey using a 200-m coil separation should be made on east-west traverses.

Al Hajrah

1. Detailed Crone electromagnetic or slingram electromagnetic traverses should be made across each induced polarization anomaly on each profile to determine the most conductive part of each anomaly. This survey probably should be done before drilling, to aid in site selection. In addition, the principal Crone electromagnetic anomalies found on 250S and 1500S should be fully delineated, and a coil spacing of 150 m is recommended.

2. The delineation of the self-potential anomaly between (0,0) and 1500N on the base line should be completed by a tightly controlled, fixed-electrode resurvey of the four cross lines from 500N to 1250N and by a new survey of intermediate lines. Coverage need not extend more than 750 m from the base line. This surveying should also be done before drilling.

3. The principal induced polarization anomalies should be tested by drilling. At least two holes should be sited in the southeastern anomalous zone, and one hole each should be sited in the northwestern, northeastern, and southwestern zones. (Holes in the southeastern and northwestern zone were also recommended by ARGAS (1978).) If the results of drilling are negative, no further work is

recommended.

4. The induced polarization anomalies should be closed by surveying additional dipole-dipole lines at 1750N, 2250S, and perhaps 2500S, and fill in profiles should be made along lines 1250S and 1750S if drilling results in the southeastern anomaly are encouraging.

Other areas

1. Airborne electromagnetic anomalies M-72 and M-73 should be tested by repeating reconnaissance Crone electromagnetic traverses or by using slingram electromagnetic methods because the results of the previous tests are unsatisfactory. If a good conductor is indicated, the anomaly or anomalies should be studied in detail by using further electromagnetic and ground magnetic surveys.

2. If warranted by the results of (1), detailed mapping and geochemical sampling should be conducted and should be possibly followed by drilling.

DATA STORAGE

No data files were established as a result of this study. Mineral localities referred to in this report are recorded in the Mineral Occurrence documentation System (MODS) data bank, and each is identified by a unique 5-digit locality number. Inquiries regarding the MODS data bank may be made through the Office of the Technical Advisor, Saudi Arabian Deputy Ministry for Mineral Resources, Jiddah.

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