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MAGNETIC SURVEYS IN THE HAJRAH-HAMDAH AREA, INCLUDING A GROUND SURVEY OF THE HAJR ANCIENT MINE, KINGDOM OF SAUDI ARABIA

by

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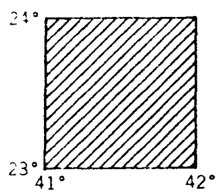

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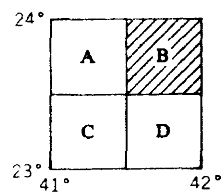
1-degree quadrangle



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ABSTRACT

A detailed total-intensity ground magnetometer survey was made of an area of about 2.3 km^2 encompassing the Hajr ancient gold mine, one of the Hajrah-Hamdah group of mines of the Jabal Ishmas-Wadi Tathlith gold belt in the southeastern part of the Arabian Shield. The Hamdah region was previously the target of a special aeromagnetic/radiometric survey in support of mineral exploration, and it was also covered as a part of Area IV in the aeromagnetic and scintillation counter survey of the shield.

The ground magnetic anomaly map of Hajr replicates aeromagnetic maps of this part of the Jabal Ishmas-Wadi Tathlith gold belt in that it reflects the strong relative magnetization of serpentinite bodies and shows similar structural trends. The contrast in magnetic expression of serpentinite and hornblende schist, the other major rock unit present at Hajr, facilitates the delineation of serpentinite masses beneath areas of shallow alluvial cover. Serpentinite is inferred to be present in much of the covered area southeast of the ancient workings.

Areas of serpentinite outcrop are characterized by a pattern of intense, sharply localized anomalies in total field intensity. Few of the anomaly spatial wavelengths appear to exceed about 100-150 m, a fact consistent with the geologic deduction of Helaby and Worl (1981), supported by drilling data, that the serpentinite is essentially rootless, that is, that it overlies hornblende schist in a low-angle, probable thrust relationship. Helaby and Worl (1981) have shown that these gently dipping contact zones were a favorable environment for auriferous mineralization.

Concentrations of magnetite in the serpentinite, assumed to be the sources of the field disturbances, apparently have a significant component of remanent magnetization with random orientation. This relationship suggests either variable tectonic rotation of initial magnetite or development of magnetite at different stages of the tectonic evolution.

The dominant magnetic structural trend interpreted from the anomaly map is produced by a northeast-trending high-angle fault set. East-trending lineaments are also numerous and are probably produced in part by a set of shear faults that displace the northeasterly set. North and northwest magnetic trends characteristic of the main Jabal Ishmas-Wadi Tathlith gold belt farther north are generally subordinate. Some lineaments of these sets may be the expression of hydrothermally altered zones in which the magnetic component is weak or absent.

INTRODUCTION

A detailed total-intensity ground magnetometer survey was made during the interval March to October 1976 over three small contiguous rectangular tracts in the vicinity of the Hajr ancient gold mine workings, located at lat 18° 54.7' N. and long 43° 40.5' E. in the southeastern part of the Arabian Shield (fig. 1). The Hajr workings are the largest of the Hajrah-Hamdah group of ancient mines, one of several separate groups that constitute the Jabal Ishmas-Wadi Tathlith gold belt. Aeromagnetic and scintillometric maps covering the area are available from airborne surveys carried out during 1965-66 and 1966-67.

The Hajrah-Hamdah area was mapped and a program of exploration and drilling at the Hajr mine was implemented concurrently with the ground magnetic survey. This work is reported in a companion paper (Helaby and Worl, 1981), which contains a full account of the geologic relations and results of the drilling. A reconnaissance study of the entire Jabal Ishmas-Wadi Tathlith gold belt has recently been completed by Worl (1979). The three projects form part of a program of mineral resource investigations carried out by the U.S. Geological Survey Mission in accordance with a Work Agreement with the Ministry of Petroleum and Mineral Resources.

Two major rock units were distinguished during the geologic mapping of the Hajr mine, serpentinite and hornblende schist, the latter consisting of a variety of metavolcanic and metasedimentary rocks including quartz-biotite schist, biotite schist, and marble. Relict bedding in the schist unit has gentle to moderate dips. The serpentinite is highly sheared and altered to asbestiform tremolite, talc, magnesite, calcite, and iron oxides. It is generally conformable with the hornblende schist and overlies it, probably in thrust contact. In addition, numerous aplitic dikes and sills lace the area, and are especially prevalent, commonly with shallow dips, in the serpentinite-hornblende schist contact zone.

Auriferous mineralization is localized chiefly in schist near the contact between schist and serpentinite and in close proximity to the aplitic dikes. An important objective of the ground geophysical work was to aid in delineation of the serpentinite-schist contact in alluvium-covered areas, on the assumption that the magnetic contrast between serpentinite and schist or aplite would be strong, as implied by aeromagnetic signatures on a regional scale. A secondary objective was to assist in mapping the principal faults and other structural elements whose disposition might affect the exploration rationale. In particular it was anticipated that magnetics might help delineate intensively altered zones

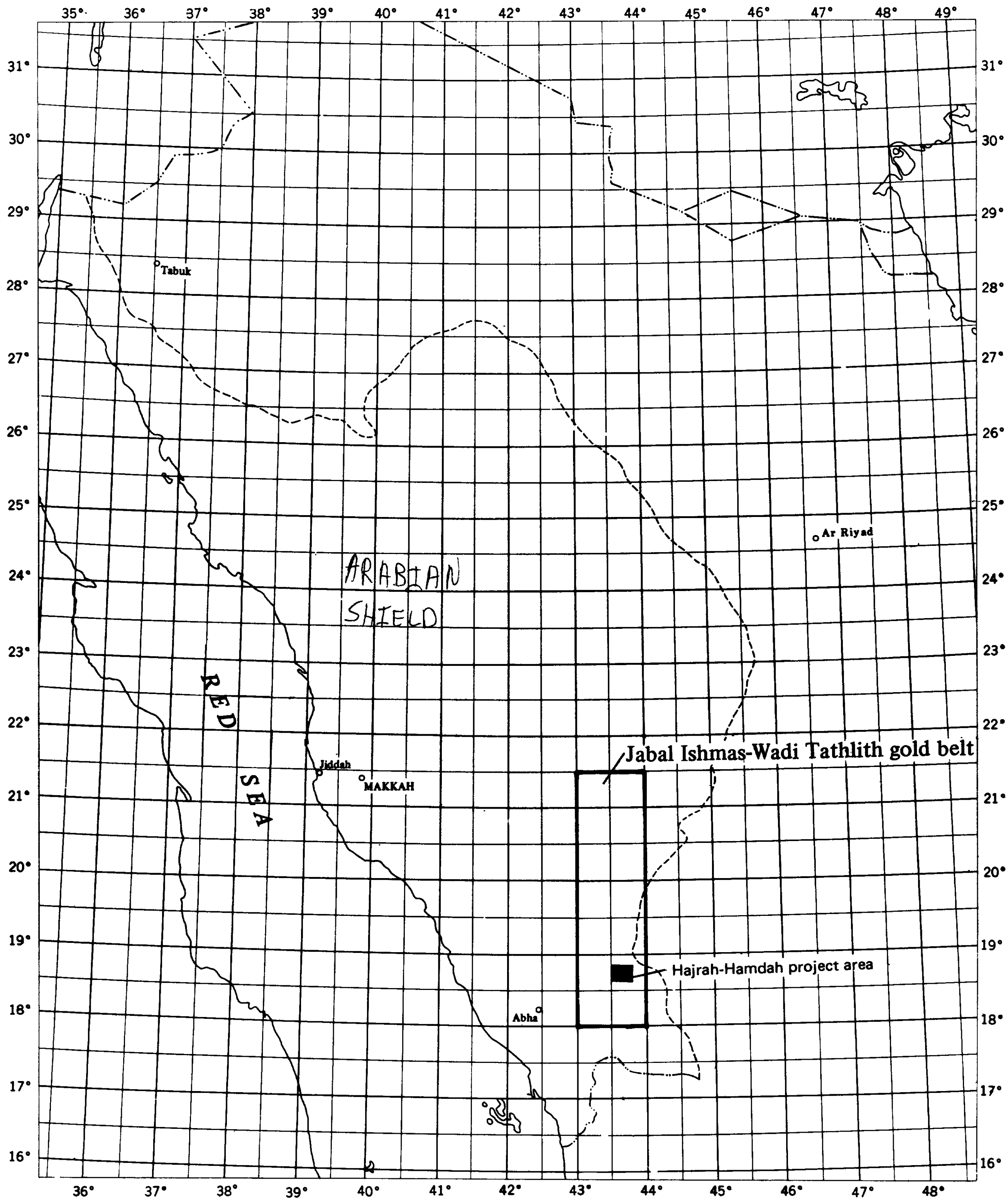

Figure 1.–Index map of southeastern Arabian Shield; showing location of Jabal Ishmas-Wadi Tathlith gold belt and Hajrah-Hamdah project area.

known to be associated with enhanced gold values within and adjacent to the bodies of serpentinite.

EARLY AIRBORNE SURVEYS

As noted above, the Hajr mine area was overflown in the course of two aeromagnetic and scintillometric surveys carried out during the middle 1960's in conjunction with regional mapping and mineral belt investigations. The first of these, a special aeromagnetic and scintillometric survey of the so-called Hamdah area, was flown in 1965-1966 for the USGS Mission by a consortium consisting of Aero Service Corporation, Hunting Geology and Geophysics Limited, and Lockwood Survey Corporation Limited. The area covered, about 450 km^2, is several times that of the Hajrah-Hamdah project area which straddles its southern boundary. Nominal flight-line spacing and terrain clearance for the Hamdah survey were 400 m and 150 m, respectively; the traverse direction was northwest-southeast. One year later (1966-67), the entire region was flown as a part of Area IV of the Arabian Shield aeromagnetic and scintillation counter survey. The contractor for this work was the same group as above, augmented by inclusion of the Arabian Geophysical and Surveying Company (ARGAS). Flight specifications for Area IV were 0.8-km line spacing, 150-m terrain clearance, and northeast-southwest traverse headings. Both the Hamdah and Arabian Shield surveys were supervised by the Bureau de Recherches Geologiques et Minieres (BRGM), and formed part of the field program of the Directorate General of Mineral Resources (DGMR).

A fluxgate magnetometer was used in these early surveys and only relative, rather than absolute, total-field intensities were recorded. Also, the scintillometers employed crystal detectors of rather low volume (about 400 in^3) by present day standards, so that the system was not responsive to weak sources of gamma radiation.

The aeromagnetic-scintillometric map resulting from the Hamdah survey is reproduced on plate 1, and the portion of the Area IV survey covering the same terrain is shown on plate 2 (from sheets 162 and 165 of the unpublished 1:100,000-scale aeromagnetic series; see also Andreasen and Petty, 1974). On both maps the Hajrah-Hamdah project area and the area covered by ground magnetics at the Hajr mine are indicated. It can be seen that only three or four traverses crossed the latter area in each airborne survey. The aeromagnetic maps for the area common to both surveys are nearly identical, except that the 1966-67 version (pl. 2) is somewhat smoother and less detailed than the 1965-66 version (pl. 1) because of wider traverse spacing. Minor differences in the contour shapes are also attributable to the fact that traverse headings for the two surveys were mutually orthogonal.

Most of the intense field disturbances in the area common to the two maps are produced by masses of serpentinite rock. The long spatial wavelengths of anomalies associated with the serpentinite are probably indicative of the relatively large depth extent of these masses; north of the Hajrah-Hamdah project area the serpentinite occurs as nearly vertical lenses, in contrast to the thin, nearly horizontal sheets exposed at Hajr (Worl, 1979). In the Hajrah-Hamdah area, a small positive anomaly of amplitude 60-80 nanoTeslas (nT), elongated east-west and bounded on the south by a steep gradient (pl. 1), is centered over serpentinite that extends north from the vicinity of the Hajr workings. The source of the sharp negative anomaly immediately south of the area covered by the ground survey (and probably associated with the steep gradient seen on plate 1) is completely concealed by alluvium, but is probably serpentinite. Disturbances in the southwestern part of the Hajrah-Hamdah area are clearly associated with serpentinite.

Strong magnetic trends on the Hamdah map (pl. 1) are directed east-west, northeasterly, and northwesterly. The north-south anomaly grain that characterizes the Jabal Isthmas-Wadi Tathlith gold belt north of latitude 19° N. (Worl, 1979) is conspicuously absent. Just east of, and parallel to, the main vehicle track (Najran-Tathlith road) crossing the northeastern corner of the Hajrah-Hamdah prospect area (pl. 1), a very weak gradient trend appears to reflect a somewhat easterly extension of a major north-south structure that has resulted in juxtaposition of the large serpentinite mass underlying Jabal al Hamdah (lat 19°01' N., long 43°38' E.) and a granodiorite gneiss-chlorite schist complex (see Overstreet, 1978, pl. 4). The gradient trend does not appear on the map from the 1966-67 survey (pl. 2), in spite of a more favorable orientation of flight lines. According to Worl (informal communication, 1980), there is some geologic evidence for a shear zone along this trend.

The remainder of the Hajrah-Hamdah area is magnetically "quiet". This relative lack of anomalies is due both to the limited depth extent of the allochthonous serpentinite remnants and to the fact that the layered rocks are very weakly magnetized. Much of the disturbance-free portion of the Hamdah aeromagnetic map (pl. 1), particularly immediately northeast of the Hajrah-Hamdah project area, is associated with similarly non-magnetic granitic rocks.

No aeroradiometric anomalies were delineated within the project area as a result of the airborne surveys. Only one such anomaly appears in the Hamdah map, whereas several appear on the corresponding portion of the Area IV map (pl. 2), probably as a result of the finer contour interval on the latter. The anomalies are closely associated with granitic bodies, as can be seen by comparison with the geologic maps of Overstreet (1978) and Warden (written commun.). One of the strongest radiometric anomalies occurs directly over a 4-km long granitic mass centered at lat 19° 5.5' N., long 43° 42.5' E., about 13 km northeast of the village of Hamdah. This stock has been determined to be the source of metallization in the so-called Jabal Mahanid group of ancient mines, whose geologic setting is almost identical to that at Hajr (Worl, informal communication, 1980). In both cases the gold is associated with silicic vein systems in a hydrothermally altered environment. The aplitic dike swarm at Hajr is inferred to have issued from a buried granitic stock located in magnetically flat terrain northeast of the Hajrah-Hamdah project area, and to be consanguineous with the stock at Jabal Mahanid. There is, however, no indication of anomalous gamma-ray activity associated with granitic rocks of this vicinity, at least on the displays of plates 1 and 2.

GROUND SURVEY AT HAJR ANCIENT MINE

Procedure

The ground magnetometer survey of the Hajr ancient mines covered an area of about 2.3 km^2 in the southern portion of the Hajrah-Hamdah project area. It was designed and implemented by M.A. Bazzari, with field assistance from A. Uthman (U.S.G.S.). Field work consisted of 104 line-km of traverse and readings taken at 4680 points of observation.

The survey was carried out in three discrete stages, each covering a rectangular tract, or block. At the onset, a grid base station was established on a low hill near the center of block 1, the first and largest block to be surveyed. This point was used as the origin of coordinates (station 0,0). North-south and east-west base lines were then laid out by Brunton compass and chain from the base station to the perimeter of the block, and marked by rock cairns at 25-m intervals. East-west traverse lines were chained off from the cairned points on the north-south base line, and stations were cairned and marked every 25 m along each traverse. The chained distances were not corrected for slope. Survey blocks 2 and 3 were added later to the west and south, respectively, by extension of the east-west and north-south base lines. Traverse lines in both of these blocks were spaced 20 m apart and stations were set up at 20-m intervals along the traverses, the tighter spacing aimed at better definition of anomalies. Lines and stations for blocks 2 and 3 were set out by rod and theodolite. The traverse lines are in a north-south direction for block 2 and in an east-west direction for block 3, in each case normal to the base line.

The set of points thus established for magnetometer readings does not comprise a rectilinear array on a horizontal plane because of the effect of slope, which, though generally negligible (maximum topographic relief in the area is only about 20 m), locally amounts to as much as a meter or two of shortening in a grid interval; the effect on any traverse line is cumulative and maximum at the end points. The base lines were later resurveyed by R. G. Worl from the grid base, using rod and theodolite, in the course of establishing reference lines for geochemical sampling; it was found that the north, east, and south (but not west) segments had been laid out in positions rotated one to two degrees clockwise with respect to the true geographic directions. Consequently, if the geophysical grid is rotated one degree counterclockwise about the origin of coordinates, the traverse direction will lie within approximately one degree of true north-south or east-west (see block index, plates 3 and 4).

All magnetic observations were made by means of a Geometrics model G816 proton magnetometer, which has a sensitivity of ± 1 nT and a reading accuracy of about ± 2 nT. Diurnal variation of the earth's field was monitored at grid point 16N, 25E, the magnetometer base station, by reading a duplicate instrument every 10 minutes. The model G816 instruments are very nearly drift free, but as a precaution the roving magnetometer was checked against the monitor at the base station three times daily. No magnetic storms were recorded during the periods of survey.

At the end of each day's work the magnetometer readings were corrected for recorded diurnal variation. The quantity 37,000 nT was subtracted from each corrected absolute value of field intensity for convenience in plotting. Because the north-south extent of the surveyed area is so small (1.32 km), it was not considered necessary to remove the planetary field from the data set in any standard way. However, a computer program for the International Geomagnetic Reference Field (a spherical harmonic representation of the earth's main field, with 80 coefficients) was used to compute the geomagnetic field components and the gradient in total intensity in the Hajr area. The parameters of interest are approximately:

Total intensity (T)	T = 39,640 nT
Inclination (I)	I = 23.62° DN
Declination (D)	D = 0.66° E.
Horizontal gradient of T, south-to-north	T = 4 nT/Km

for epoch 1976.5, the approximate time of the survey.

Results

The total-intensity magnetic anomaly map derived from the ground survey of the Hajr ancient mine and vicinity is shown on plate 3. Contour intervals on this map are 50, 100, and 500 nT. Corresponding isopleths are represented by dashed, solid, and heavy solid lines, respectively. Each data point of the survey grid is shown as a dot, and the magnetometer base station is indicated by a solid triangle. An index of the survey blocks is also given (note rotation of grid base lines with respect to geographic coordinates, as described above).

The Hajr area has a total magnetic relief of about 4000 nT. However, most of the anomalies are sharply localized. The maximum intensity, + 4675 nT (relative to the datum of 37,000 nT), occurs on a local anomaly that has an apparent peak-to-trough amplitude of about 3100 nT and a half-wavelength of 20 m, the high being delineated by the field intensity at a single point of observation. (Field perturbations of this severity can affect the reading of a Brunton compass, and possibly even the stability of a proton magnetometer reading.) The regional background level of the map appears to be about 2250 nT, so the maximum is more than 2400 nT above background.

Plate 4 is a map of the same area showing qualitative magnetic interpretations superimposed on the main geologic features. Magnetically disturbed zones, lineaments (inferred faults or contacts), and apparent anomaly dipolar axes are obtained from the field intensity map (pl. 3); outcrops of serpentinite and hornblende schist, serpentinite-schist contacts, and inferred faults are taken from the geologic work of Helaby and Worl (1981, pl. 2 and pl. 2 overlay). Aplite dikes shown on the Helaby and Worl map have been omitted. Commonly, the serpentinite-schist contact was mapped on the basis of exposures in ancient workings. Plate 4 also shows the locations of 12 diamond drill holes, and the depth to the base of the serpentinite as determined from drill cores.

It is seen that magnetically disturbed zones in most places coincide with outcrops of serpentinite or occur in alluvium-covered areas. Therefore the sources of the local anomalies are most likely concentrations of magnetite (or other iron oxide) in the serpentinite. The source material cannot be specified exactly, as no measurements of magnetization nor analyses of oxide minerals have yet been made for Hajr rock specimens. Whatever the composition of the sources, the anomalies appear to be predominantly associated with the serpentinite and to be more or less randomly distributed within it. The hornblende schist and aplite dikes must be for the most part magnetically transparent.

The magnetic zonal boundaries shown on plate 4, although very much generalized, predict the existence of large areas of serpentinite beneath alluvial cover. The most extensive area is in the eastern half of survey block 3, south and east of the ancient mining community and ancient workings. No magnetic evidence of serpentinite is seen anywhere in block 2 except possibly for one small zone in the northern half. The serpentinite-magnetic anomaly association is only approximate, as evidenced by the imperfect agreement between zonal boundaries and mapped geologic contacts. To some extent this imperfect agreement may reflect difficulties in distinguishing highly altered serpentinite and highly altered hornblende schist in the field. On the other hand, it seems reasonable to infer that parts of the serpentinite are essentially non-magnetic, particularly where hydrothermal alteration was most pervasive and destructive of iron oxides. Also the anomalies in covered areas need not all be associated with serpentinite. Nevertheless, the magnetic zonal map is probably useful for extrapolating the serpentinite-schist contact beneath alluvium, which ______ was a major objective of the ground magnetic survey.

By inspection of the anomaly map (pl. 3), it is seen that the spectral content of the magnetic field intensity (the distribution of anomaly spatial wavelengths) in the area surveyed has a sharp upper cutoff, that is, few anomalies have spatial wavelengths greater than about 100-150 m (the lower limit is twice the grid interval). In view of the association of magnetic sources with serpentinite and their apparently random distribution within it, this sharp upper cutoff can be taken as a strong indication that the serpentinite masses have no roots, for if they extended to great depths one would expect to find a continuum of spectral energy to comparably long wavelengths. The relatively gentle dips of the basal contact and shallow extension of the serpentinite bodies are already known from field mapping and drilling results (as previously remarked, the contact has been interpreted as a low-angle thrust fault). However, it is noteworthy that the same geometrical concept could have been obtained from magnetic spectral information alone. The power spectrum of a total-intensity anomaly map can be readily produced from the digital image of the map, thus permitting the thickness of the source layer to be quantified.

Although some of the local anomalies are delineated on the basis of too few field points for an accurate rendition of their shape and amplitude, the dipolar character (maximum-minimum association) of many anomalies is clear. Several apparent anomaly dipolar axes are indicated on the interpretation map (Fig. 4) by arrows connecting maxima and minima that seem to be associated with the same polarized body. A few anomalies consist only of highs or lows, and in these cases the anomalies are indicated by "X" or "O", suggesting a down- or up-directed axis respectively. The indicated axes do not in general represent the projection of the actual magnetization vectors for the source bodies, because source shape and the projection of the secondary field on the total intensity vector are determining factors for the shape of the resulting anomaly. However, in most cases, the axes probably correctly indicate the magnetization quadrant and polarity. The majority of the axes are northerly, but the orientations show considerable scatter. We infer from this that the magnetization of much of the serpentinite is in directions other than that of the present inducing field and therefore that remanent magnetization is an important if not dominant component. If it can be assumed that the serpentinite masses were at one time uniformly magnetized, then the scatter is probably attributable to tectonic rotation. This disorientation of magnetization, the erratic distribution of the local sources, and the complex internal structure indicated by the pattern of magnetic trends (see next paragraph) all seem to be consistent with the interpretation of the serpentinite as remnants of an allochthonous thrust sheet. It is also possible that concentrations of magnetic oxides were produced at different times during the tectonic development of the region, for example, prior to serpentinization, during serpentinization, and during a post-serpentinization, largely post-orogenic stage of hydrothermal alteration.

Trends observed on the magnetic anomaly map may or may not be indicators of geologic structure. The vector gradient, like anomaly dipolar axes, is determined by both shape and magnetization of source. Contour trends defined by uniform gradients, if continuous through distances of more than one local anomaly wavelength, probably indicate faults or other contacts between units of contrasting magnetic properties; if a trend is more or less linear as well as continuous, the suspicion of a high-angle fault is reinforced, because a low-angle serpentinite-schist contact might be expected to show more curvature. East-west trends must be regarded with some scepticism because of the east-west direction of traverse in most of the area surveyed, but they are also found in block 2, which was surveyed along north-south lines. The trends therefore are probably valid; there is no particular reason to doubt the accuracy of base-line readings. Moreover, east-west trends are prominent on the aeromagnetic map covering the southern part of the Hajr area (pl. 2).

Linear trends from the anomaly map are plotted on the interpretation map of plate 4. They have been drawn on the basis of contour directions in uniform gradients and from zonal boundaries (the trends of maxima and minima are excluded). Uniform gradients associated with only one local anomaly were not used unless the trend was both linear and probably continuous with that in an adjacent anomaly.

The most prominent and continuous trends depicted on plate 4 are those striking northeast-southwest across the surveyed area. These are regarded as the expression of a high-angle fault set mapped by Helaby and Worl (1980). The pattern is somewhat convex to the southeast, implying that the faults, if indeed high angle, most likely dip northwesterly. Individual traces of this set differ from those inferred by Helaby and Worl but on the whole the agreement is good. The magnetic data tend to confirm and extend the extrapolation of the fault traces beneath areas of cover.

Trends that strike roughly north or northwest are numerous but generally not continuous, possibly because they are interrupted by the northeasterly set. Such trends may in part reflect the serpentinite-schist contact, but it is likely that at least some represent structurally controlled variations in the degree of hydrothermal alteration. The east trends are numerous and commonly more nearly continuous than the northerly or northwesterly set. In many places they are indicated only by weak gradients. Locally they seem to be associated with offsets of the major northeast-trending faults, and thus they may represent the youngest faults that can be inferred from the magnetics. East-trending faults at Hajr may belong to a regional system of east-trending shear faults known to have strong magnetic expression elsewhere in the southern Arabian shield. These regional shears are not necessarily associated with mapped displacements.

SUMMARY AND CONCLUSIONS

Early airborne surveys covering the Hamdah part of the Jabal Ishmas-Wadi Tathlith gold belt, including the Hajrah-Hamdah project area and the Hajr ancient mine, resulted in delineation of strong magnetic anomalies associated with large masses of serpentinite. Areas of metavolcanic and metasedimentary rocks, as well as granitic bodies, show weak or neglible perturbations of the total field. Granitic bodies in some places are associated with pronounced aeroradiometric anomalies; at least one such body (Jabal Mahanid) is a source of auriferous metallization. Structural trends inferred from magnetic lineaments are easterly, northeasterly, and northwesterly, but the north-south trends characteristic of the northern part of the gold belt are not present.

The ground magnetic survey in the vicinity of the Hajr ancient mines presents a picture similar to that of the regional surveys with regard to anomaly sources and trends. Strong total-intensity anomalies are associated with outcops of serpentinite; in contrast, areas mapped as hornblende schist are relatively featureless. The contrasting magnetic zones can be used as a general guide for the extrapolation of serpentinite-schist contacts into areas covered by alluvium. Most of the local anomalies have spatial wavelengths less than about 150 m, indicating a shallow depth extent of the bodies. Examination of the dipolar signatures suggests that many of the anomaly sources have a significant component of remanent magnetization in various directions other than that of the present inducing field. These observations are consistent with the geologic interpretation of Helaby and Worl (1981) that serpentine masses in the Hajrah-Hamdah area are relatively thin remnants of an allochthonous, flat-lying thrust sheet. At a number of points in the vicinity of the Hajr mines, the depth to underlying, non-magnetic hornblende schist has been established by drilling. A mean depth could also have been established from the anomaly spectrum.

The economic significance of the magnetic data lies chiefly in their utility in tracing out the serpentinite-hornblende contact, for it has been established that the contact zone, particularly where it is flattish and associated with aplitic dikes, is a locus of gold deposition from hydrothermal ore finds. Delineation of hydrothermally altered areas with the aid of magnetic data is much less feasible, but might conceivably be accomplished with further detailed study of the origin of the magnetic anomaly patterns.

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