UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

AN AEROMAGNETIC INTERPRETATION OF ELEVEN MAP SHEETS, SCALE 1:250,000, IN THE SOUTHERN NAJD AND PART OF THE SOUTHERN TUWAYQ QUADRANGLES, KINGDOM OF SAUDI ARABIA

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U.S. Geological Survey

Open-File Report

82-1048

April 1983

An Interagency Report prepared by the
U.S. Geological Survey
Saudi Arabian Mission
for the
Ministry of Petroleum and Mineral Resources
Kingdom of Saudi Arabia

The work on which this report was based was performed in accordance with a cooperative agreement between the U.S. Geological Survey and the Ministry of Petroleum and Mineral Resources.

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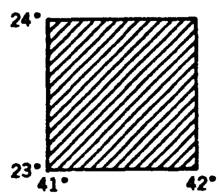

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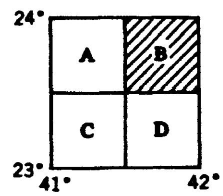

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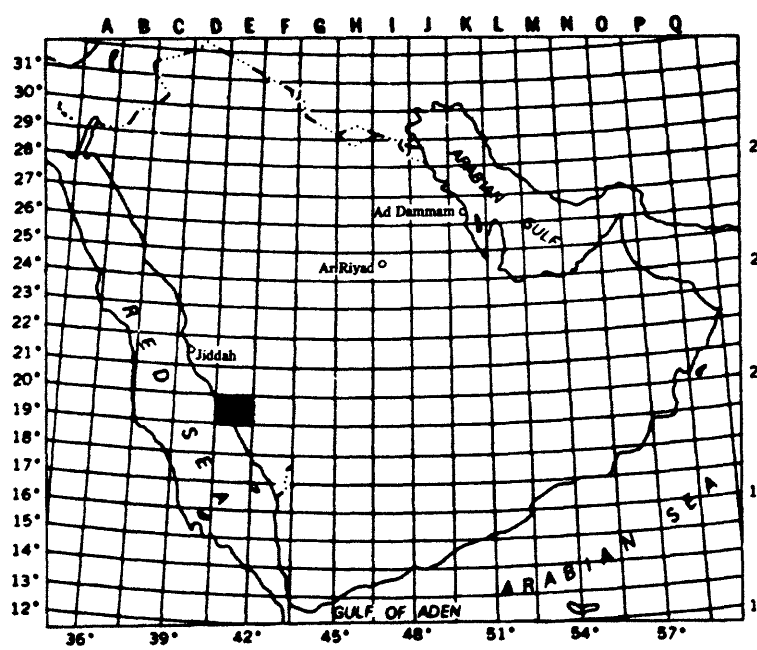

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ABSTRACT

Eleven magnetic interpretation maps (scale 1:250,000) have been prepared for the area of exposed crystalline rocks in the Southern Najd and part of the Southern Tuwayq quadrangles (scale 1:500,000) from available published data. Boundaries of a variety of rock units that produce distinctive magnetic anomalies or anomaly patterns are delineated. In some cases these magnetic boundaries correspond with previously mapped geologic contacts, and in other cases they indicate the possibility of additional, as yet unmapped, geologic contacts. The magnetic boundaries also allow the extrapolation of geologic contacts across areas covered by Quaternary deposits. Many boundaries are identified as part of the Najd fault system, and offset magnetic anomalies may be correlated across certain fault zones. Approximate dips were calculated for a few boundaries that represent igneous contacts, faults, or unconformities. Some characteristic anomalies appear to be associated in a general way with areas of gold mineralization and thus provide a guide for further prospecting.

INTRODUCTION

This report provides an aeromagnetic interpretation for 11 map sheets of 1:250,000 scale located in the eastern part of the Arabian Shield (fig. 1). The study area includes the Southern Najd and Southern Tuwayq quadrangles (Bramkamp and others, 1956; Jackson and others, 1963) of 1:500,000 scale. A preliminary interpretation in manuscript form was completed in 1972 at a scale of 1:500,000, and the present interpretation was done during February 1981. The purpose of the interpretation is to support the geologic mapping program within the Arabian Shield by identifying magnetic boundaries, which, in general, may correlate with geologic contacts.

These aeromagnetic data have been available since 1967, and several regional interpretations in various degrees of detail have been previously reported (Maillard, 1968a; Hase, 1970; Kabbani, 1970; Millon, 1970; Moore, 1979). In addition, interpretations of individual sheets of 1:100,000 scale are available for some areas and are listed in the subsequent section on interpretation methods.

1/ U.S. Geological Survey, Menlo Park, California

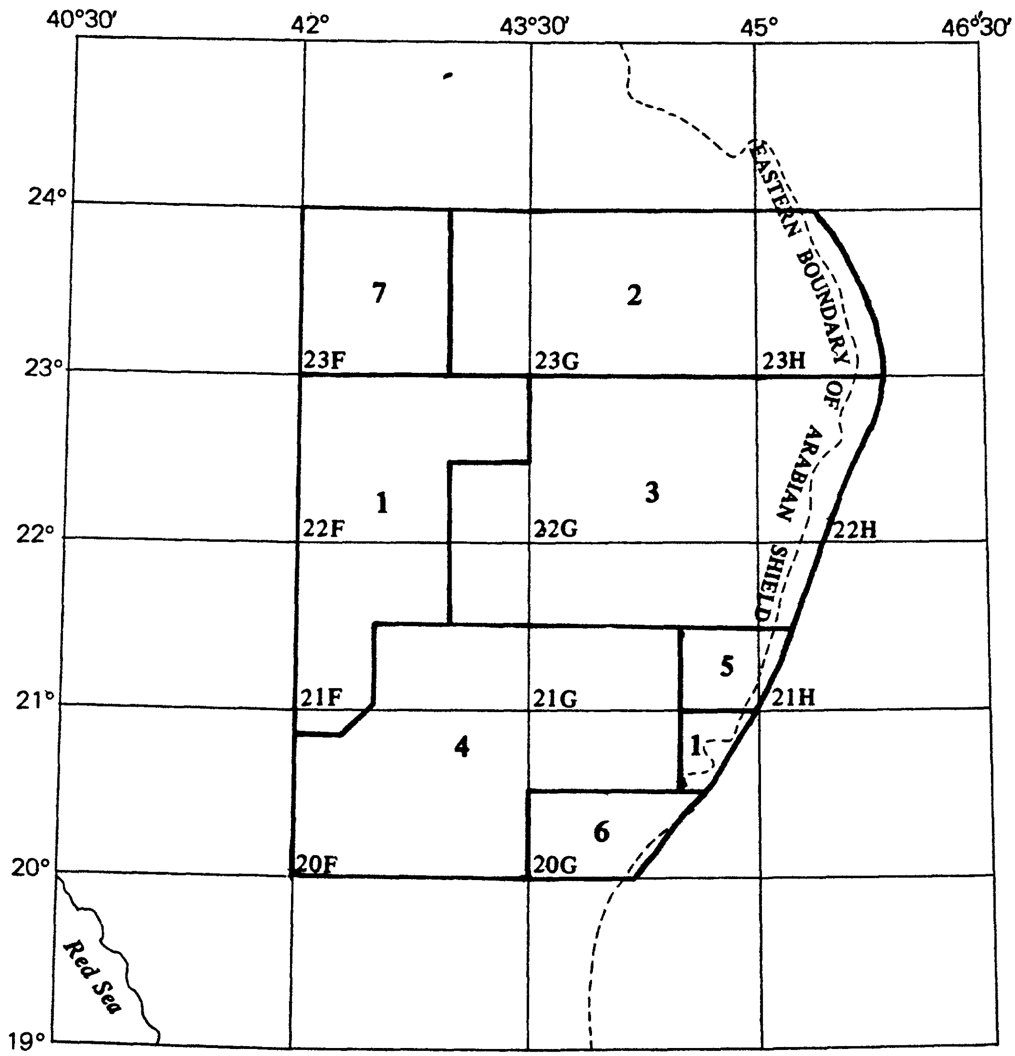

Figure 1.–Index map of area of report showing the sources of data for the lithologic base maps used on plates 1-11, as follows: (1) Jackson and others, 1963; (2) Riofinex Geological Mission, 1979; (3) Barnes and Johnson, 1980; (4) Riofinex Geological Mission, 1980; (5) Kashkary, 1974; (6) Karl Kellogg, unpublished geologic maps, 1981; (7) Letalenet, 1979.

AEROMAGNETIC DATA

The aeromagnetic data were collected in 1962, 1965, 1966, and 1967 by a consortium of companies (Aero Service Corporation, Hunting Geology and Geophysics, Ltd., Lockwood Survey Corporation, Ltd., and Arabian Geophysical and Surveying Company) under the supervision of the U.S. Geological Survey (1962) and the Bureau de Recherches Geologiques et Minieres (1965-1967). The data were compiled at a scale of 1:50,000 with a 20-gamma contour interval and are available at scale 1:100,000 with the same interval or at scale 1:500,000 with a 100-gamma contour interval and with the intervals colored according to the spectrum (Andreasen and Petty, 1973). The surveys were flown along northeast-southwest flight lines 800 m apart and 150 m above the ground. The flight-line locations were obtained from aerial photographs and plotted on semicontrolled photomosaics. The locations, as shown on the magnetic maps, can be in error by as much as a kilometer (H. R. Blank, oral commun., 1981) but can be accurately recovered by relocating the data on controlled photographs.

The aeromagnetic maps used in this report are assemblies made in 1980 at a scale of 1:250,000 by the Riofinex Geological Mission. A total of 11 sheets (fig. 1) are needed to cover all of the available aeromagnetic data between lat 20° and 24° N. and long 42° and 46° E. These 11 sheets are combined with the magnetic interpretation on plates 1 to 11 of this report.

The work on which this report was based was performed in accordance with a cooperative work agreement between the U.S. Geological Survey (USGS) and the Saudi Arabian Ministry of Petroleum and Mineral Resources.

GEOLOGIC DATA

In order to understand the significance of the aeromagnetic interpretations, it is useful to have a geologic map at the same scale. Accordingly, a series of lithostratigraphic maps of the study area were compiled from various sources (fig. 1). The compilations were based primarily on a series of three maps (sources 2, 3, and 4 of fig. 1) prepared by the Riofinex Geological Mission at a scale of 1:250,000 and are combined with the magnetic interpretation on plates 1 to 11 of this report. I somewhat arbitrarily have translated the units of the other map sources into the same lithostratigraphic units as used on the Riofinex maps and have used the same pattern codes for those units. The three original Riofinex maps do not have exactly the same explanations and unit patterns, and unfortunately the compilations of this report for sheets 21F and 21G each overlap two Riofinex map sheets (fig. 1). These maps are not entirely satisfactory for this report because they generally do not display lithologic or age relationships. Colored geologic maps of sheet 23F (Letalenet, 1979) and sheet 23G (Delfour, 1979) are available and can be used in place of the geologic maps used in this report. Additional colored maps are in preparation and can be substituted in the future.

MAP PROJECTIONS

The aeromagnetic interpretations have been drawn on a Universal Transverse Mercator (UTM) projection at a scale of 1:250,000. Similarly, the lithostratigraphic maps were compiled onto individual 1:250,000-scale UTM grids. The grids were provided by Gary I. Selner of the U.S. Geological Survey Saudi Arabian Mission, who produced them using a computer program. Certain parts of the original source material for the lithostratigraphic maps (sources 2, 3, 4, and 7 of fig. 1) were already available on Lambert Conformal Polyconic projections, and no attempt was made to modify their form before compiling onto the UTM grid. Accordingly, various mismatches of as much as 5 mm are present along the borders of certain map sheets and the grids do not coincide. The aeromagnetic map sheets are all Lambert Conformal Polyconic projections.

GENERAL GEOLOGY

The geology of the study area, which is in the eastern Arabian Shield (fig. 1), has been described in several papers from the recent symposium on the evolution of the Arabian-Nubian Shield (Fleck and others, 1979; Schmidt and others, 1979; Hadley and Schmidt, 1980). Individual geologic summaries are available for the 1:250,000-scale geologic maps covering sheets 23F (Letalenet, 1979) and 23G (Delfour, 1979). It is not the purpose of this report to provide an extended description of the geology of the study area; the lithostratigraphic map compilations with their explanations are intended to provide most of this information.

A short summary of late Proterozoic crustal history of the eastern Arabian Shield is quoted directly from the abstract of Schmidt and others (1979, p. 41-42):

> The Arabian Shield was formed by successive accretions of newly formed crust between 1,000 and 600 Ma ago. Successively younger island arcs formed to the east as west-dipping subduction zones shifted eastward. West of Bishah, the volcanic-plutonic crust had consolidated against Africa by about 780 Ma ago when westward-directed subduction ceased at the Nabitah suture.
>
> A new marginal island arc formed subsequently east of Bishah in the southern Najd, and subduction was

renewed at the Idsas suture in the eastern Najd. The volcanic arc consisted of calc-alkaline volcanic rocks (Halaban group), dominantly andesite but ranging from basalt to dacite, and comagmatic, subvolcanic plutonic rocks, dominantly diorite but ranging from gabbro to trondhjemite. About 725 Ma ago this primitive crust was thickened by large intermediate-depth plutons of hornblende tonalite and mafic granodiorite. Compressive tectonism produced folds and faults of northerly trends and was accompanied by greenschist-facies metamorphism.

A continental collision occurred east of the Najd Province about 625 Ma ago and initiated extensive compressional orogeny and potassic granite plutonism throughout the Shield. Large, syntectonic batholiths of calc-alkaline, leucocratic, biotite granodiorite-monzogranite formed the cores of large north-trending gneiss domes that were asymmetric toward the west. The domes consist of tonalitic and granodioritic orthogneiss that represents the low-density, plutonic part of the earlier Halaban crust. Strong compression resulted in northerly trending structures including large west-directed thrust faults.

Posttectonic diapiric plutons of granite and alkalic granite intruded the eroding crust at progressively shallower levels until about 600 Ma ago. Molasse deposits of the Murdama group transgressed westward across the eroding crust and were subsequently deformed along northerly trends. Renewed compression of the now thick continental crust resulted in large northwest-trending Najd faults that have left-lateral displacements aggregating 300 km. The Najd faulting terminated about 560 Ma ago. Transgressive, quartzose sandstone of early Paleozoic age subsequently covered the stabilized craton.

METHOD OF INTERPRETATION

The purpose of this study was to produce interpretive maps that would be of use to geologists mapping in this area. The scale of the interpretation was originally intended to be 1:500,000, but subsequently it was changed to 1:250,000 for consistency with current mapping plans in the Kingdom. The 1:250,000-scale aeromagnetic and lithologic compilations by the Riofinex Geological Mission became available at the time this report was being prepared. For this scale of interpretation, only the more general magnetic features could be analyzed and a detailed understanding of the smaller anomalies awaits future work at larger map scales.

The magnetic anomalies result from small amounts of magnetic minerals (less than 10 percent by volume in most cases), commonly magnetite, that are distributed throughout certain rock units. Many rock units contain characteristic amounts of magnetite such that they display characteristic magnetic anomalies on aeromagnetic maps. Thus, the locations of the boundaries of rocks that produce anomalies will commonly approximate the location of geologic contacts, whether of sedimentary, igneous, or fault origin.

The general method of interpretation was to delineate boundaries around the more distinctive magnetic rocks units and also to delineate those boundaries that separate areas that have distinctively different magnetic patterns. Delineation of boundaries of the latter sort may become rather subjective, and only the more certain boundaries have been retained. Before any boundaries were delineated, two important steps were taken. First, the aeromagnetic data were examined to ascertain the approximate distance or depth of the anomaly-producing masses below the aircraft. Except for a few special situations, the resulting distances were all approximately 150 m, such that the causative magnetic masses are generally believed to be exposed at the surface of the Shield. Second, in 1971 I prepared, with the assistance of G. I. Selner and G. E. Andreasen, an atlas of calculated magnetic curves showing the appearance of magnetic anomalies across contacts between magnetic and nonmagnetic rocks; the contacts have a variety of dips and strikes. This atlas was of great assistance in determining the correct location of a magnetic boundary relative to the observed magnetic anomaly. Similar curves have since been published by Blank and Andreasen (1980). In Saudi Arabia the inclination of the main magnetic field of the Earth ranges from 23° in southern Saudi Arabia to 45° in northern Saudi Arabia. At these magnetic inclinations the contacts of a normally magnetized body tend to be near the crest of the magnetic high on the south side of the body and near the bottom of the magnetic low on the north side of the body, and the boundaries on the interpretation maps have been delineated accordingly. A useful feature of the atlas of curves is that the shapes of the curves vary with the dip of the magnetic boundaries. Thus, one can compare the form of an observed curve with those of the atlas until a similar curve is located and so make an estimate of the dip of the contact. The dips shown on the interpretation maps were all estimated using this method.

The interpretation maps (plates 1-11) were prepared as follows. Boundaries were drawn on overlays placed over the individual 1:100,000-scale aeromagnetic map sheets. These overlays were photoreduced to a scale of 1:250,000 and the boundary locations revised and refined. The interpretation maps were then overlain on geologic maps available for the area and a few boundaries moved or deleted for situations in which boundary interpretation had been somewhat ambiguous. I have not adjusted magnetic boundaries having unequivocal locations in order to force agreement with geologic maps because it is expected that any discrepancies between boundaries and geologic contacts may provide useful information for future geologic investigations. The final results were compared with published interpretations of 1:100,000-scale magnetic maps (Lambolez, 1968, 1969; Maillard, 1968b; Maillard, 1969; Millon, 1969; Andreasen and others, 1974; Flanigan, in Gonzalez, 1974; Flanigan, 1981), but no changes were made in the interpretation maps, either because they were in general agreement with the previously published interpretations or because I preferred my interpretation.

Certain magnetic anomalies on these maps are termed "reversed", which for this report means that the remanent (permanent) magnetization of the causative rock mass is larger than its induced magnetization and also that the remanent vector points up and toward the south rather than in the "normal" magnetization direction of down and toward the north. Rock units characterized by reversed anomalies have a magnetic low on their south side and a magnetic high on their north side; these locations are exactly the reverse of those for a normally magnetized body.

MAGNETIC INTERPRETATION

General comments

Examination of the aeromagnetic maps, together with the magnetic interpretation maps, should generally indicate the reasons for the locations of the boundary lines. These lines have been delineated according to the methods described in the previous sections. As can be observed on plates 1 to 11, many geologic contacts correspond to the magnetic boundaries. However, many magnetic boundaries either transgress lithologic units or are in areas where the geology is obscured by overlying Quaternary deposits. Further study of both magnetic data and geology will be needed to understand these situations.

Most of the curvilinear boundaries probably are of plutonic or gneissic rocks, and most of the straighter boundaries, especially those that interrupt magnetic patterns, are assumed to be faults. A few volcanic rock units and ultramafic rocks are identified by the magnetic patterns as described in subsequent sections of this report. The magnetic expression of several unconformities and one thrust fault are described in a subsequent section. A few contacts are shown that are believed not to be exposed at the surface of the Shield.

Magnetic expression of layered rocks

Layered rocks in the study area range from predominantly sedimentary rocks through mixed volcanic-sedimentary rocks to predominantly volcanic rocks. Most of the rocks in these assemblages are weakly to moderately metamorphosed, but some are strongly metamorphosed and deformed. The volcanic rocks may be mixed assemblages of basaltic, andesitic, or dacitic composition or may be predominantly either mafic or felsic in character.

The magnetic character of such a diverse suite of rocks is highly variable. Areas underlain predominantly by sedimentary rocks or their metamorphic equivalents are usually almost nonmagnetic. Areas underlain predominantly by volcanic rocks tend to display numerous short-wavelength, irregular magnetic anomalies that are commonly higher in amplitude for mafic rocks and lower in amplitude for felsic rocks. Low-grade regional metamorphism may have substantially reduced the magnetic intensities of the volcanic rocks; such rocks may not then recover increased magnetic intensities unless strongly metamorphosed to the amphibolite facies. Examples of the rocks described above may be found throughout the area of study, and the above generalities may aid in understanding their magnetic character.

Unusual features of possible economic interest are the zones of narrow magnetic lows (labeled ZR) associated with certain belts of layered rocks. These zones are described in the section, "Relationship to metalliferous deposits", and are believed to be caused by reverse remanent magnetization.

Magnetic expression of belts of gneissic rocks

A series of north-trending belts of gneissic rocks extends across the study area. The magnetic expression of these rocks is highly variable, ranging from a featureless magnetic field to magnetic anomalies of very large amplitude similar to those observed over mafic plutons. The variable character is to be expected because, according to Schmidt and others (1979), these gneisses result from syntectonic plutonism involving ductile rise of tonalitic and granodioritic rocks and conversion to orthogneiss. At the same time granitic plutons rose into the cores of these gneiss domes. A variety of rocks ranging from mafic to felsic in composition are thus involved, and their variable magnetic character is not unexpected.

Magnetic expression of plutonic rocks

Numerous plutons intrude the rocks of the study area. The compositions of these plutons range from mafic to felsic,and individual plutons may themselves be composed of a variety of igneous rock types. Accordingly, the magnetic expression of plutons may be rather variable. The contacts of some large complex plutons with country rocks may only be identifiable where a substantial contrast in magnetic intensities exists between the plutonic and country rocks. If both plutonic and country rocks are magnetic or if both are nonmagnetic, it may not be possible to delineate the contact using a magnetic boundary. Generally, the mafic rocks, gabbros, and diorites are more magnetic than the granitic rocks, but this generalization is not entirely reliable because some mafic rocks are only weakly magnetic and many of the younger granitic plutons are strongly magnetic.

The older plutons, especially those that are large and irregular in outline, have complex magnetic patterns that may not be easy to understand. In the southwestern corner of sheet 20F (plate 1), large areas of diorite and granodiorite display complex magnetic patterns that are not readily distinguishable from the irregular magnetic patterns of the metamorphosed layered rocks. Only the smaller subcircular plutons and the two gabbro bodies (identified by intense reversed remanent magnetization) are easily identified by their magnetic expression. Along the western edge of sheet 23F plate 9), complex magnetic patterns do not clearly delineate most of the various mapped masses of gabbro, diorite, granodiorite, and granite. Elsewhere in the study area the magnetic data are somewhat more definitive in delineating older plutonic rocks, as examination of the interpretion maps will show.

The smaller subcircular plutons can generally be identified by their magnetic expression, regardless of whether they are mafic or granitic, because of the circular form of the anomalies. This is particularly true for the part of the study area that lies northeast of the southernmost Najd fault zone, in which the country rocks are only weakly magnetic, thus enhancing the magnetic expression of the plutons. Some of the subcircular plutons are large (as much as 40 km in diameter; see sheet 23G, plate 10) and may form coalescing groups as much as 60 km in longest dimension, such as in sheet 22G (plate 7). Several of these plutons have sufficiently intense reverse remanent magnetizations to display reversed magnetic anomalies (magnetic lows on the south instead of the north side of the plutons), a feature that is relatively uncommon among granitic plutons elsewhere according to my experience in studying magnetic maps of the United

States, including Alaska. A few of these plutons display large-amplitude magnetic highs in their contact metamorphic aureoles that suggest that the hornfels zones contain abundant metamorphic magnetite. I have observed similar magnetic metamorphic aureoles in northern Maine and central Alaska inthe United States. The magnetic patterns of many of these subcircular plutons display one or more concentric magnetic units within the pluton, suggesting the presence of more mafic border phases or possibly ring dikes. These concentric patterns should be particularly useful in mapping plutons that are poorly exposed. In a few plutons, such as one on the eastern border of sheet 23F (plate 9), these concentric patterns are interrupted by linear boundaries, which are interpreted to represent faulting within the plutons. Doubtless more such features will be identified when geologic mapping of certain intrusions is coordinated with detailed examination of their magnetic patterns.

For several of the plutons having clearly defined marginal magnetic gradients, it was possible to estimate the dip of the magnetic boundary by curve matching with the atlas of calculated curves. These dips range from vertical to outward 75° and, in one case, outward 60°. The results of the curve matching are plotted on the interpretation maps.

Magnetic expression of serpentinites

Several occurrences of serpentinite have been mapped in the study area: (1) the eastern border of sheet 20F (plate 1; Nabitah fault zone), characterized by reversed magnetic anomalies; (2) the northwestern corner of sheet 20G (plate 2), displaying normal magnetic anomalies; (3) the northeastern corner of sheet 22G (plate 7), displaying normal magnetic anomalies; (4) along the western margin of sheet 23H (plate 11; the Al Amar-Idsas fault), displaying both normal and reversed magnetic amonalies; (5) in the center of sheet 23G (plate 10), the serpentinite here being part of an ophiolitic complex (Delfour, 1979), displaying reversed magnetic anomalies; and (6) a few small masses within sheet 23F (plate 9), including one at the southwestern corner of the area believed to be part of an ophiolite belt correlating with the Nabitah fault zone, all characterized by normal magnetic highs (Brown, 1972; Schmidt and others, 1979).

In general, the ultramafic rocks display high-amplitude, short-wavelength magnetic anomalies having relatively narrow marginal gradients that indicate the limited vertical extent of these rock masses. The magnetic lows on the south flanks are caused by intense reverse remanent magnetization that is substantially greater than the induced magnetization. In my examination of magnetic data over several hundred serpentinites in North America, I have located only one other small serpentinite mass (near Washington, D.C.) that exhibits such strong reverse remanent magnetization. D. L. Schmidt (oral commun., 1981) has suggested that the serpentinites of the Arabian Shield may have been emplaced at a deeper level in the crust than those in North America and, accordingly, may have had very different thermal histories that may account for the unusual magnetic properties.

Boundaries with low dips--unconformities and faults

Examination of the aeromagnetic data indicates that several magnetic rock units have boundaries that dip at low angles beneath relatively nonmagnetic rocks. One such feature is the Al Amar-Idsas fault, discussed in a subsequent section. In the southeastern corner of sheet 23F (Letalenet, 1979; plate 9) and the southwestern corner of sheet 23G (Delfour, 1979; plate 10) are two unconformities where clastic rocks (Murdama group) lie on older volcanic rocks with interbedded metasedimentary rocks (Halaban group correlatives). These unconformities dip from 45° to 75° NE., according to the magnetic data, and extend southeast into sheet 22G (plate 7).

In the top center of sheet 23G (plate 10), a third unconformity can be deduced from magnetic data. This unconformity marks the western side of a half-graben of sedimentary rocks of the Jibalah group (Delfour, 1970, 1979) and is estimated by curve matching to have an average dip of 40° E. Magnetic anomalies caused by rocks of the underlying ophiolitic complex may be seen at successively greater depths eastward across this basin of sedimentary rocks. The Jibalah group consists of the youngest Proterozoic sedimentary rocks in the Shield and is usually restricted to grabens and half-grabens produced by the Najd faults (Hadley and Schmidt, 1980). Because of the lack of evidence for significant strike-slip movement on the eastern border fault of this half-graben, it is not shown as a major Najd fault on the 1:500,000-scale map (plate 12).

In the extreme northwestern corner of sheet 21G (plate 4), one other boundary trends N. 10° E. and may be an unconformity. This magnetic boundary dips at a low angle to the west and is located in a terrain composed of undifferentiated metavolcanic rocks. Magnetic anomalies caused by rocks on the eastern side of this boundary may be observed extending to the west at successively greater depths beneath the overlying nonmagnetic rocks. Further geologic mapping is needed to explain this feature.

The Al Amar-Idsas fault

The Al Amar-Idsas fault is a major geologic boundary in the eastern part of the Arabian shield. An excellent summary of past investigations on this feature is provided by Nawab (1978, 1979). The fault is located in the northeastern part of the study area and trends generally north at approximately long 45°10' E. and extends from lat 22°30' to 24°30' N. Because of the association of the fault with ultramafic rocks and the juxtaposition of grossly different terranes and rock ages on each side of the fault, it is generally considered to be a suture (Brown and Coleman, 1972; Al-Shanti and Mitchell, 1976; Nawab, 1979; Schmidt and others, 1979). Structural attitudes near the fault are very steeply dipping (Nawab, 1979), and recently the fault has been interpreted as an east-dipping thrust (Brown, 1972; Al-Shanti and Mitchell, 1976; Delfour, 1979; Nawab, 1979).

The aeromagnetic data prove to be of great value in elucidating the nature of the Al Amar-Idsas fault because the exposed rocks east of the fault are highly magnetic, whereas the rocks west of the fault (schist of the Abt formation) are virtually nonmagnetic. Accordingly, the boundary between the magnetic and nonmagnetic rocks can be defined accurately and is indicated both on the individual map sheets and on the 1:500,000-scale map (plate 12). Curve matching of the magnetic gradients along the fault (sheets 23G, 23H; plates 10, 11) clearly indicates that the magnetic boundary dips from 45° to 60° W. on average. It is concluded that this fault, although possibly vertical close to the surface, must rapidly become west dipping at shallow depths. The west dip is in agreement with the plate tectonic interpretation of Schmidt and others (1979, fig. 8) for the Idsas suture and for the Halaban crust at the end of the Proterozoic Era.

Major east-west magnetic anomalies in the southern Arabian Shield

During their preparation of the colored aeromagnetic maps of the Arabian Shield (scale 1:500,000) in the early 1970's, Andreasen and Petty (1973) noticed that major east-west magnetic anomalies exist southwest of the southern Najd fault zone and generally south of lat 24° N. The anomalies are perhaps best developed south of lat 20°30' N. (Andreasen and Petty, 1973), where they appear on the map as a series of east-west red stripes having peak-to-peak wavelengths of from 25 to 35 km and peak-to-trough amplitudes of from 800 to 1,200 gammas. Papers referring to these anomalies are being prepared for colored aeromagnetic map compilations at scales of 1:1,000,000 (Blank, Andreasen, and Petty, written commun., 1981) and 1:2,000,000 (Blank and others, written commun., 1981) and for major lineament studies at a scale of 1:250,000 by J. McMahon Moore (written commun., 1981). These anomalies can be difficult to see on the larger scale aeromagnetic maps because they tend to be obscured by the high-frequency details of the 20-gamma contours. A generalized outline of the 6100-gamma contours in the southwestern corner of the study area is compiled from Andreasen and Petty (1973) onto the 1:500,000-scale map (plate 12) and illustrates the east-west anomalies.

The cause of these magnetic anomalies has not been definitely determined, but a few generalizations can be made by comparison with geologic maps and with the tectonic map (Brown, 1972).

1. The east-west anomalies tend to be interrupted by or not to coincide with the major north-trending belts of layered Precambrian rocks. However, they do cut across the north-trending belts of gneiss and migmatite.

2. The anomalies are associated with areas of plutonic rocks ranging from 900 to 570 Ma in age, as summarized by Fleck and others (1979).

3. The very high amplitude magnetic anomalies associated with subcircular or east-trending mafic plutons tend to fall on the east-west anomalies. These plutons tend to be younger plutons.

4. Gradient measurements suggest that the magnetic rocks causing these anomalies crop out for much but not all of the linear extent of these features.

5. The magnetic rock masses causing the anomalies are probably heterogeneous and have north-south widths of from 8 to 12 km and vertical extents of several kilometers.

In summary, the most likely cause of these features seems to be east-west belts of magnetic plutons whose trends transgress the north trends of the older layered rocks and gneiss domes. Because the younger plutons in the study area do not generally intrude the older north-trending belts of downfolded layered rocks, there seems no reason to assume that the east-west magnetic anomalies are produced by rocks older than the north-trending belts of downfolded layered rocks that interrupt the anomalies. I believe the best explanation to be east-west belts of younger magnetic plutonic rocks, but the cause of this trend remains to be discovered.

Magnetic expression of dikes

Many thousands of dikes, both magnetic and relatively nonmagnetic, cut all of the rocks of the study area. In general, the narrow linear magnetic anomalies, both normal and reversed, caused by these dikes have not been identified on the interpretation maps. An exception has been made for certain very long and prominent magnetic anomalies that appear to be caused by major dikes. One such dike (sheet 21G, plate 4) is at least 110 km long and crosscuts two young granitic plutons but is cut by a third. All of these prominent dikes trend between N. 60° W. and N. 90° W. and appear young because they generally cut the younger granitic plutons. Some of the dikes may be related to the Najd fault system and, as described in that section of this report, may be responsible for some of the linear magnetic features mapped within the fault zones.

Abundant dikes in two areas (sheet 23F, plate 9) cause such prominent lineated magnetic patterns that both areas have been indicated as an "area of magnetic dike swarm".

The area with the most abundant dike anomalies lies east of long 43°30' E. and between the two main fault zones of the Najd fault system. In this area as well, a prominent magnetic grain can be observed on the 1:500,000-scale colored map of Andreasen and Petty (1973), with trends ranging from N. 70° W. to N. 90° W.

The Najd fault system

A group of northwest-trending magnetic boundaries that cuts across the study area is clearly related to the Najd fault system (Moore, 1979; Moore and Al-Shanti, 1979; Schmidt and other, 1979). Many of these boundaries represent faults, but some of the boundaries may represent either dikes that have been injected parallel with the faults or steeply dipping layers of magnetic volcanic rocks that are conformable with the faults. Additional geologic mapping will be necessary in some areas to differentiate between the several possibilities. These boundaries have been selected and compiled at a scale of 1:500,000 (plate 12) from the various interpretation maps of this investigation and provide much information concerning possible fault locations, especially in areas covered by alluvial deposits.

The magnetic data, according to my interpretation, also contradict the assignment of certain major lineaments in topography or geology to major faults of the Najd fault system. One example is a geologic contact that trends approximately N. 30° W. from lat 23°15' N., long 44°30' E., to beyond lat 24° N. This contact is shown as a normal contact between sedimentary units by Delfour (1979) and as a Najd fault by Moore and Al-Shanti (1979, fig. 1). The magnetic boundary (sheet 23G, plate 10) associated with the contact appears to be too irregular and discontinuous for it to be one of the major Najd faults; additionally, several large geologic units transgress this boundary without significant offset (Delfour, 1979), such that the amount of possible strike-slip faulting appears to be less than 1 km. For the above reasons, this fault or series of faults is not shown on the 1:500,000-scale compilation (plate 12). Another example is a possible fault that is shown by Schmidt and others (1979, fig. 1) to extend northwest along the south side of the central fault zone of the Najd system from lat 21°45' N., long 45° E., through lat 22°50' N., long 43° E., and to rejoin the main zone at lat 23°50' N., long 42°20' E. Again, the magnetic data indicate this boundary as being so irregular that it is not likely one of the Najd faults.

The general trend in plan of the zones of magnetic anomalies on each side of the southern zone of the Najd fault system is that of a sinistral bend, which therefore indicates left-lateral offset. According to Schmidt and others (1979), this southern zone has a total left-lateral offset of approximately 165 km, such that the ophiolitic rocks in the Nabitah fault zone are correlated with the ophiolitic assemblage exposed on the western edge of this study area (long 42° E.) at approximately lat 23° N., in what is perhaps the northernmost splay fault of this southern zone. This northernmost fault is shown by Moore and Al-Shanti (1979, fig. 1) and by Brown (1972) as being part of the Najd fault system, though not by Schmidt and others (1979, fig. 1).

Examination of the 1:500,000-scale colored map of Andreasen and Petty (1973) indicates several magnetic features having apparent left-lateral offset. A cluster of large magnetic anomalies caused by highly magnetic plutons appears to be successively offset approximately 140 km and is outlined on the 1:500,000-scale map (plate 12). In addition, each part of the cluster has an associated magnetically quiet zone extending to the southeast for distances of about 125 km parallel with the Najd fault zone. For this correlation to be valid, the plutons must be younger than the offset Nabitah fault zone (about 800 Ma old) of Schmidt and others (1979) because the group of magnetic anomalies presumably cuts across the zone. Outlines of these two clusters of magnetic anomalies are indicated on plate 12. The possibility also exists that the zone of intermittent intense negative magnetic anomalies extending north-south along the meridian of long 42°45' E., between lat 22°30' and 22°50' N., may be caused by ultramafic rocks, and, if so, this zone may correlate with the Nabitah fault zone. These suggested magnetic correlations across the southern Najd fault zone appear to indicate left-lateral offsets of from 100 to 140 km, somewhat less than the 165 km suggested by Schmidt and others (1979).

Relationship of magnetic anomaly patterns to metalliferous deposits

Direct expression of ore deposits on magnetic maps is rare, with the exception of those deposits containing abundant magnetite. I have not definitely observed any such anomalies on these aeromagnetic maps, but, as geologic knowledge of this area increases, this sort of magnetic anomaly may be identified.

A possible magnetic target to look for in this area is the magnetic expression of a porphyry copper deposit. I have not had the time to familiarize myself sufficiently with the geology and geophysics of this area to search for such anomalies, which characteristically form local magnetic lows within the area of larger, broad magnetic highs caused by a magnetic pluton. The magnetic lows result from local alteration around the porphyry copper deposit that has destroyed the original magnetic minerals of the pluton. Geologists mapping areas within the Arabian Shield should be aware of the possible significance of the alteration associated with local magnetic lows within magnetic plutons.

Using the locations of mineral deposits plotted on the three 1:250,000-scale lithologic maps of the Riofinex Geological Mission (1979 and 1980), in addition to those on the map of Letalenet (1979) and the unpublished data of D. L. Schmidt and K. S. Kellogg (written commun., 1981), I have prepared a 1:500,000-scale location map of known metalliferous mineral deposits in the Southern Najd and Southern Tuwayq quadrangles (plate 12). Most of these mineral occurrences are available on a computer file, the Mineral Occurrence Documentation System (MODS), established and regularly updated by the Bureau de Recherches Geologiques et Minieres, Jiddah, for the Saudi Arabian Directorate General of Mineral Resources (Delfour, 1975). Similar plots of occurrences for the central and eastern Shield have been published by Al-Shanti and Roobol (1979).

I have arbitrarily classified the deposits into four groups: precious metals (gold, silver), base metals (copper, lead, zinc), mafic or ultramafic rock associations (nickel, chromium), and gossans (iron oxide or iron sulfide). Comparison of this map with the colored 1:500,000-scale aeromagnetic map of Andreasen and Petty (1973) indicates that many of the gold and gossan deposits are closely associated with a series of zones of magnetic lows. These zones have been compiled from the 1:250,000-scale interpretation maps and plotted on the map of the mineral deposits (plate 12), together with the set of magnetic lineations believed to be associated with the Najd fault system (described in the previous section). The layered rocks associated with these zones south of lat 21° N. have been mapped as volcanic and metavolcanic rocks of the Halaban group (Gonzalez, 1974; Schmidt and others, 1979), the two western zones also being associated with serpentinite that appears to cause most of the magnetic lows. The eastern zone is composed predominantly of Halaban volcanic rocks metamorphosed to amphibolite facies, but a few very small exposures of serpentinite are also known along this belt (D. L. Schmidt, oral commun., 1981).

North of lat 23° N. (Letalenet, 1979; plate 9), the zones of magnetic lows are associated with layered rocks assigned to several formations that are composed of either volcanic rocks with subordinate sedimentary rocks, coarse-grained sedimentary rocks and their metamorphic equivalents, or metamorphosed interbedded volcanic and sedimentary rocks. The specific rocks causing these magnetic lows, which in general result from reverse remanent magnetization, are unknown, and serpentinite has not been identified in the rock units. Between lat 21° and 23° N. there is little recent geologic information, but the zones of magnetic lows tend to coincide with a unit mapped as interbedded volcanic and sedimentary rocks of the Halaban Formation (Jackson and others, 1963) and to not be associated with the plutonic rocks and gneisses. Again, the specific rocks causing the magnetic lows have not been identified, but the most likely candidates are interbedded volcanic rocks and possibly serpentinite. It is necessary to explain why a series of zones of negative anomalies covers such a large area, extending an additional 250 km north of lat 24° N., and is associated with rocks of relatively diverse ages and dips. Disregarding the diverse dips and only considering the relatively rapid rate of alternation in direction of the Earth's main field, one might expect both magnetic highs and lows in approximately equal proportions over such a large area of diverse rocks. Such equal proportions are not observed, and, I suggest, as an explanation for the consistent reversed direction of the magnetization, that the reversed magnetizations all formed at approximately the same time as the result of a metamorphic event, long after the rocks were emplaced and after the final folding of the rocks. The association of these rocks with gold mineralization suggests that these magnetic zones between lat 21° and 23° N. should be carefully examined.

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