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TO ACCOMPANY BRGM-TR-05-1 to 53

TOTAL-INTENSITY AEROMAGNETIC MAPS OF THE ARABIAN SHIELD, KINGDOM OF SAUDI ARABIA[1]

By Jean-Marie Georgel, Jacques Bobillier, Jacques Delom, and Marcel Bourlier

CONTENTS

Abstract – Aeromagnetic surveys, using a fluxgate magnetometer with analog recording, were carried out in three campaigns between 1962 and 1967 over the greater part (550 000 km^2) of the Arabian shield; terrain clearance was 150 m over flat terrain and 300 m over rugged terrain, with a basic traverse spacing of 800 m. The data were presented in 1:50 000- and 1:100 000-scale maps, and were used for mainly qualitative interpretation in geologic mapping. To carry out more sophisticated interpretation using computerized magnetic data-processing techniques required digitization of the analog data. This was done by BRGM between 1970 and 1980, and digitized aeromagnetic data of the shield are now available in a master file which includes the flight-line number, the 1:50 000-scale and 1:100 000-scale photomosaic numbers, the geographic coordinates, and the value of the magnetic field.

Using the digitized data with a new regional field correction based on computation of a first-order trend surface best fitting the magnetic values of 3025 stations, and integrating digital aeromagnetic data from later surveys over the basalt plateaux and the coastal plain, aeromagnetic maps have been prepared for each of the 1:250 000-scale quadrangles covering the Arabian shield. They consist of (1) total-intensity residual aeromagnetic maps upward continued to 800 m AGL (above ground level) and (2) total-intensity residual aeromagnetic maps reduced to the pole and upward continued to 800 m AGL. The upward continuation to 800 m AGL was chosen so as to obtain a smooth map through elimination of superficial anomalies; it also allowed the different areas flown at different altitudes to be tied together. Reducing to the pole transforms the usual dipole (positive and negative) into a symmetrical anomaly surmounting the causative body. As reduced-to-the-pole magnetic-anomaly maps correlate directly with the geology, they are more easily interpreted by a geologist; qualitative interpretation can reveal lithostratigraphic units, dikes, faults, and intrusive bodies. Where discrepancies are found during such an interpretation, the upward-continued maps can be used to check for possible artifacts in the reduction-to-the-pole transformation, possibly provoked by strong remanent magnetization or lack of data in partly surveyed areas.

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INTRODUCTION

As part of the DMMR (Deputy Ministry for Mineral Resources) 1:250 000-scale mapping program, transformed aeromagnetic maps for the entire Arabian shield have been prepared from all available sources of aeromagnetic data. These maps comprise (1) a total-intensity aeromagnetic map upward continued to 800 m AGL (above ground level) and (2) a total-intensity aeromagnetic map reduced to the pole and upward continued to 800 m AGL for each of the 53 quadrangles covering the Arabian shield.

SOURCES OF AEROMAGNETIC DATA

Total-intensity aeromagnetic data for the Arabian Precambrian shield were collected at different times by different companies using different flight specifications. The first aeromagnetic flights requested by the DGMR (Directorate General of Mineral Resources) were made by Hunting Survey Corp. Ltd. in 1961-62 covering a total area of some 41 000 km^2 (Hunting Survey Corp. Ltd., 1962). The remainder of the shield, excluding the basalt plateaux, was flown later during two seasons by a consortium of companies under the supervision of BRGM (Bureau de Recherches Géologiques et Minières) acting on behalf of DGMR. This consortium, comprising Lockwood Survey Corp., Aero Service Corp., and Hunting Geology and Geophysics Ltd., covered more than 300 000 km^2 (Areas I and II) in 1965-1966 (Consortium Members, 1966) and, joined by ARGAS (Arabian Geophysical and Surveying Company), a further 200 000 km^2 (Areas III, IV, and V) in 1966-67 (Consortium Members, 1967). The three surveys all used the same type of equipment: Fluxgate Gulf Mark III magnetometers with analog recording and simultaneous scintillometric and altimetric data recording.

The remainder of the shield area, comprising the Cenozoic basalt plateaux and the fringing Red Sea coastal plain, were flown much later as follows:

1. The Cenozoic basalts were flown in 1976 and 1981 by ARGAS, under the supervision of BRGM, using a cesium-vapor magnetometer with digital recording (ARGAS, 1976a; 1981).
2. The north part of the coastal plain was flown in 1976 by ARGAS, under the joint supervision of BRGM, USGS (United States Geological Survey), and the Red Sea Commission, using a cesium-vapor magnetometer with digital recording (ARGAS, 1976b).
3. The south part of the coastal plain was flown in 1983 by Geosurvey International Ltd., under the supervision of USGS, using a Geometrics G 813 proton precession magnetometer with digital recording (Geosurvey International Ltd., 1984).

Due to flight restrictions, no data were obtained around the holy cities of Makkah and Madinah.

AEROMAGNETIC COMPILATIONS

The 1962 and 1965-1967 surveys were compiled manually by the contractors (Hunting Survey Corp. Ltd., 1962; Consortium members, 1966, 1967). Flight-path recovery was made by spotting characteristic topographic features on the film taken during the flight by the positioning camera and plotting them on semi-controlled air photomosaics; straight lines joining these points (fiducial points) represent the track of the aircraft over the survey area. The analog magnetic data were then compiled using classical manual methods. An inclined reference datum line was determined and drawn on all the survey traverses prior to contouring; this line integrated corrections for (1) the earth's regional magnetic field (determined by visual examination of the paths and traverses), (2) instrument drift, (3) diurnal magnetic field variations, and (4) inexact flight altitude as determined from a levelling network established using magnetic values computed at the intersection of tie lines with every fifteenth traverse (Consortium Members, 1966, 1967). Magnetic intervals at 20 nT (nanoteslas), along with peaks and lows, were then recorded between the datum line and the magnetic profiles. The 1965-67 data, incorporating the results of the earlier 1962 survey areas which had not been reflown, were presented as a series of total-intensity contour maps compiled at 20-nT intervals to a scale of 1:50 000, with direct reductions to scales of 1:100 000 and 1:500 000 (Millon, 1969a). The data were later recompiled by the USGS as a series of colored 1:500 000-scale 100-nT-interval total-intensity maps corresponding basically to the 1:500 000-scale Miscellaneous Geological Investigation Maps of the shield (Andreasen and Petty, 1973, 1974). The USGS also prepared a shield-wide color-composite map at 1:2 000 000 scale which was released as a special edition for the 26th International Geological Congress in Paris (Andreasen and others, 1980) and as a technical record by the USGS Saudi Arabian Mission (Blank and others, 1980). This same map was later prepared at 1:1 000 000 scale with an explanatory text (Blank and others, 1984).

The 1976 surveys were compiled by the contractors at 1:100 000, 1:200 000, and 1:500 000 scale for both residual-magnetic-field maps and reduction-to-the-pole maps (ARGAS, 1976a,b) whereas the 1981 surveys were compiled by the contractors at 1:50 000 scale then reduced to 1:100 000 scale and 1:250 000 scale (ARGAS, 1981). The compilation of the 1976 and 1981 surveys, as well as of the 1983 survey, was done using automatic computer-processing techniques digitally removing the International Geomagnetic Reference Field (IGRF) (Cain and Cain, 1971) and the diurnal magnetic field variation recorded at a ground station.

DIGITIZATION OF THE ANALOG AEROMAGNETIC DATA

BACKGROUND

The aeromagnetic maps of the 1965-67 surveys were used routinely by BRGM, USGS, and DGMR geophysicists for mainly qualitative interpretation at various scales, but the interpretations were limited in scope because modern computerized magnetic-data-processing techniques cannot be used with analog data. A few maps were hand digitized (Blank and others, 1984) but this is a laborious task, which is why, in 1970, BRGM decided to digitize the analog aeromagnetic records for the zones in which BRGM geologists were mapping (BRGM Geologists, 1972; Georgel, 1978) – i.e. Area I (1965-66 survey), Area III (1966-67), and the Hulayfah and 'Aqiq areas (1962 survey). The program was initiated at the UPM (University of Petroleum and Minerals, Dhahran) Data Processing Center and was completed in 1975 (BRGM Geologists, 1976). The BRGM was then requested, following a proposal made by the USGS in late 1977, to extend its digitization program to include the remaining areas of the 1962 and 1965-1967 surveys, and digitization of the entire shield was completed in mid-1979 (BRGM Geologists, 1980).

All data processing and correcting were carried out at the UPM Data Processing Center in Dhahran until, in 1982, the DMMR installed a DEC VAX 11/780 computer in Jiddah. The processing programs had then to be adapted to the new computer and the opportunity was taken to integrate the digital aeromagnetic data of the 1976, 1981, and 1983 surveys over the coastal plain and the basaltic plateaux (harrats).

DIGITIZATION METHOD

Two alternative approaches were possible for the digitization of the aeromagnetic data: (1) digitization of the Consortium's 1:50 000-scale contour maps by hand digitizing the values at a regular grid interval or hand digitizing the position and magnetic field value at each intersection between flight line and contour level; or (2) digitization of the original analog record and of the fiducial point positions as plotted both on the records and on the 1:50 000-scale photomosaics. The latter method was chosen because of its advantages; it would capture all the original data, compilation errors of the contractor could be easily corrected, and two-dimensional quantitative interpretation using interactive computer programs along the original profile would then be possible.

The original analog output from the magnetometer was a continuous graph on rectilinear chart paper with a width of approximately 25 cm, which represents a variation in the total magnetic field of 600 nT (fig. 1); chart speed was 7.62 cm/min and an automatic step of 500 nT (about 21 cm) had been applied so as to keep the recording within the width of the paper; the maximum permissible noise level was 1 nT.

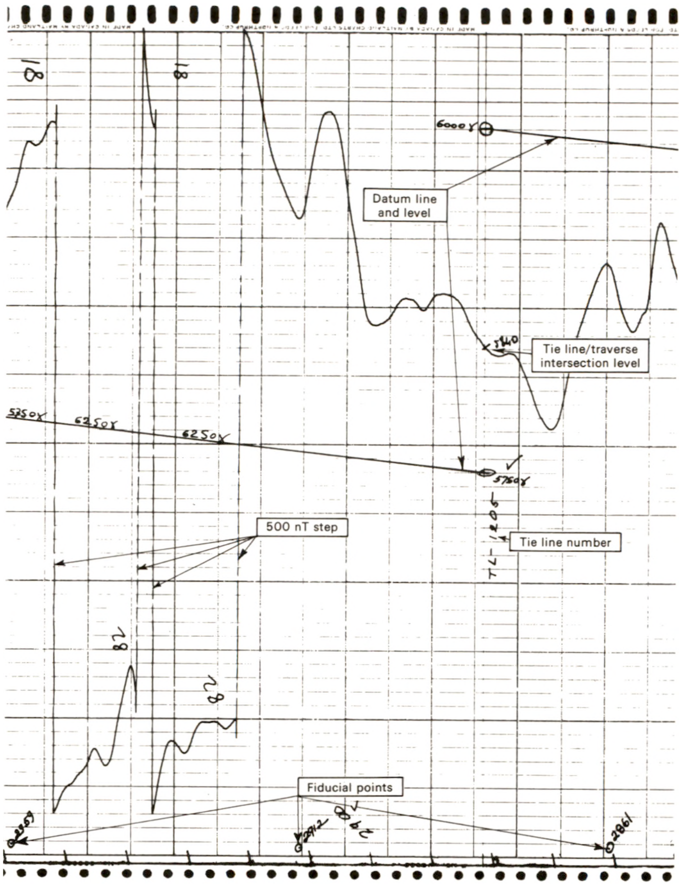

FIGURE 1. – Original strip chart of analog aeromagnetic record prepared by the Consortium for compilation.

HARDWARE

Computer

The digitization program was begun in August 1970 at the UPM Data Processing Center, Dhahran, on an IBM model 360-50 computer with 256 kbytes core memory. This computer was changed in 1972 for an IBM model 370-145 with 256 kbytes memory, upgraded in 1973 to 512 kbytes and in 1975 to 768 kbytes. The computer was changed again in 1976, to an IBM model 370-158 with 4 megabytes memory, and this was replaced in mid-1980 by a more powerful IBM model 3033 computer with 8 megabytes memory. In 1982 the entire project was transferred to the new DEC VAX 11/780 with 2 megabytes memory, installed by DMMR in Jiddah.

Digitization equipment

A Benson digitizer was specially designed to carry out the digitization project. It comprises the following units:

1. A digitizing table (model LNC610 – 75 cm long and 50 cm wide) capable of semi-automatic curve digitizing with a selectable sampling interval between 0.1 mm and 999 mm and an accuracy of approximately 0.5 mm (i.e. about 1 nT), and also of manual point digitizing. This table was used to digitize the analog record of the magnetic field on the strip charts and, in manual mode, the position of the tie lines and the fiducial points along the analog records. Because of the limited size of the table, each aeromagnetic analog record was divided into sectors of maximum 70 cm length.
2. A digitizing table (model LNP620 – 120 cm long and 84 cm wide) for manual digitizing of the position and numbers of the fiducial points on the photomosaics at 1:50 000 scale (fig. 2).
3. A control unit (model UC400) for entering numeric data through a digiswitch and a keyboard.
4. A magnetic tape drive (model 430) providing a compatible IBM tape at 800 BPI.

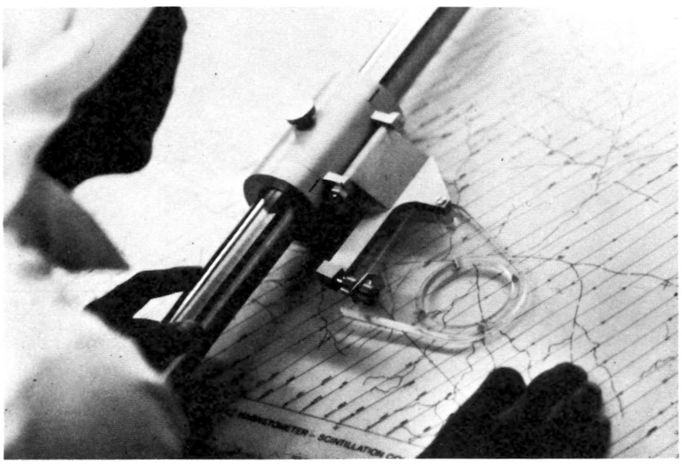

FIGURE 2. – Digitization of fiducial points along flight paths plotted on a 1:50 000-scale transparent overlay.

Each digitized point was coded on the IBM magnetic tape by a 28-bytes (EBCDIC coded) record (fig. 3), comprising:

1. *A label of 8 bytes* set by a digiswitch. For the analog-record digitizing it was used to code information such as area number, aircraft, flight direction, and line number; for the fiducial-point digitizing from the 1:50 000-scale photomosaics, it was used mainly to record area number and photomosaic number.
2. *The Cartesian coordinates* with x = 6 bytes (sign + 5 digits), and y = 5 bytes (sign + 4 digits).
3. *A function code of 1 byte* used to identify the type of record: in automatic mode this function is set automatically to a special code; in manual mode, seven different types of function can be coded (beginning

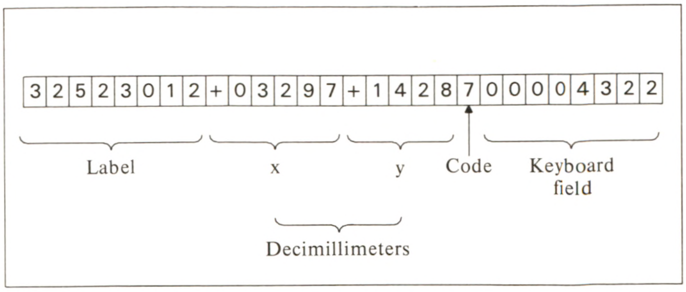

FIGURE 3. – Structure of the digitizer record output.

of record, beginning of sector, end of sector, origin, error, step, and keyboard data recording).
4. *A keyboard field of 8 bytes* used to enter, in manual mode only, numeric data such as fiducial-point number, tie-line number, and value of the magnetic field at the intersection between traverse and tie line. For digitizing fiducial points from the photomosaics, this field was also used to record traverse numbers.

Plotting equipment

All plotting was originally carried out on an offline flatbed plotter EAI 430 provided by the USGS. Then, in 1977, BRGM bought a fast drum offline 1330 Benson plotter which has since been used for all the routine plotting required by the project. The final 1:250 000-scale maps were scribed in France from magnetic tapes prepared in Jiddah and using a model 2532 flatbed Benson offline plotter.

SOFTWARE

The software used comprised two stages: digitization and map preparation (fig. 4).

Digitization

The digitization stage involved transferrence of the digital data output from the digitizer into a file of corrected aeromagnetic data containing magnetic field value and geographic coordinates for each point. The software for this stage had to be especially developed because of its specificity, and the PL/1 programming language was chosen as (in 1970) being the most efficient for program development because of its capabilitites for both scientific application and data handling. Two sets of editing programs were required, each with the same purpose, because of digitizing two different types of data: (1) the data recorded on strip charts (magnetic field, and fiducial-point and tie-line position each with the value of the magnetic field), and (2) the coordinates of the fiducial points from the 1:50 000-scale photomosaics. Both editing program sets contain decoding and correction programs, and also plotting programs which can replot the digital data as strip charts and maps in the same format as the original documents for comparative checking. Because of the huge amount of data,

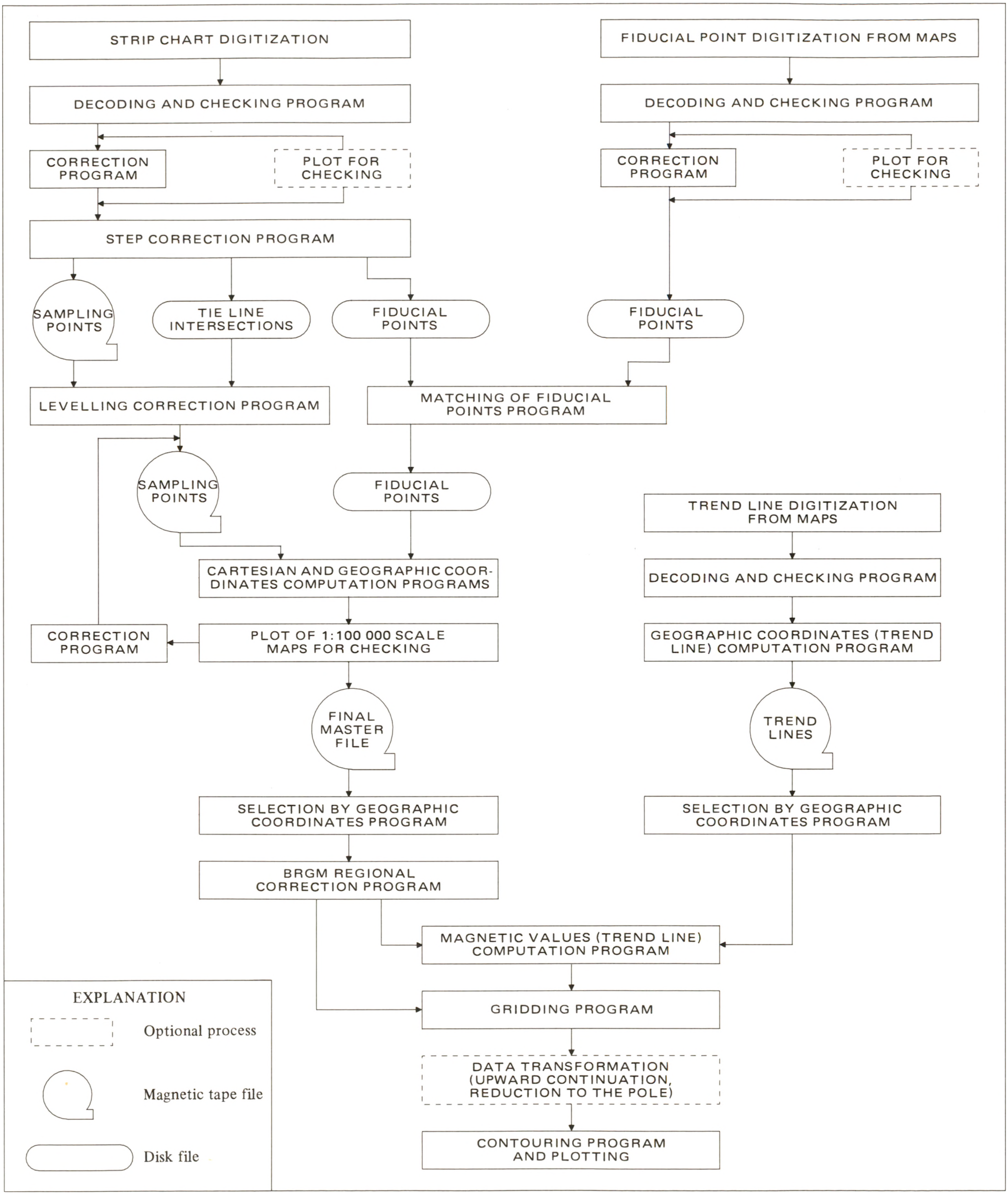

FIGURE 4. – Simplified flow chart for digitization and processing.

comparative checking was used only at the beginning of the programs, mainly for testing the digitizing equipment, the operators, and the decoding software.

After initial editing, the output of the digitized aeromagnetic record was run through a 'step correction' program to supress the 500 nT steps and so obtain a continuous value of the total magnetic field. The 'step correction' program was also used to build a 'sequential' file of the value of the magnetic field, and two 'direct access' files: the 'fiducial-points' file, and the 'tie-line' file (containing the tie-line number and the magnetic-field value at the intersection with the traverse).

A 'levelling correction' program was then used to compute the magnetic field from the same datum line as that used by the contractors. It was decided to keep the original data, at this stage, in order to facilitate comparison between the maps compiled by the contractors and the maps prepared from digitized data. As the 1962 surveys had not been originally tied with the 1965-1967 surveys, they were processed twice: first with the original data for checking, and again after computation of a new levelling correction in order to tie them with the 1965-1967 surveys.

The data obtained from digitizing the traverse path from the photomosaics after processing through an editing step for decoding, checking, and correcting, were sorted by traverse number and organized in a 'direct access' file, with the traverse number being used as a key.

The next step was to compute the coordinates of the points digitized on the strip charts, after 'matching' them with those from the photomosaic maps. This was done through a special program which checked the acceptability of the match by computing the speed of the aircraft. Only about one out of five fiducial-point numbers had been recorded on the map by the contractors, which made the checking both difficult and time consuming.

After data correction a new 'direct-access' file (keyed by line number) was built; it contains each fiducial point with its number, its coordinate along the strip chart, its cartesian coordinates within the photomosaic, and the photomosaic number. By linear interpolation between each fiducial point, a program then computed the cartesian coordinates for each digitized point, and from these another program computed the geographic coordinates.

The final master file is a sequential file which comprises line number, photomosaic map numbers (both 1:50 000 scale and 1:100 000 scale), cartesian coordinates within each 1:50 000-scale photomosaic, geographic coordinates, and the value of the magnetic field.

Map preparation

To prepare an aeromagnetic map, the corresponding set of digitized data is first selected from the master file by coordinates using a 'selection' program. The data are then run on 'gridding' and 'contouring' programs that were adapted mainly from existing programs using FORTRAN programming language.

Gridding program

The gridding program used is based on the CRAM program system acquired by the USGS in 1970 (Engineering Computer Systems Pty. Ltd., 1970) and largely modified and corrected to adapt it to the special needs. As do most gridding programs, the CRAM system works with a 'weighting' program from a window of selected size and is not generally capable of correlating narrow anomalies with widths of less than half the distance between the traverses; such anomalies are usually represented by discontinuous anomalies known as 'potato' anomalies or 'magnetic boudinage' (Hood and others, 1979). To avoid this effect, trend lines following the top of narrow anomalies were drawn on the original contoured magnetic anomaly map prepared by the Consortium, and the positions of points situated between the traverses along the trend lines were digitized using a special set of programs. A CRAM program then computed, by interpolation, the magnetic values at the digitized points and also at the intersections of the traverses and the trend lines, and the new lines were incorporated into the aeromagnetic data master file for use by the gridding program. This improved the contoured map by giving a better correlation between narrow anomalies.

A data grid (usually computed with an interval of 500 m, which is well adapted to an 800-m spacing between flight lines and to map preparation at 1:100 000 to 1:250 000 scale) was then used to compute a subgrid (with four points between each couple of main grid points) by bicubic spline interpolation using the method described by Bhattacharyya (1969).

Contouring program

The contouring program used for plotting the aeromagnetic maps was modified from the program proposed by Holroyd and Bhattacharyya (1970). In particular, modifications were added so as to be able to plot incomplete maps limited by boundaries of any shape.

Final checking

Before proceeding to the next stage in the preparation of the 1:250 000-scale maps – that of applying a magnetic field regional correction to the aeromagnetic data as described in the following chapter – all the digitized data were gridded and plotted at 1:100 000 scale on transparent paper. These plots were then carefully compared to the maps prepared by the Consortium at the same scale and any discrepancies were studied carefully by returning to the original records. When necessary, corrections were made to the master file of the digitized data.

Obvious levelling errors introduced by the Consortium during compilation, such as those giving a 'herringbone' pattern (i.e. anomalies parallel to the traverses), were also corrected by going back to original data to modify the levelling correction. Such errors were common, especially in the northern part of Area III where magnetic anomaly trends parallel to the flight-line direction make correction especially difficult.

STATISTICS

The main statistics of the digitizing project are given in table 1, in addition to which it is interesting to note that:

1. The total number of 1:50 000-scale photomosaics used in digitizing fiducial points was 480.
2. The digitizing equipment was in operation for more than 8000 hours with more than 100 km of magnetic tape being written.
3. Including the digital data from the 1976, 1981, and 1983 surveys, the total number of points used to compile the 53 aeromagnetic maps was 7 900 000.

TABLE 1. – *Digitizing statistics*

Survey	1962	1965-67	Total
Number of traverses	1372	6151	7523
Length of digitized strip chart (m)	1970	11508	13478
Number of digitized points on traverses	1023989	6203703	7227692
Number of fiducial points	16527	191735	208282
Number of created trend lines	1106	7366	8472

REGIONAL MAGNETIC FIELD CORRECTION

The Consortium's corrections for the regional magnetic field (Consortium, 1966, 1967) were quite sufficient for the interpretation of magnetic maps at 1:100 000 or 1:50 000 scale. When the shield-wide colored maps were prepared to 1:500 000 scale (Andreasen and Petty, 1973, 1974), however, a change in magnetic field intensities from north to south across the shield was shown by a color gradation from blue (low magnetic-intensity value less than 5800 nT) to red (high magnetic-intensity value greater than 6100 nT). Blank and others (1984) showed that this can be explained by an overestimation of the correction due to the gradient of the earth's main field, and they estimated that the average gradients used for correction by the Consortium were about 3.9 nT/km for the northern component and 1.2 nT/ km for the eastern component. These values, when compared with the IGRF (International Geomagnetic Reference Field) for the time of the survey (3.70 and 1.17 nT respectively for the northern and eastern components) lead to a difference of about 300 nT over the north-south length of the shield, and this is sufficient to explain the north to south difference in the magnetic field intensities as plotted by Andreasen and Petty (1973, 1974).

With all the original data available in digital form it was decided to apply a more accurate correction to the regional field. The overall corrections applied by the Consortium had integrated correction factors such as regional magnetic field, instrument drift, diurnal magnetic field variation, and error due to inexact flight altitude, and it was not feasible to return to the original value of the field to apply an IGRF correction. Departing from the residual magnetic field as compiled by the Consortium, it would have been possible simply to apply an average gradient correction obtained from the differences between the average gradient used by the Consortium and that of the IGRF – i.e. 0.2 nT/km and 0.03 nT respectively for the northern and eastern components of the gradient correction by using the values quoted previously by Andreasen and Petty (1973, 1974). It was decided, however, that it would be more accurate to compute a new gradient correction. The magnetic values and the coordinates of 3025 stations, chosen in areas of low magnetic relief, were digitized from the Consortium-compiled 1:100 000-scale magnetic maps and the data reprocessed to find a first-order trend surface best fitting the magnetic values. Processing of data from Areas II and V (1030 values) flown at 300 m above ground level was carried out separately from processing of data from Areas I, III, and IV (1995 values) flown at 150 m above ground level.

PROCESSING OF AREAS I, III, AND IV

The map plotted from the residual magnetic values of the sampled stations (fig. 5) shows a positive north to south gradient for Areas I, III, and IV. The difference of the average magnetic level is about 400 nT between the northern and the southern parts of the shield, which is greater than the 300 nT suggested by Andreasen and Petty (1973, 1974). The first-order trend surface best fitting the magnetic values for Areas I, III, and IV, computed by a least square method, is also shown on Figure 5. This plane has the same west-northwest strike as the IGRF and is defined by a gradient of 0.37 nT/km for its northern component and 0.12 nT/km for its eastern component.

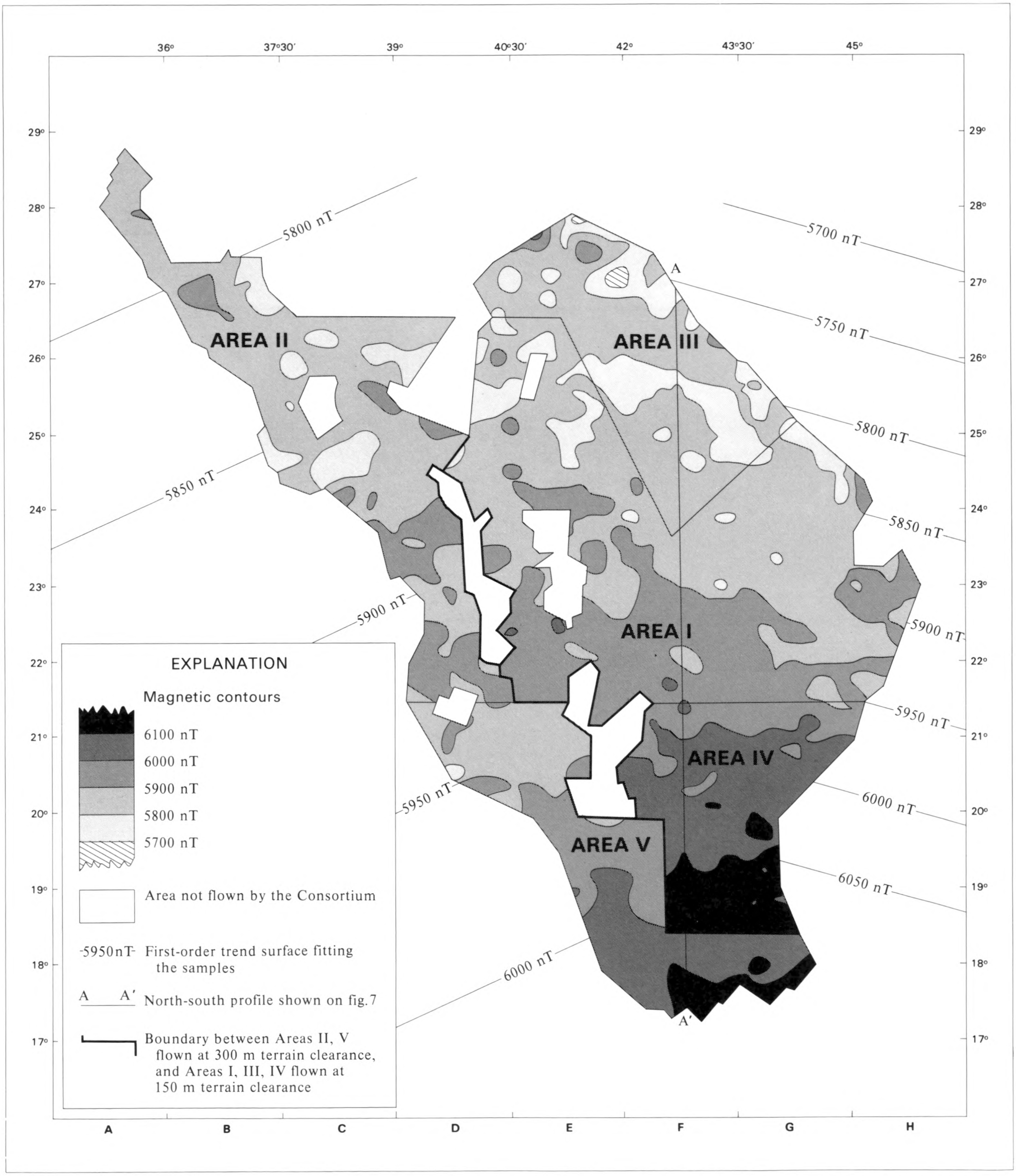

FIGURE 5. – Average residual magnetic field of the Arabian shield plotted fom original Consortium data (contour map obtained from 3025 points).

Plotting the residual values obtained from the difference between the original values and the values of the first-order trend surface (fig. 6) puts 95 percent of the magnetic field values within a 200-nT interval (5800 to 6000 nT). It can also be seen that the values in the center of the shield are slightly lower than those in the northern or southern parts, a feature that cannot be explained from data at hand; it could be due either to the fact that the central shield is less magnetic or to the fact that correction of the regional field should have been done by a second-order surface. For the purpose of the 1:250 000-scale maps, however, the first-order surface correction is sufficient.

PROCESSING OF AREAS II AND V

The north to south gradient plotted from the magnetic values of sampled stations for Areas II and V is lower than that for Areas I, II, and IV (fig. 5), with a difference of only 200 nT between the average magnetic levels of the northern and southern parts. It is also noticeable that whereas Areas I and II are at almost the same magnetic level, a 100-nT step exists between Areas IV and V.

The first-order trend surface best fitting the magnetic values for Areas I and II by a least square method is shown on Figure 5. The southwest strike of this plane, which is roughly perpendicular to the IGRF direction, is strongly influenced by the distribution of magnetic values along the narrow northwest-trending Areas II and V.

It was decided, here, to compute a plane having the same strike as the one used to correct Areas I, II, and IV, and giving almost the same correction as the first-order trend surface. This plane is defined by a gradient of 0.22 nT/km for the northern component and 0.07 nT/km for the eastern component, and when the corrected magnetic values are plotted (fig. 6), 85 percent of the average residual-magnetic values fall within a 200-nT interval (5800 to 6000 nT). As with Areas I, III, and IV, the average values of the residual magnetic field in the central part of Areas II and V are lower than in the northern and southern parts.

A north-south profile A–A′ plotted across the shield before and after correction shows the improvement given by the proposed correction (fig. 7). This profile also shows the corrected aeromagnetic data upward continued to 800 m AGL and also both upward continued to 800 m AGL and reduced to the pole. It shows that the correction of the regional field is quite acceptable for the transformed maps.

TOPOGRAPHIC BASE MAPS

The 1:250 000-scale total-intensity residual aeromagnetic maps have been printed on the base maps that were prepared for the corresponding 1:250 000-scale geologic maps.

MAP PROJECTIONS

Unfortunately, two projections have been used in the DMMR 1:250 000-scale map series (fig. 8): (1) the Lambert conformal conic projection, with standard parallels 17° and 33°, was chosen (a) for the early base maps that were compiled from an assembly of 1:100 000-scale semi-controlled photomosaics originally prepared by Aero Service Ltd. in 1958, and (b) for three later Landsat-image base maps completing the block of BRGM mapping (comprising quadrangles 26B, 25B to 25E, 24B to 24H, 23C to 23H, 22G and 22H), and (2) the UTM (Universal Transverse Mercator) projection, used for the remaining quadrangles, which were compiled later from controlled Landsat imagery. The use of two projections meant that the aeromagnetic data had to be computed in both modes so that the 1:250 000-scale maps could be assembled over the entire shield area.

MAP ACCURACY

The fiducial points were plotted originally onto semi-controlled photomosaics which were the only topographic documents in existence at the time of the survey, and even then there were three photomosaic series prepared from three different aerial surveys (the so-called WSA, SAG, and GS-MO photomosaics; fig. 8). Mismatch between photomosaics of adjacent areas is, in places, as much as 5 cm on the 1:50 000-scale series. The Consortium, in its final preparation of the aeromagnetic data, produced two sets of maps which showed the differences between the two series of photomosaics but which did not tie in the data between them. For the present series of 1:250 000-scale aeromagnetic maps of the Arabian shield it was decided to avoid this problem by manually smoothing the coordinate differences of the same fiducial point in the two different photomosaic series.

Unfortunately, the new controlled Landsat photobases were not available at the time the data were being digitized, and to have prepared, checked, and corrected the aeromagnetic data against the controlled bases would have meant a further delay in the preparation of the maps without being sure of the results obtained. Thus it should be borne in mind, when interpreting the aeromagnetic data overlain on a controlled Landsat base, that the aeromagnetic data may be notably displaced from the relevant topographic features, especially in areas where the original data were plotted on the older SAG or GS-MO photomosaic series.

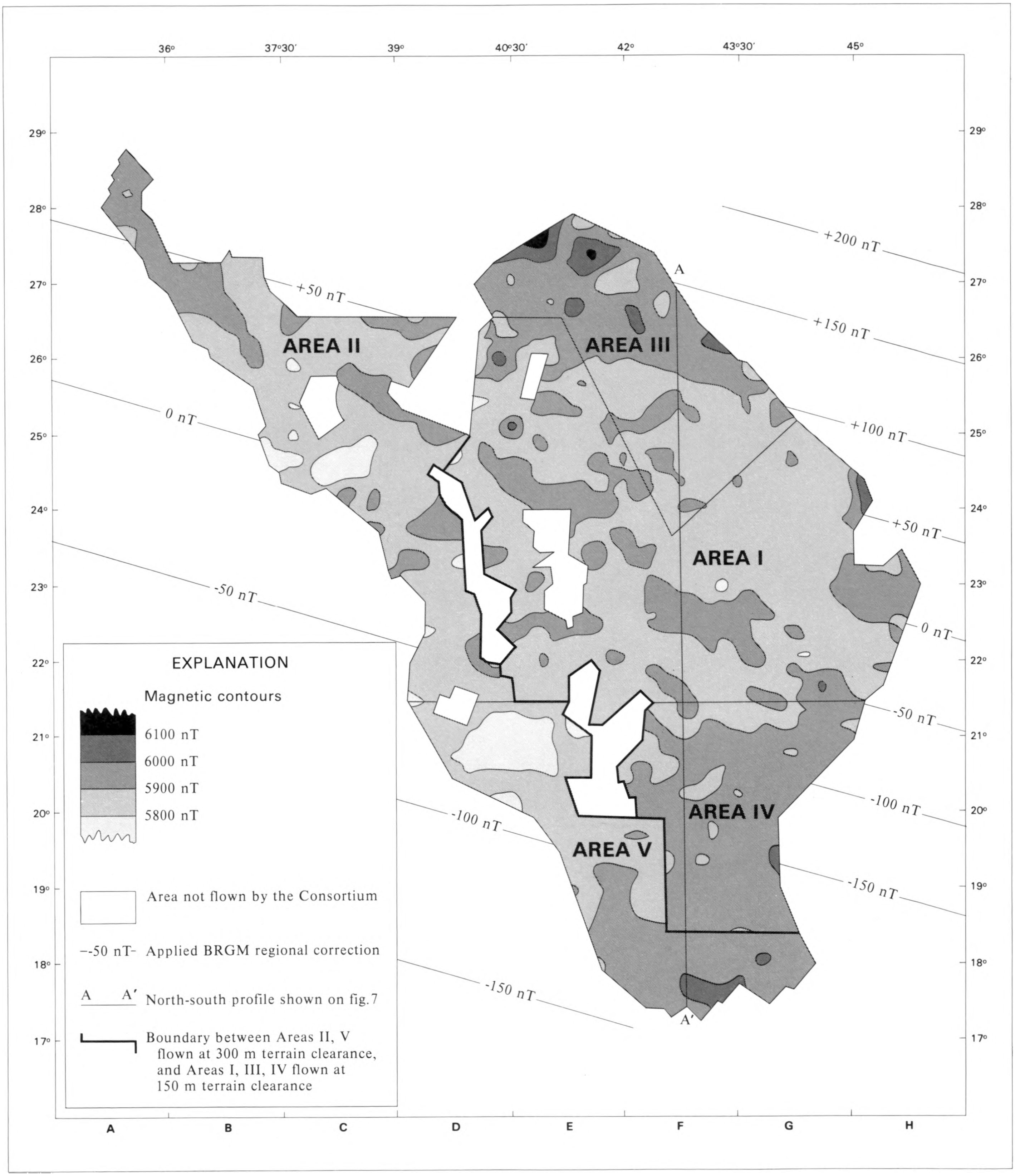

FIGURE 6. – Average residual magnetic field of the Arabian shield plotted from Consortium data after BRGM regional correction (contour map obtained from 3025 points).

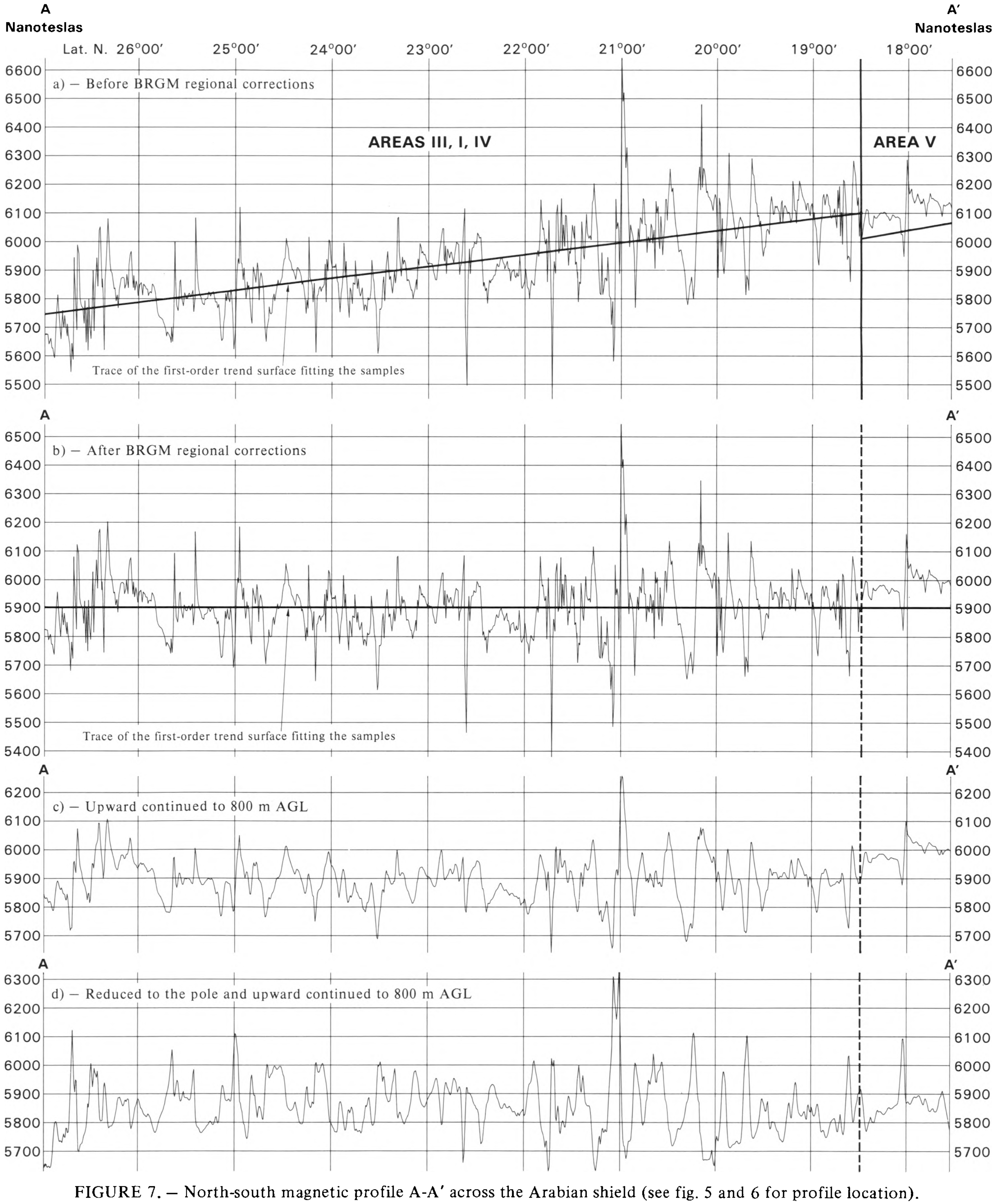

FIGURE 7. — North-south magnetic profile A-A′ across the Arabian shield (see fig. 5 and 6 for profile location).

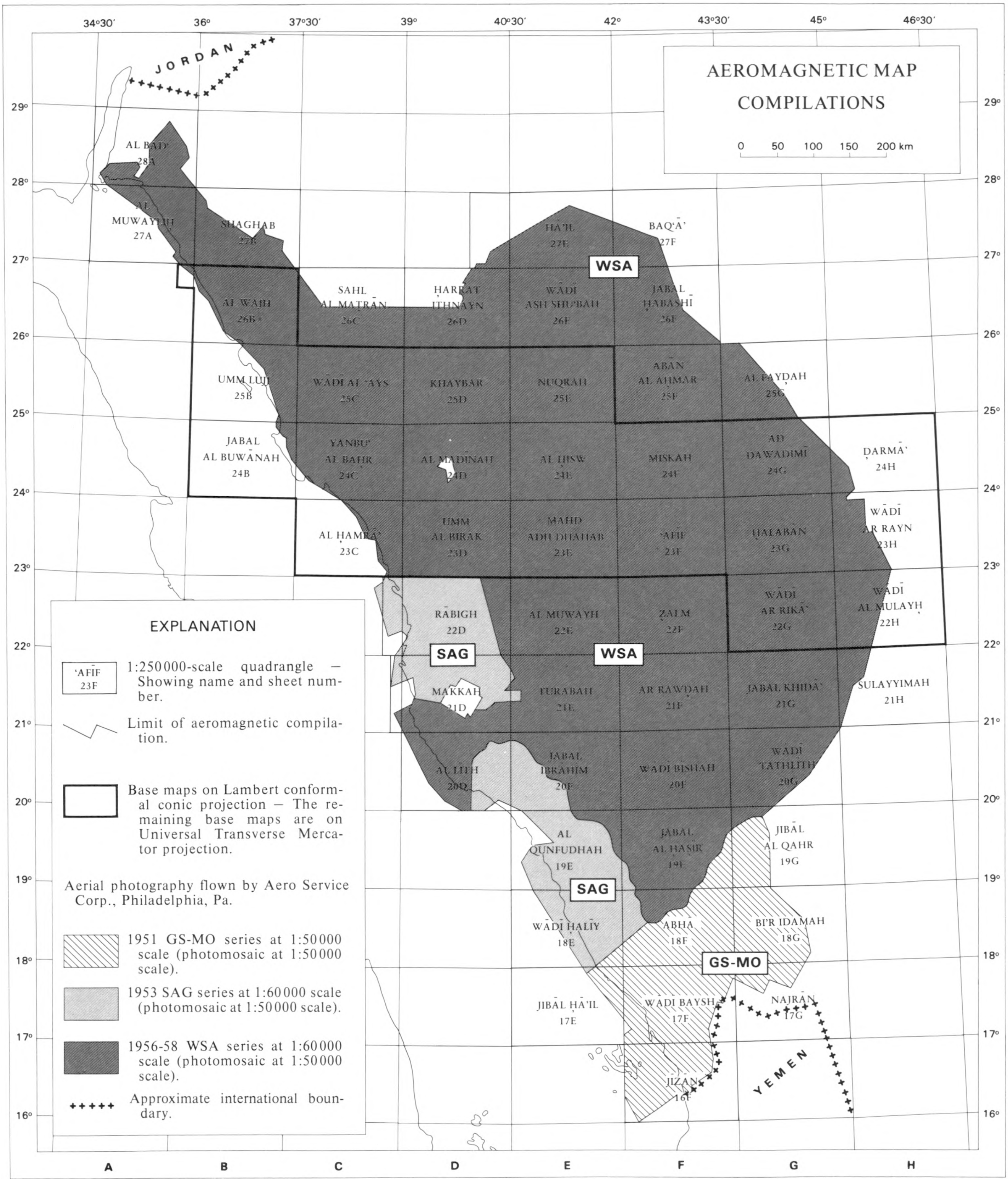

FIGURE 8. — Topographic base maps used for the aeromagnetic map compilations.

TRANSFORMED AEROMAGNETIC MAPS

BACKGROUND

The idea of computing transformed maps using the potential field theory to help in interpretation of gravity or magnetic data is usually attributed to Evjen (1936). Almost concurrently Tsuboi and Fuchida (1937, 1938) and Nagata in 1938 (*in* Hahn, 1965) introduced the Fourier series for the interpretation of gravity data and magnetic data respectively. Methods based on the utilization of sets of coefficients in the spatial domain to compute transformed maps were first developed based on utilization of hand calculators (Henderson and Zietz, 1949a,b; Baranov, 1957), but the first description of an electronic computer program using this method is given by Henderson (1960).

Baranov (1957) and Baranov and Naudy (1964) were the first to propose the use of 'Poisson's formula' to compute a reduction to the pole for facilitating interpretation of magnetic surveys. Dean (1958) showed that the operations of downward and upward continuation, derivation, and smoothing were analogous to the filtering action of an electric circuit, and proposed a method of processing field potential data in the frequency domain using the Fourier Transform. Since then, many papers have been written describing various applications of the Fourier Transform to magnetic-data processing, but it was Bhattacharyya (1967), in a now-famous paper, who proposed the use of Fourier transform general expressions in the frequency domain for the computation of continuation, differentiation, and reduction to the pole. Among the great number of computer programs now using the Fourier transform in the frequency domain to compute transformed maps, are those proposed by Cordell (1971), Cordell and Taylor (1971), and Gerard and Griveau (1972). Examples of transformed maps in Saudi Arabia have been given by Georgel (1978), Kleinkopf and Cole (1982), and ARGAS (1976a,b).

METHOD OF COMPUTATION

The theoretical formula for the computation of upward-continuation and reduction-to-the-pole transformation of magnetic data using the Fourier transform has been given by Bhattacharyya (1967) and Cordell and Taylor (1971). The program used to prepare the present 1:250 000-scale maps was developed from the method described by Cordell (1971), modified so as to be able to compute simultaneously both the reduction to the pole ('gradient of pseudogravity anomaly' of Cordell) and the upward continuation. Spatial north-south filtering was also added in order to avoid the systematic north-trending anomalies given by small anomalies or by border effects in areas of low magnetic inclination.

The so-called 'Fast Fourier Transform' algorithm, or FFT, described by Cooley and Tukey (1965) was used to reduce computer time (which was very expensive when this project was initiated). When using the FFT, however, it is mandatory to have a grid in which the number of rows and columns is equal to a power of two, and this makes it less flexible when processing large-size maps.

Data for each 1:250 000-scale map were processed in the method previously described: after selection, they were gridded to a 500-m grid interval using the CRAM system programs. If the data came from surveys flown at different altitudes, they were first upward continued and tied together before being reduced to the pole; exceptions were Jibal Radwa and the Al 'Ays, Sawawin, Rabigh, and Jizan Mineral areas, which, so as to speed up map preparation, were considered to have been flown at 300 m AGL after a test had shown that this approximation was acceptable for qualitative interpretation.

The grid size used for complete 1:250 000-scale maps was 352 columns and 272 rows. This grid, because of the limited size of the computer memory when the program was written, had to be divided into 20 overlapping blocks of 120 x 120 points, which were then increased to 128 x 128 points (to be able to process by FFT) by adding 'margins' of eight values computed at the eastern and northern sides of each block. The added values were computed by interpolation between east and west and north and south data values so as to avoid discontinuity when periodizing the data. The next step was to use a special routine for removing the added margins and tying the different blocks together through computing an average value along the overlapping area and modifying the levels of the blocks accordingly. It was also necessary, for reduction to the pole, to link one block to another by an averaging method between common borders; simple adjustment of the level was not sufficient.

Tying different 1:250 000-scale quadrangles together in order to be able to produce shield maps at a smaller-scale by photo-reduction was done in the same way by using an overlay area between adjacent maps.

PARAMETERS USED FOR MAP TRANSFORMATION

The 1:250 000-scale maps presented here were processed through two types of transformation: (1) upward continuation and (2) reduction to the pole of the upward-continued data. These two transformations were chosen as being the most suitable to provide both geophysicists and geologists with maps that can be easily interpreted and correlated with the geology at a regional scale.

UPWARD CONTINUATION

Due to the terrain clearances of 150 m and 300 m used for most of the surveys over the shield, the original anomaly maps show a lot of small superficial anomalies which effectively act as 'noise' and disguise the more significant magnetic features corresponding to geologic structures at the scale used. After making several different tests, it was decided to present the data upward continued to 800 m above ground level. This allowed all the data flown at different altitudes and the data flown over the basalt plateaus to be tied together and the structure of the shield to be seen, even beneath the basalt plateaux which give typical superficial anomaly patterns. This results in a clear map that is easier to 'read', even by geologists unaccustomed to interpreting magnetic data. Any detailed geophysical studies required can be carried out at a larger scale using the original data and adopting the filtering parameters best suited to the relevant geologic problem.

REDUCTION TO THE POLE

Magnetic anomalies, especially in areas of low magnetic inclination such as the Arabian shield, are difficult to correlate with the geologic features which provoke them unless one is a specialist in this type of magnetic-data interpretation. This, as noted by Boyd (1967), can be quite confusing.

A reduction-to-the-pole map is the map which would be obtained if the data were captured at the 'pole' – i.e. with a vertical magnetic field. This transformation has the advantage of giving simpler and more symmetrical anomalies, with the centers of the anomalies directly over the causative magnetic bodies. Reduction-to-the-pole transformation thus helps geologists by providing a good correlation between the geologic and the aeromagnetic maps; contacts between geologic formations with different magnetic properties should correspond exactly to the aeromagnetic contour pattern.

A serious objection to the use of the reduction to the pole is the fact that rocks can present strong remanent magnetization with a direction different to that of the present inducing field (Baranov and Naudy, 1964). Artifacts can also be produced by the computing method, especially in areas (such as the Red Sea) where deep-seated anomalies with a low-frequency spectrum are imperfectly defined because of lack of data. Where suspect anomalies are indicated from reduced-to-the-pole data, these can be checked against the upward-continuation map using methods such as that proposed by Schnetzler and Taylor (1984), which was designed in order to evaluate remanent magnetization.

COMPARISON BETWEEN THE TRANSFORMED AND THE ORIGINAL MAPS

A comparison between the original total-intensity aeromagnetic data as plotted by the Consortium, and brought to 1:250 000 scale through photo-reduction, and the transformed total-intensity aeromagnetic data (upward continued to 800 m AGL, and upward continued to 800 m AGL and reduced to the pole) of the present 1:250 000-scale maps is given Figure 9. This shows an extract from the aeromagnetic maps of the Yanbu' al Bahr quadrangle (sheet 24 C).

1. Typical surficial anomalies due to a basaltic lava flow can be seen on the eastern part of the aeromagnetic extract. The upward continuation has filtered the magnetic data leaving only the deeper anomalies, which are provoked either by thicker lava flows corresponding probably to volcanos in the northeastern part of the figure and to mainly intrusive diorite in the Hadiyah group in the south-central part of the figure (Pellaton, 1979).

2. The anomalies A and B were chosen by Millon (1970) as typical of the 'circular anomalies' which are quite common in the Arabian shield. In this case the advantage of reduction to the pole, transforming a complex positive-negative anomaly to a circular anomaly sited at the top of the intrusive body, is quite obvious. Anomaly A is provoked by the Jabal Marbadah ring complex which comprises concentric rings of diorite and gabbro. Detailed geologic studies and magnetic interpretation of this anomaly have been carried out by Lindqvist (1971) and Lindqvist and Dehlavi (1970). Anomaly B is produced by a massive layered olivine gabbro intrusive in the Hadiyah group (Pellaton, 1979).

3. Anomaly C is of particular interest as it shows the usefulness of the transformed maps for rapid qualitative interpretation. This anomaly, corresponding to a scintillometric anomaly, is quite clear on the reduced-to-the-pole map but is not at all clear on the original map. Comparison with the 1:250 000-scale geologic map (Pellaton, 1979) shows that the anomaly is caused by a small peralkalic granite intrusion in the Hadiyah group.

4. The three linear magnetic anomalies trending north-northwest or northwest, belong to the 'Red Sea' aeromagnetic system of Millon (1970). A detailed geologic and magnetic study by Blank (1977) shows that they are produced by reversely polarized dikes of late Tertiary age. The two main dikes appear as negative anomalies in the reduced-to-the-pole map. The third anomaly, which starts from Anomaly A, is much thinner and more limited in length; it appears on the reduced-to-the-pole map as a gradient which in fact outlines the contact between the essentially arenaceous and non-magnetic Tura'ah formation and the Siqam volcanic formation which is magnetic (Pellaton, 1979).

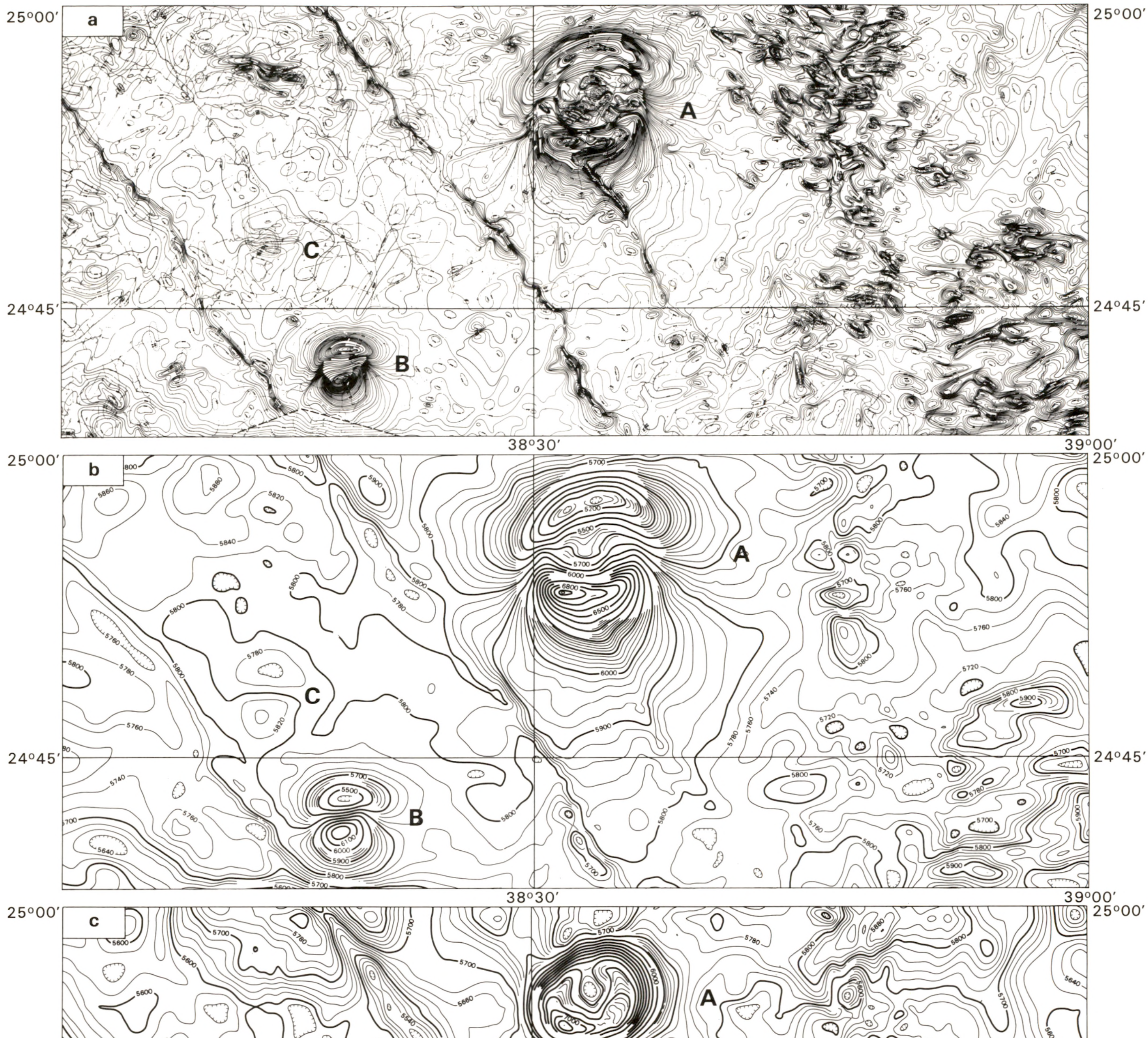

FIGURE 9. – Comparison between the Consortium's magnetic anomaly map (a) and the transformed upward-continued (b) and upward-continued reduced-to-the-pole (c) maps.

INTERPRETATION

BACKGROUND

The original aeromagnetic maps of the 1965-1967 surveys were used for routine qualitative interpretation, predominantly by BRGM, USGS, and DGMR geophysicists, mainly to support the 1:100 000-scale geologic mapping, as for instance by Lambolez (1968a,b); Lambolez and Pilet (1968), Maillard (1968b; 1969 a,b,c), Millon (1969b), Pilet (1968a,b), Gonzalez (1974), Ratte and Andreasen (1974), Hadley (1975), Irvine (1979), Smith (1980), and Kleinkopf and Cole (1982). Various regional interpretations have also been carried out on shield maps at 1:500 000 scale (Maillard, 1968a), at 1:250 000 scale (Griscom, 1982), and at shield-wide scale (Millon, 1970; Hase, 1970; and Blank and others, 1984). The present 1:250 000-scale maps have also been produced mainly as an aid to regional geologic interpretation, but it is not intended here to give an interpretation; only to give indications to help the non-specialist make an interpretation.

Anomalies in the aeromagnetic field are produced by variations of intensity in the magnetization of the rocks. This magnetization ($\overline{J}$) is the sum of two vectors – the induced and the natural remanent magnetization (Hood and others, 1979) – given by $\overline{J} = \overline{R} + k\overline{T}$ (where k is the magnetic susceptibility of the rock formation, $\overline{T}$ the total magnetizing force of the earth's magnetic field, and $\overline{R}$ the remanent magnetization).

Apart from the geometry of the causative rocks, the type, size, and shape of any anomaly depends only on the two vectors ($\overline{R}$ and $\overline{T}$) and the dimensionless factor of susceptibility (k) which is, in general, a tensor. With diamagnetic substances, such as graphite, quartz, marble, rock salt, and gypsum, the susceptibility has a negative value (Parasnis, 1978).

CHARACTERISTICS OF THE EARTH'S MAGNETIC FIELD

The inclination of the earth's magnetic field over the entire Arabian shield varies from about 18° in the south to about 40° in the north, whereas the declination ranges between 1° and 2° easterly. The intensity of the field varies from about 42000 nT (0.42 oersteds) in the north to about 38000 nT in the south.

SUSCEPTIBILITY OF ROCKS

The magnetic susceptibility of rocks is controlled not only by their contents of ferrimagnetic minerals (mainly magnetite, pyrrhotite, ilmenite) but also by their grain size and mode of distribution. Unfortunately there have been only a few measurements of magnetic susceptibility of the rocks of the Arabian shield, and these have been published mainly in conjunction with remanent magnetization studies. Systematic measurements of samples collected during geologic mapping, however, are in progress (Blank and others, 1984); magnetic susceptibility measurements for granitic rocks of the northern part of the Arabian shield have been reported by Kleinkopf and Cole (1982) and Gettings (1982), and for various volcanic and plutonic rocks of the central and northwestern parts of the Arabian shield by Last and Oskoui (1983a,b) and Last (1983). An approximate idea of the range of susceptibility for different rock types, given by Parasnis (1978), is reproduced in Table 2.

TABLE 2. – *Magnetic susceptibility of various rock types (Parasnis, 1978).*

Graphite	−100
Quartz	−15.1
Anhydrite	−14.1
Rock salt	−10.3
Marble	−9.4
Dolomite	−12.5-+44
Granite (without magnetite)	10-65
Granite (with magnetite)	25-50000
Basalt	1500-25000
Pegmatite	3000-75000
Gabbro	3800-90000
Dolomite (impure)	20000
Pyrite (pure)	35-60
Pyrite (ore)	100-5000
Pyrrhotite	10^3-10^5
Hematite (ore)	420-10000
Ilmenite	$3x10^5$-$4x10^6$
Magnetite (ore)	$7x10^4$-$14x10^6$
Magnetite (pure)	$1.5x10^7$

[to correct to CGS units, divide these values by 4π]

NATURAL REMANENT MAGNETIZATION

Blank and others (1984), through comparing anomalies on the aeromagnetic map of the shield with theoretical anomalies caused by models of simple geometry and magnetized by induction, have noticed that most of the Arabian shield anomalies are 'normal' – i.e. they have the form of anomalies produced by sources magnetized in the direction of the present magnetic field. They also noted that 'normal' anomalies will be produced if the natural remanent magnetization vector is oriented in the same direction as the earth's magnetic field, or if its intensity is small in comparison to the induction vector.

'Reversed' anomalies (anomalies in which the 'highs' and 'lows' are interchanged in comparison to the anomalies obtained with induced magnetization) are also present in the shield. They are commonly seen in serpentinized rocks (Griscom, 1982) and are common in Tertiary lava flows; an example of such an anomaly due to Miocene mafic dikes can be seen on Figure 9.

Measurements of remanent magnetization of the shield formations are still rare; they are limited to few areas and special cases such as the Marbadah ring complex in the west of the shield (Lindqvist, 1971), Jabal Sha'i' in the southwest o the shield (Griscom, 1977), volcanic rocks in the Mahd adh Dhahab area (Gettings, 1981), the Lakathah layered intrusive complex in the southwest of the shield (Gettings and Andreasen, 1982), volcanic rocks in the Jiddah region (Gettings and Andreasen, 1983), a suite of rocks of different formations of the east of the shield (Kellogg and Beckmann, 1982), and Tertiary mafic dikes and intrusives (Blank, 1977). In summarizing the studies, Blank and others (1984) noted that the Königsberger ratio Q = R/kT (where R is the permanent intensity, k the susceptibility, and T the total magnetic force of the earth's magnetic field) for many of the studied rocks of the Arabian shield is greater than 1. This is not surprising as most of the measurements were carried out on mafic rocks (basalt, gabbro and, to a less extent, andesite) in which the remanent intensity usually dominates the intensity induced by the earth's magnetic field (Parasnis, 1978).

Another interesting result noted by Blank and others (1984) is that the TRM (thermo-remanent magnetization) direction most commonly present is close to the present earth's magnetic field either in a 'normal' or 'antinormal' sense, the two occurring with nearly the same frequency. This result is confirmed by the excellent correlation existing in most cases between the geologic map and the reduced-to-the-pole map. In the case of reverse magnetization, the reduced-to-the-pole anomaly becomes a symmetrical negative anomaly sited over the body. Other TRM directions also occur in rocks of the Arabian shield but are much less common (Gettings and Andreasen, 1982; Gettings and Andreasen, 1983; Blank and Bazzari, 1981); their presence, however, confirms the necessity of comparing the reduced-to-the-pole map with the upward-continued map to detect obvious anomalies due to remanent magnetization with a direction different to that of the earth's present magnetic field. It also indicates a need for laboratory measurements of remanent magnetization and magnetic susceptibility for the different rock types of the shield.

QUALITATIVE INTERPRETATION

The first step in all magnetic interpretation is qualitative, involving distinctions of lithostratigraphy and structure. Different areas of similar magnetic patterns should be considered in terms of lithostratigraphic units, linear trends in terms of dikes and (or) faults, and circular and subcircular anomalies in terms of different types of intrusion. These magnetic features should all be compared to known geologic outcrops within the study area.

Lithostratigraphic interpretation

A comparison between the reduced-to-the-pole aeromagnetic map and the geologic map will enable the magnetic patterns of certain lithostratigraphic units to be distinguished. In particular, contacts between rock formations of different susceptibilities will be very clearly marked by a steep gradient of the isomagnetic curves on the reduced-to-the-pole map. Examples of such qualitative interpretation are given by Griscom (1982) in the central part of the shield and by Kleinkopf and Cole (1982) for the northern part of the shield. Blank and others (1984) have made such interpretations at 1:1 000 000 scale and, on the basis of dominant aeromagnetic trends and anomaly patterns, have distinguished nine 'magneto-tectonic' provinces for the shield.

The main indications for lithostratigraphic interpretation can be summarized as follows:

1. The magnetic response of the layered rocks varies according to their composition. Rocks of predominant metasedimentary composition are easily recognized as giving very low magnetic responses with subcircular anomalies indicating intrusions: this is common for the Murdama group and equivalent formations and for the Abt formation.
2. The magnetic response of silicic plutonic rocks is highly variable (Blank and others 1984); the rocks themselves are usually of variable composition. The syntectonic granitic rocks shown on the tectonic map of the Arabian peninsula (Brown, 1972) generally produce a strong magnetic relief due to the fact that they are composed predominantly of rock of intermediate composition. Younger, posttectonic, leucocratic granite is generally nonmagnetic, although in places it does give rise to typical annular anomalies. Ishihara (1981) has shown that the distinction between magnetic and non-magnetic granitic rocks has a mineral resource implication.
3. Mafic intrusive rocks (gabbro) give rise to large magnetic anomalies with, in places, negative reverse anomalies as in the case of serpentinite and of Tertiary basaltic rocks.
4. Basaltic lava flows give a typical complex pattern of intense magnetic anomalies that are sometimes reversely magnetized. On the borders of the lava flows, where they are fairly thin, their signature disappears with upward continuation and only the Precambrian structures are obvious.

Structural interpretation

An important step of the qualitative interpretation of aeromagnetic data is the study of the anomaly with a special shape: linear anomalies corresponding to dikes and (or) faults, and circular anomalies corresponding to intrusive bodies. Such interpretations at shield-wide scale have been carried out by Brown and Hase (1971), Millon (1970), and Blank and others (1984).

Linear anomalies

Millon (1970), and Blank and others (1984) have distinguished four main sets of linear aeromagnetic trends corresponding to:

1. The northwest-trending Najd system, which dominates the magnetic pattern in all the east-center of the shield and occurs less conspicuously in the northeast of the shield. The set of anomalies is caused by massive basic dikes injected into the Najd fault system.
2. The north-northwest-trending Red Sea system existing only in an area of 150 km width along the Red Sea. This set of anomalies, usually negative (fig. 9), is caused by a series of Tertiary mafic dikes emplaced during the opening of the Red Sea (Blank, 1977).
3. A north-trending system in the southern, central, and north-central parts of the shield interpreted by Millon (1970) as being younger than the Najd system. Millon thinks that it could have been reactivated during the Tertiary, thus explaining the main northerly trend of most of the basaltic 'harrats'. Blank and others (1984), however, noted that this system is truncated and offset by Najd trends, and have reinterpreted it as fold belts and secondary splay faults of the Najd fault system.
4. An east-trending system (Millon, 1970) which has been reinterpreted by Blank and others (1984) as corresponding to two systems – one trending east-northeast to the north of lat 26° N. in the north-central shield and between lat 21° and 24° N. in the west-central shield, and the other trending almost east and occurring throughout the shield. The east-northeast-trending system is interpreted as being a Precambrian system reactivated during the opening of the Red Sea and probably comprising fundamental basement structures that influenced the loci of transform faults. The east-trending system is interpreted as being caused by deep sources with extensive roots.

In addition to these four main trends, there is also a southwest trend, such as the Taif fault (Millon, 1970), which exists mainly in the west-central part of the shield. This trend corresponds to the main tectonic direction of the At Taif-Jiddah terrane of Johnson and Vranas (1984).

Circular anomalies

The round-shaped anomalies on the aeromagnetic maps have been classified by Millon (1970) as 'annular' and 'circular'. The 'annular' anomalies occur mainly in the Murdama group and Millon (1970) interpreted them as being caused by enhanced magnetization in metamorphic rocks due to granitic intrusions. Hase (1970), on the other hand, has interpreted them as due to a more mafic border of the granite or to a ring dike within the granite. The 'circular' anomalies appear circular only on the reduced-to-the-pole maps; on the original aeromagnetic maps of the Consortium (1966, 1967) they occur typically as an anomalous pair with a positive anomaly to the south and a negative anomaly to the north. They are provoked by intrusive bodies of various compositions, with the more intense anomalies being given generally by gabbro, granite, syenite, or diorite. Interpretation of some of the more remarkable circular anomalies have been proposed by Millon (1970), Hase (1970), Griscom (1982), and Blank and others (1984).

QUANTITATIVE INTERPRETATION

Following the qualitative interpretation, quantitative interpretation can be carried out on selected anomalies of special interest; this consists in defining the shape, position, and intensity of magnetization of the body causing the anomaly. It is important, in quantitative interpretations, to have remanent-magnetization and susceptibility measurements of representative samples in the survey area; measurements that are still scarce for the Arabian shield.

The start of a quantitative interpretation is the calculation of geometric bodies giving anomalies of certain simple magnetic shapes, assuming that the magnetization is due only to induction. Relevant models for such calculations are: a set of two-dimensional step and dike models calculated for the average geomagnetic inclination of the Arabian shield (Blank and Andreasen, 1980); three-dimensional prismatic models proposed for anomalies resulting from induction (Vacquier and others, 1951); some general models taking into account remanent magnetization proposed for prismatic models (Andreasen and Zietz, 1969); and a set of programs allowing direct computation of different models, (Godson, 1974). Some quantitative interpretations of the aeromagnetic data of the Arabian shield have been carried out, but they are still very limited. Interpretations based on manual comparison with sets of models have been reported, in particular, by Gettings (1981), Griscom (1982), and Kleinkopf and Cole (1982), whilst interpretations using computers to compute anomalies fitting the observed anomaly have been published by Blank (1977), Griscom (1977), and Gettings and Andreasen (1982). A more sophisticated interpretation using spectral analysis on aeromagnetic profiles was made by Blank and Sadek (1983) to determine the thickness of Tertiary basalt lava flows. Blank and others (1984) carried out statistical analyses of linear trends and also made a study of deep-seated anomalies by low-path wavelength filtering techniques; they computed the depths of the magnetic sources and showed that they are mainly rocks of mafic composition.

The existence of the digital aeromagnetic data for the whole shield will allow future development of the most modern techniques of interpretation at different scales, utilizing filtering and interactive curve-fitting techniques such as described by Hood and others (1979).

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