U. S. GEOLOGICAL SURVEY

SAUDI ARABIAN PROJECT

MISCELLANEOUS DOCUMENT 1

(INTERAGENCY REPORT 279)

STATUS OF REGIONAL GRAVITY PROJECT, KINGDOM OF SAUDI ARABIA, AS OF 1 JANUARY 1979

by

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U.S. Geological Survey
Open-File Report 81-165

U.S. Geological Survey
Jiddah, Saudi Arabia

1981

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

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ABSTRACT

Regional gravity data have now been obtained for approximately 33 percent of the area of the Arabian Shield, associated harrat areas, and the Red Sea coastal plain. Virtually no surveys have been done on the Phanerozoic platform around the edges of the shield, and although regional gravity coverage is available for the Eastern Province from the Arabian American Oil Company, it is confidential. Approximately 4,500 more gravity stations at 10 km spacing are needed to complete the coverage of the shield, and 5,250 are needed on the Phanerozoic platform to the north and east of the shield.

The initial gravity maps compiled from the regional gravity project will be along the "geophysical strip", a band approximately 150 km wide across the shield from Al Qawayiyah to the Farasan Islands. As more data become available, additional maps will be compiled at 1:500,000 scale covering the same areas as the USGS Miscellaneous Investigations Maps I-200-A to I-220-A.

Computer software development and implementation for gravity data reduction, storage, retrieval, and display are 80 percent complete. Development and implementation of software for routine semi-quantitative and quantitative interpretation are 50 percent complete.

If the Directorate General of Mineral Resources were to commit full support for the regional gravity project, phase 1 (data acquisition) and phase 2 (data reduction and publication of maps and principal facts) could be completed and phase 3 (interpretation) could be about 50 percent completed by the end of the Third Five Year Development Plan (1985).

INTRODUCTION

The regional gravity project is being carried out under the mandate of section 6.1 of the Sectoral Plan of the Directorate General of Mineral Resources (DGMR) for the Second Development Plan. The stated objective of this project is "to compile and interpret a comprehensive Bouguer gravity anomaly map of the Kingdom," and principal responsibility for the execution of the project has been delegated to the U.S. Geological Survey (USGS) Mission. This report summarizes progress to date on the various phases of the project.

The regional gravity project has been divided into three phases or sections, which have proceeded more or less concurrently. These phases are: 1) data acquisition; 2) data reduction and processing; and 3) data interpretation. Because of the large amount of numerical data required in gravity work, the only practical means of reliable processing is by digital computer. Thus, efforts in phases 2 and 3 have been devoted mainly to acquisition and implementation of operational software for the DGMR PDP 11/45 computer system to accomplish data reduction and interpretation. Data acquisition has proceeded at a relatively slow pace; about 30 percent of the Arabian Shield has been completed at the required 10 km spacing.

The initial product of the project will be a Bouguer gravity anomaly map at a scale of 1:500,000 along the "geophysical strip" approximately 150 km wide across the southern shield from Al Qawayiyah to the Farasan Islands. As coverage becomes available, maps with a preliminary interpretation will be compiled at 1:500,000 scale covering the same areas as the Miscellaneous Investigations Maps I-200-A to I-220-A. Additionally, each map will include a detailed semi-quantitative or quantitative interpretation, and the "principal-fact" (computer) file, which lists the latitude, longitude, elevation, observed gravity, terrain correction and uncertainties in these quantities for each gravity station. The principal-fact file will constitute the data base for all future work and, as such, will be the primary product of the project.

Investigations described in this report were carried out in accordance with the work agreement between the Directorate General of Mineral Resources of the Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia, and the U.S. Geological Survey.

PHASE 1. DATA ACQUISITION

Accuracy and precision requirements

The objectives of this project are twofold: first, to define the variations in the gravity field of the Kingdom of Saudi Arabia adequately for regional geological and geophysical studies; and second, to establish a network of gravity observations sufficiently accurate to be incorporated into later, more detailed gravity surveys of local targets that may be undertaken as a result of the regional work. Both the considerable expense of gravity surveys and the objectives of the project require that high standards of accuracy in the data be maintained in order to produce a data base of lasting utility.

A nominal station spacing of 10 km has been selected as adequate to define the gravitational field for regional work, based on wide experience documented for North America and Australia.

The following minimum general standards have been adopted for maximum probable errors to be tolerated in the principal facts: horizontal position, ± 100 m (usually a pin-prick on an aerial photograph); vertical position, ± 2 m precision as determined by two independent pairs of altimeters; observed gravity, ± 0.25 mgal absolute accuracy, ± 0.10 mgal precision of measurement within the particular survey; and terrain correction precision, ± 20 percent of correction. Further, realistic estimates of uncertainties are required for all principal facts at every gravity station. Adherence to the above standards will not only guarantee that data are of high quality, but also will help to determine which stations must be reoccupied to increase their accuracy if later desired.

Existing gravity survey coverage

D. R. Mabey (unpub. data) was among the first to argue for high-quality, regional gravity data coverage; his review of gravity data extant in 1964 for the Kingdom indicated that it was not adequate for regional gravity project purposes.

The first high-quality stations established in the Kingdom are those done by V. J. Flanigan and H. A. Akhrass (unpub. data, 1972) on 42 of the first-order geodetic stations of the National Geodetic Network. These stations are relatively evenly distributed over the Kingdom (except in the Rub al Khali; see fig. 1) and constitute the base station network to which all regional gravity surveys will be tied. Precision of the observed gravity differences of these stations is high relative to Jiddah Airport base station, probably better than ± 0.03 mgal, but as the Jiddah base station lacks high-quality ties to the worldwide gravity network (Morelli, et al., 1971), accuracy cannot be evaluated. Establishment of reliable ties to worldwide stations with calibrated gravimeters and reoccupation of the National network with the same meters will be necessary to establish an absolute datum for gravity measurements. However, data based on the old base net values can be adjusted to the new datum at a later date by purely computational procedures.

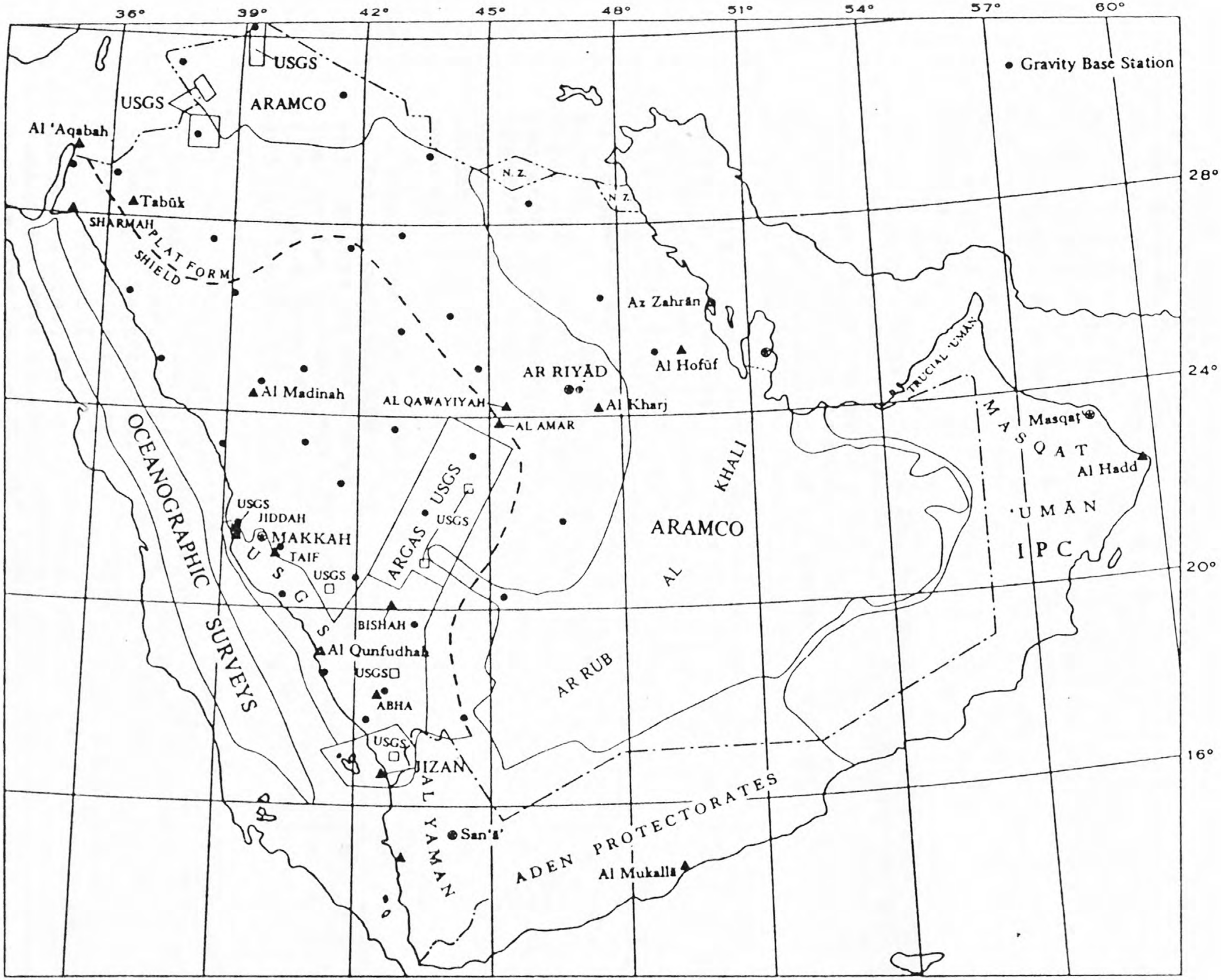

Figure 1.--Map showing areas of existing regional gravity survey data in the Kingdom of Saudi Arabia and in surrounding regions. The gravity base stations established by the USGS are also shown. Scale is approximately 1:13,000,000.

Areas in the Kingdom with existing gravity survey data are shown on figure 1. The most extensive coverage is that of the Arabian American Oil Company (ARAMCO), which has generously contributed its maps (not principal facts) to the DGMR for its internal use, but not for publication (S. Bowers, pers. commun., 1976). The maps are based on data that have an average station spacing of 10 km, but their reliability is difficult to assess because we lack access to the original data. Arranging the release of this data set is an objective worthy of consideration by the DGMR, as resurveying this vast area for the Kingdom gravity map would seem to be a needless duplication of effort.

Gravity surveys in the Red Sea have been made, and efforts to update the DGMR coverage from available data are presently under way. With the exception of the area of the Common Sector of the Saudi Arabian-Sudanese Joint Commission, gravity coverage is generally restricted to the axial trough in the central portion of the Red Sea.

A gravity survey of about 3,000 stations was completed in 1975 by the Arabian Geophysical and Surveying Company Ltd. (ARGAS) for the Aerial Surveys Department (ASD) of the Ministry of Petroleum and Mineral Resources. Observations were made at stations of the National Geodetic Network and on benchmarks spaced about 6 km apart along many of the roads in the Kingdom. All efforts to obtain a copy of the maps or the principal facts from that survey have failed. This failure is regrettable because it implies that the DGMR must repeat those observations as well as fill in areas not covered by the ASD survey. Work already completed on the shield area south of Jiddah would have been considerably facilitated had those data been available.

Only one survey "ARGAS/USGS" in figure 1 has been done so far by contract specifically for the DGMR regional program and consists of 868 gravity stations. The data are of marginal quality for regional gravity purposes; the lack of detailed field notes makes exact reoccupation of the stations impossible, and the field procedures employed were definitely not reliable.

Notwithstanding the questionable reliability of the data, a simple Bouguer gravity anomaly map without terrain corrections (fig. 2) was constructed by the USGS/DGMR Geophysics Section Staff. This map shows many interesting features and is probably representative of the relief in the gravitational field to be expected on the Arabian Shield. In gross features, the map is almost certainly correct; however, subsequent work in the Kushamiyah area has shown that caution must be exercised when data from that survey are used to define individual anomalies. Some additional field gravity survey work will be necessary to resolve ambiguities in the map.

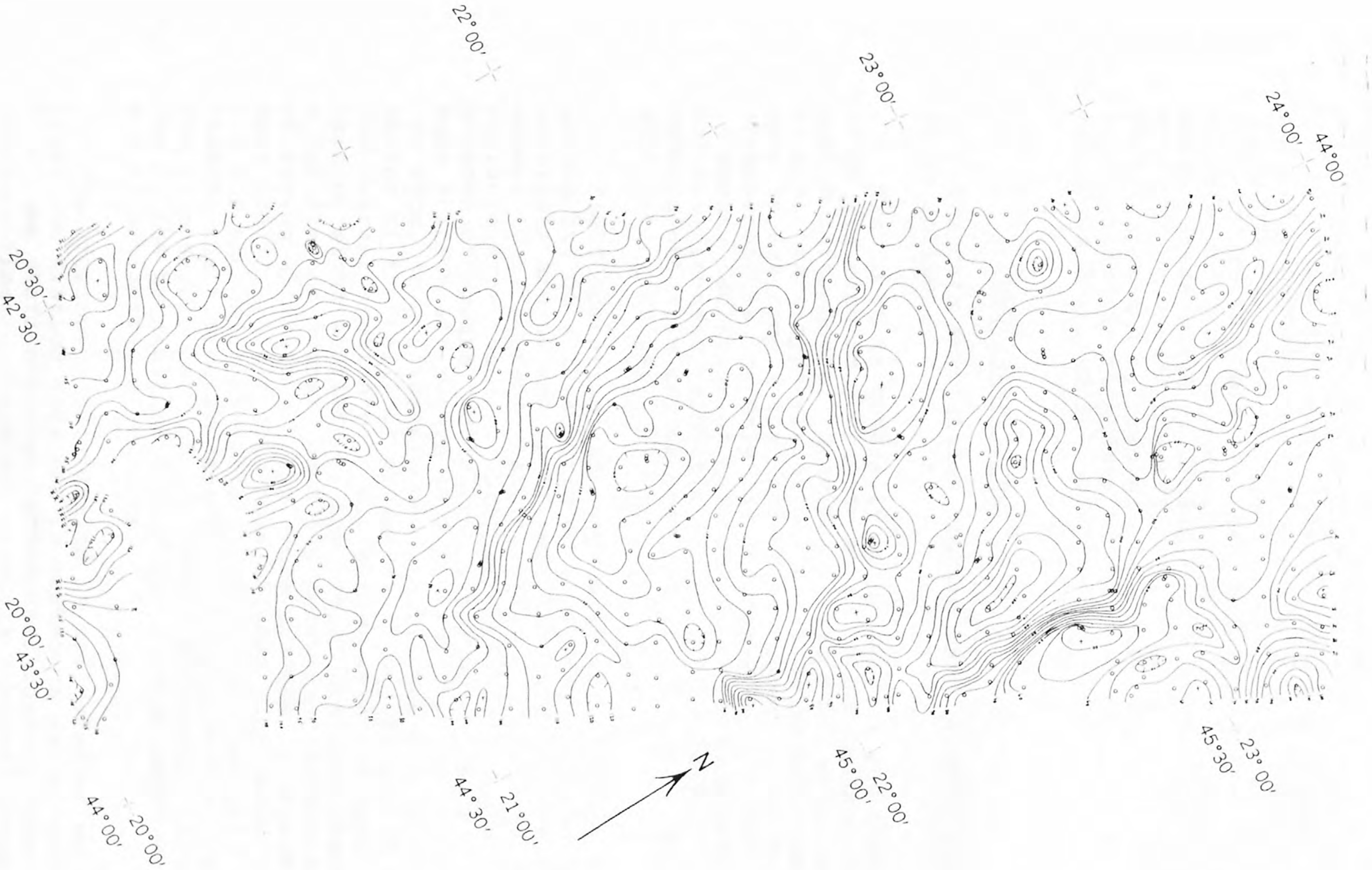

Figure 2.−−Simple Bouguer gravity anomaly map of the Bishah−Al Amar area, Kingdom of Saudi Arabia. Map area is that labeled "ARGAS/USGS" in figure 1; contour interval is 5 mgal. Scale is approximately 1:2,000,000. Small circles are locations of gravity stations.

Data for the areas labeled "USGS" in figure 1 have been acquired in-house by USGS geophysicists. The smaller areas are generally related to the study of a specific geologic target; ground positions have generally either been surveyed or determined by high-quality photogrammetric methods. In the larger areas south of Jiddah, position control has been achieved by visual identification on 1:50,000 scale aerial photographs and by precision altimetry surveys. Number of stations and station density data for areas of existing coverage are summarized in table 1.

USGS gravity survey field procedures

The data acquisition routine used by USGS geophysicists is as follows:

Transport is generally by helicopter and usually station loops are tied to a gravity base station within the survey area within three hours. Gravimeters are carried in cases equipped with aircraft-type vibration isolation mounts, and the whole case is set upon a foam rubber pad about 10 cm thick. This arrangement is the only one attempted so far that provides necessary isolation of the gravity meter from both the high- and low-frequency vibrations of the helicopter. LaCoste-Romberg geodetic series gravimeters have been used throughout, with good results.

Field operations are typically initiated by preflight laying out of a 10-km grid on 1:50,000-scale photomosaics. Locations are picked on or near the grid intersections that appear to be suitable landing sites and that are uniquely identifiable from the air. Gravity observations are made in sequences of square "cells" of nine stations each. A pair of base station altimeters (Wallace and Tiernan precision surveying type, or equivalent) and an observer are set out in the center of the cell, an altimetric tie (usually 20 km away to the nearest station of the previous cell) is made, and the remaining eight stations of the "cell" are then observed using a LaCoste and Romberg geodetic gravimeter (G-series) and a pair of roving altimeters. The whole process is repeated for the next "cell". Altimetric observations (including the altimetric tie for the cell) are thus always within two grid intervals or less of the altimeter base monitoring pressure changes. Insofar as possible each of the roving altimeters is matched with one of the base altimeters, which further improves the accuracy of altimetric elevations.

The following information is collected at each station. First the station location is marked on aerial photographs. Next, the station number, gravimeter reading (checked three separate times), altimeter readings (checked three separate

Table 1.--*Summary of existing gravity data coverage of usable quality in the Kingdom of Saudi Arabia*

Agency responsible for data	Approximate coordinates of center of survey Latitude	Longitude	Area, (km^2)	Number of Stations	Area per station (km^2)
ARAMCO	--	--	817,900	∿ 8,000	∿ 100
USGS	22.0°	44.0°	60,980	868	70.3
USGS	19.0°	42.0°	106,690	1,025	104.1
USGS	17.0°	42.5°	24,189	145	166.8
USGS	17.0°	43.0°	400	129	3.1
USGS	18.7°	42.8°	81	156	0.5
USGS	21.5°	39.2°	774	∿ 170	4.6
USGS	20.3°	41.3°	0.06	105	0.0006
USGS	21.0°	43.5°	69	170	0.4
USGS	22.5°	44.5°	150	∿ 225	0.7
USGS	29.8°	38.2°	5,100	54	94.4
USGS	30.7°	38.1°	240	137	1.8
USGS	31.8°	39.4°	5,400	47	114.9

times), date, time, gravimeter internal temperature, and wet- and dry-bulb air temperatures (psychrometric readings) are recorded in a bound notebook. An oral description of the station including quality of location (± 50 m, ± 100 m, and so forth) on the photographs, information necessary to relocate the station later, and information necessary to calculate the local terrain correction for the station, is recorded on a portable tape recorder and transcribed later. Finally a painted stone is placed at the position of the gravimeter observation and a photograph taken showing the surrounding area. Average elapsed time at each gravity station is about 4 minutes.

A temporary gravity base station is generally established at or near the helicopter refueling points, and the base ties for all loops are made at these points. Standard practice has been to tie the temporary gravity base stations to the nearest gravity base station or stations of Flanigan and Akhrass (unpubl. data) at least three separate times, usually with loops that initiate and terminate on one of the temporary gravity bases.

Due both to lack of staff and lack of aircraft time, the rate of accumulation of data has been slow, and closely monitored contract work seems to be the only way to accomplish complete coverage of the Kingdom in the near future. Completion of the data acquisition phase as soon as possible is a desirable goal because it would make available data bearing on the regional structural framework *during the reconnaissance stages* of geologic mapping. The advantages of a three-dimensional regional geologic framework over a two-dimensional one to the mineral exploration program are obvious.

New gravity surveys to be acquired

Areas to be surveyed to complete the project are shown on figure 3. Assuming that the region covered by the ARAMCO surveys will not need to be redone, a total of about 9,750 stations will be required. This includes approximately 4,500 gravity stations at 10-km spacing necessary to complete the coverage of the Arabian Shield and about 5,250 on the Phanerozoic rocks of the platform to the north and east of the shield, of which 900 are in the area of the Great Nafud. The Great Nafud is considered separately because it is anticipated that special survey procedures will be necessary there.

The most satisfactory way to complete the project would be as a single large contract to finish the job in a period of three years or less. A number of contractors have indicated interest in all or part of the job. Such a contract would have to be closely monitored, as the results of the ARGAS survey of 1975 indicate, and it would probably be best to hire a full-time geophysicist specifically for the job.

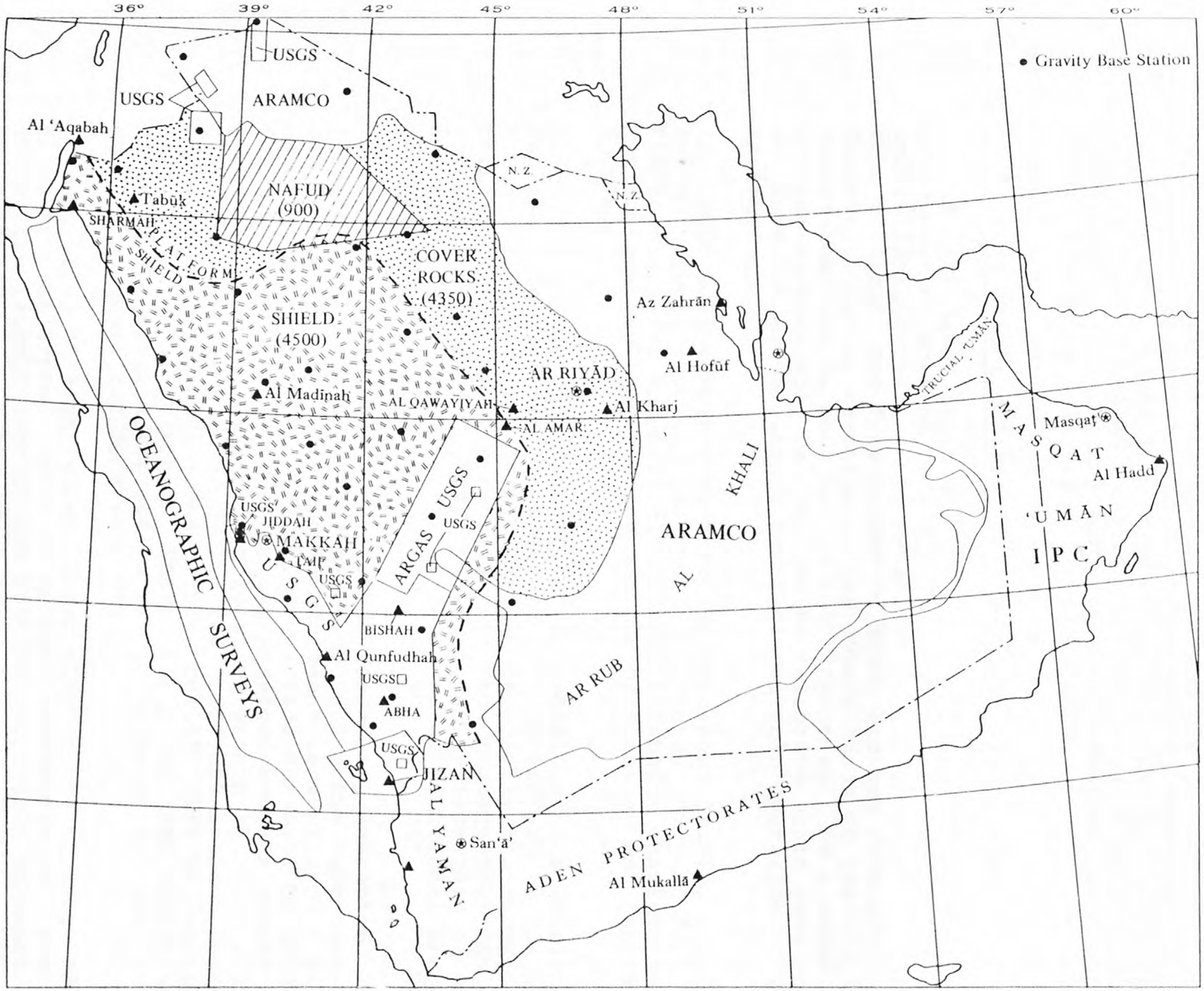

Figure 3.- -Minimum remaining areas to be surveyed to complete the data coverage for a regional gravity anomaly map of the Kingdom of Saudi Arabia. Numbers in parentheses are the estimated number of stations necessary for a nominal station spacing of 10 km.

Reliability of results will be the prime requisite, speed of data acquisition the second. An example of technical specifications designed to insure acquisition of high-quality data is given in Appendix 1. Rigid enforcement of specifications such as these, coupled with independent field checks of random areas by the contract monitor using DGMR/USGS gravimeters, should guarantee delivery of reliable data.

Gravimeter calibration and international ties

A gravimeter calibration range consisting of three lines will be established by USGS for calibration of gravity meters and reliability tests. By establishing three lines, one from Abha to Jizan, one from Jiddah to Taif, and one from Ash Sharmah to Tabuk, essentially the entire range of gravity values that can be observed in the Kingdom will be covered. All contractors will be required to calibrate their gravimeters on these ranges and submit proof of reliable operation of the instruments.

USGS will complete ties to International Gravity Standardization Network stations (Morelli and others, 1971) at Port Sudan, Khartoum, Cairo, and Beirut, and thus establish absolute values for the gravity base station network of Flanigan and Akhrass (unpub. data).

Acquisition of a digital terrain model for the Arabian Peninsula is necessary in order to perform terrain corrections to the gravity data. In many areas, especially the escarpment, terrain corrections are necessary to reduce adequately the data for regional purposes. The ability to study isostatic effects and deep crustal structure will be a useful additional benefit of the terrain model.

Present plans call for several stages of generation of the terrain model. Initially, the 1:4,000,000-scale topographic map of the Arabian Peninsula and adjacent seas will be digitized by machine at the USGS Mission. This data set will be adequate for outer zone terrain corrections (Hayford-Bowie standard zones J-O) and estimates of corrections within 15 km of a station (Hayford-Bowie zones D-J). The 1:250,000-scale topographic maps, which cover most areas of high relief, will be digitized next, probably by contract. These will yield much better estimates of the terrain correction within 15 km of the station and will be adequate for most stations.

In areas of high relief, especially in the vicinity of the Hijaz-Asir escarpment south of Jiddah, accurate inner zone correction (within 3 km of the station) will have to await the availability of 1:50,000-scale maps.

PHASE 2. DATA REDUCTION AND PROCESSING

Activity in Phase 2 has been aimed at the development and implementation of a versatile computer-based system to store and retrieve the gravity principal facts, to reduce field data, and to prepare contour maps by computer-driven plotter. So far, every effort has been made to utilize the DGMR PDP 11/45 computer system, although it is not clear that this system has the capacity to carry out all aspects of the project while serving other DGMR needs as well. A gravity data storage and retrieval system has been established by Godson and Andreasen (1974); a modification of this system will ultimately be used for the Kingdom gravity principal-fact file.

Gravity reduction is a straightforward though tedious process. Raw gravity data must first be corrected for instrumental drift and earth tidal accelerations, yielding an observed gravity value at each station. These values are then adjusted for free-air and Bouguer effects (the normal decrease in gravity with elevation) and compared with theoretical gravity on a reference spheroid (values calculated assuming a standard homogeneous layered earth model). The resulting residual values describe what is known as the Bouguer gravity anomaly field. If variations in topography surrounding the stations have been taken into account, that is, if terrain corrections have been made (usually out to a standard distance of 167 km from each station), the residual values describe the so-called "complete" Bouguer gravity anomaly field. This field is the basis for most gravity interpretation in support of local and regional investigations. Gravity investigations of the deep crust may require additional corrections to the basic data set for the effect of isostatic compensation.

Figure 4 presents a flow chart of the computer-based system of programs that performs the reductions. Implementation of this system on the DGMR computer is now (January, 1979) about 80 percent complete. Throughout the system, the detection and correction of errors has been an important consideration. The format of input gravity field data is shown in table 2 and that of the principal-fact file in table 3.

Terrain corrections beyond 15 km from the station are computed utilizing prisms having a cross section of three minutes latitude by three minutes longitude and a constant average elevation. Within 15 km of the station, a surface integral technique (Gettings, unpub. data.) is used which calculates the terrain effect of a smooth surface passing through the station and the points defining the topography. In areas of high relief, corrections for the immediate topography (within 200 m of the station) are computed manually. As many as five alternate Bouguer reduction densities are available for studies in areas

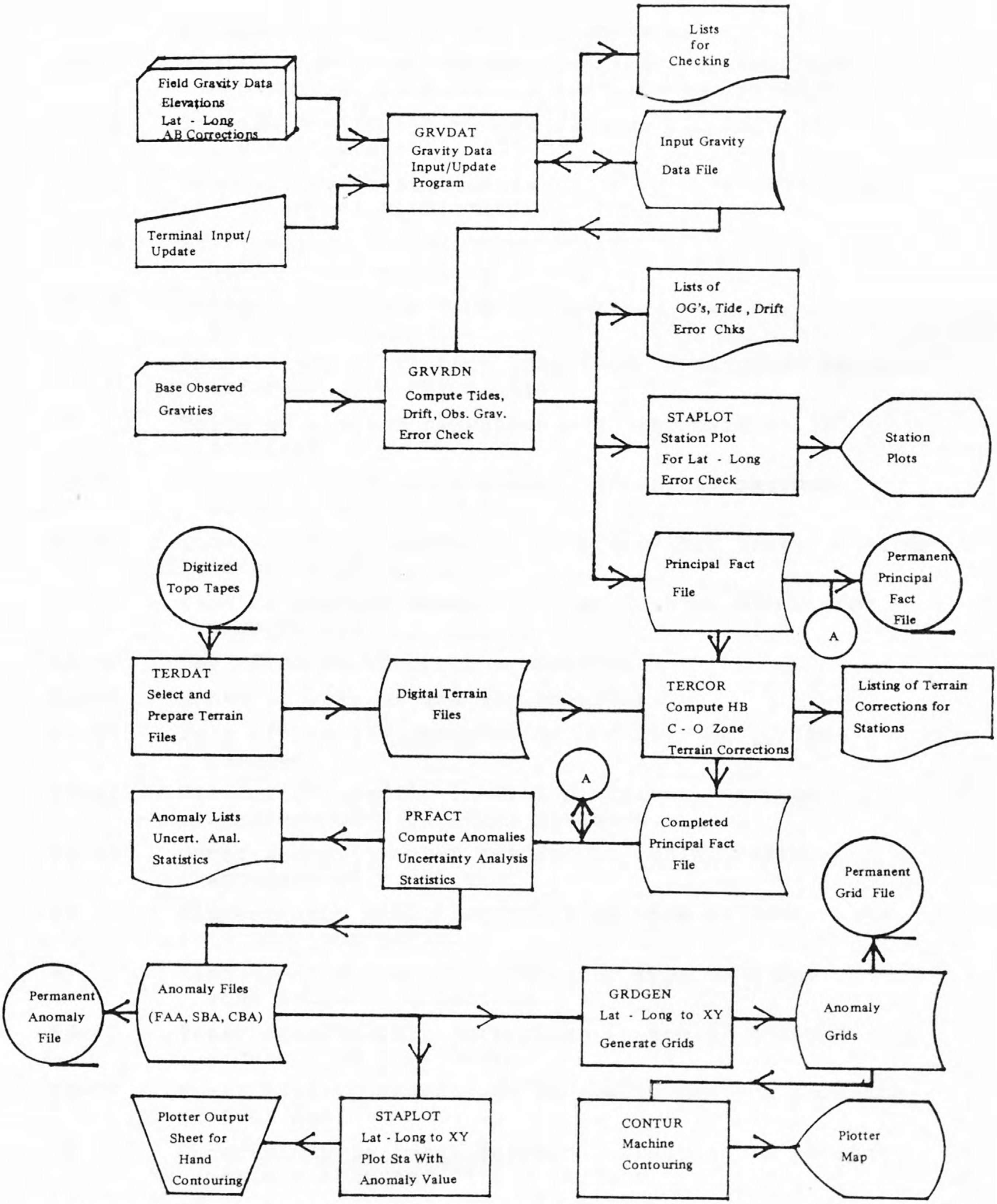

Figure 4.--Flow chart showing data input, program modules, and output products of the gravity data reduction system.

Table 2.--*Format of input field data from gravity surveys*

Columns	Item description
1-8	Station identification, alphanumeric
9-11	Station latitude, degrees, positive in northern hemisphere, negative in southern hemisphere
12-16	Station latitude minutes; maximum accuracy of 0.001 minute
17-20	Uncertainty in station latitude in minutes; maximum accuracy of 0.001 minute
21-24	Station longitude degrees, positive in eastern hemisphere, negative in western hemisphere
25-29	Station longitude minutes; maximum accuracy of 0.001 minute
30-33	Uncertainty in station longitude in minutes; maximum accuracy of 0.001 minute
34	Units of station elevation: "M" for meters; "F" for feet
35-40	Station elevation in prescribed units; maximum accuracy of 0.1 unit
41-44	Uncertainty in elevation in prescribed units; maximum accuracy of 0.1 unit
45-48	Time of gravity observation on 24 hour clock, for example 1043
49-50	Day of month of gravity observation
51-52	Month of year of gravity observation
53-54	Year of gravity observation (2 digits only, 1900 assumed)
55-61	Gravimeter reading in dial divisions; maximum accuracy of 0.001 dial division
62-65	Uncertainty in meter reading in mgals; maximum accuracy of 0.001 mgal
66	Alphanumeric character defining type of inner zone terrain correction
67	Alphanumeric character defining type of outer zone terrain correction
68-72	Inner zone terrain correction in mgals; maximum accuracy of 0.01 mgal.
73-77	Total terrain correction in mgals; maximum accuracy of 0.01 mgal
78-79	Uncertainty in total terrain correction in percent; maximum accuracy of 1.0 percent
80	Type of station: blank, field station; "B", base station; "R", repeated field station

Table 3.--*Format of gravity principal-fact file entries*

Columns	Item description
1-8	Station identification, alphanumeric
9-11	Station latitude degrees, positive in northern hemisphere, negative in southern hemisphere
12-16	Station latitude minutes; maximum accuracy of 0.001 minute
17-20	Uncertainty in station latitude in minutes; maximum accuracy of 0.001 minute
21-24	Station longitude degrees, positive in eastern hemisphere, negative in western hemisphere
25-29	Station longitude minutes; maximum accuracy of 0.001 minute
30-33	Uncertainty in longitude in minutes; maximum accuracy of 0.001 minute
34	Units of station elevation: "M" for meters; "F" for feet
35-40	Station elevation in prescribed units; maximum accuracy of 0.1 unit
41-44	Uncertainty in elevation in prescribed units; maximum accuracy of 0.1 unit
45-53	Observed gravity in mgals; maximum accuracy of 0.001 mgal
54-57	Uncertainty in observed gravity in mgals; maximum accuracy of 0.001 mgal
58	Alphanumeric character defining type of inner zone terrain correction
59	Alphanumeric character defining type of outer zone terrain correction
60-64	Inner zone terrain correction in mgals; maximum accuracy of 0.01 mgal
65-69	Total terrain correction in mgals; maximum accuracy of 0.01 mgal
70-71	Uncertainty in total terrain correction in percent; maximum accuracy of 1.0 percent
72-80	Time of gravity observation in days since 0000 hours 1 JAN 1900 in days; maximum accuracy of 0.0001 day

of abnormally high or low average bulk density in addition to the standard value of 2.67 gm cm^{-3}. An error analysis is carried out for each station, utilizing the uncertainties in each variable (horizontal position, vertical position, observed gravity, and terrain correction) and a propagation-of-errors analysis.

The data-reduction system produces a permanent principal-fact file, a file of anomaly values, a file of anomaly values on a regular grid, and the desired map or maps at any scale or projection.

Each 1:500,000-scale map to be compiled will include a text describing the data and their uncertainties, a list of the principal facts, and a preliminary interpretation. In order to expedite access to the data, detailed semi-quantitative and quantitative interpretations will be prepared subsequently as separate documents.

PHASE 3. DATA INTERPRETATION

Ultimately, all of the regional gravity data should be subjected to routine interpretations that will yield estimates of the depth, geometrical form, and density contrast of the causative bodies responsible for all significant gravity anomalies present. Any other geophysical data (especially aeromagnetic), all geologic data available, and measurements of the physical properties of the surface rocks should be utilized in these interpretations to place as many constraints as possible on the resulting models. Where justified, these regional models will then form the basis for detailed investigations.

Typical interpretations will include a regional-residual anomaly separation at various scales accomplished by orthogonal polynomial fitting (usually first, third, fifth, and tenth orders) and Fourier transform techniques. The resulting regional map will then be analyzed by modeling techniques for large-scale (generally crustal) structures, and some attention will be directed toward isostatic considerations.

Interpretation of the residual anomalies generally will be done by modelling techniques; utilization of data from other investigative methods will be important to eliminate models that satisfy the gravity constraints but are otherwise untenable. For long narrow ("two-dimensional") anomalies, modelling is straightforward and rapid. Interpretation of "three-dimensional" anomalies is more complex. It is anticipated that the method of Cordell and Henderson (1968) will be extensively used and, accordingly, a program of this method has been made fully operational on the DGMR computer. This program also yields the excess mass of both the observed anomaly and the computed model.

Other methods, such as comparison with the "pseudo-gravity" field computed from the magnetic field by Poisson's equation, and estimates of bulk physical properties (Cordell and Taylor, 1971) also will be used. Depth estimates and modelling using modern inversion theory and fast Fourier transform techniques will be utilized as required.

It is not clear that the present DGMR computer system can meet the demands of this project. Accordingly, a pilot study is being carried out in the Kushamiyah area (part of fig. 2) by Gettings and Andreasen to obtain data to evaluate this question in addition to providing a first quantitative interpretation of regional gravity data on the shield.

SUMMARY

Significant progress has been made in all three phases—acquisition, reduction, and interpretation—of the regional gravity project. Regional gravity data have been collected at a nominal spacing of 10 km for about 30 percent of the Arabian Shield, mostly in the area south of Jiddah, and are in various stages of reduction and interpretation. These data include the major portion of a roughly 150 km-wide "geophysical strip" across the southern part of the shield approximately normal to the strike of the major tectonic features. Analysis of this data set, combined with information from the seismic deep-refraction profile down the center of the strip, aeromagnetic data, and geologic information, will provide a basic regional geologic model of the Arabian Shield on which future work may be based.

Development and implementation of the software system for the data reduction and processing phase of the project are 80 percent complete, and reduction of all existing data will be completed within the next six months. Preliminary interpretation and compilation of the gravity anomaly maps of the geophysical strip will follow as soon as possible.

Adequate software for semi-quantitative and quantitative interpretation of gravity data is now extant on the DGMR computer facility and will be upgraded and supplemented as required. Table 4 summarizes the status of the three phases of the project.

If the DGMR should decide to budget funds for a major effort to complete this project, it appears that data acquisition could be completed in about 2 to 3 years. Partially concurrent data processing should enable completion of Phases 1 and 2 and significant progress in the interpretive phase by the end of the Third Development Plan (1985).

Table 4.--*Summary of the status of the regional gravity project as of January 1, 1979*

Phase 1. DATA ACQUISITION

A. Field surveys

Survey region	Category	Number of stations (at 10 km spacing)	Area, (km^2)	Percent complete
Arabian Shield and Red Sea coastal plain	existing	2,038	191,900	33
	needed	4,500	396,300	67
	totals	6,538	588,200	100
Phanerozoic platform ("cover rocks")	existing	54	5,100	1
	needed	5,250	503,600	99
	totals	5,304	508,700	100
Eastern Province (ARAMCO coverage)	existing	ca. 8,000	817,900	100
	needed	0	0	0
	totals	ca. 8,000	817,900	100
Grand totals	existing	ca.10,092	1,014,900	53
	needed	ca. 9,750	899,900	47
	totals	ca.19,842	1,914,800	100

B. Other activities

Activity	Percent complete
Terrain model	10
Calibration lines, ties to international network	10

Phase 2. DATA REDUCTION AND PROCESSING

Activity	Percent complete
Software development and implementation	80
Processing of existing data (except ARAMCO data)	40

Phase 3. REGIONAL GRAVITY DATA INTERPRETATION

Activity	Percent complete
Software development and implementation	50
Interpretation of existing data	15

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APPENDIX 1. EXAMPLE OF TECHNICAL SPECIFICATIONS FOR A REGIONAL GRAVITY SURVEY

I. GENERAL SPECIFICATIONS

A. Area to be surveyed

1. The area to be surveyed is enclosed approximately by lines connecting Khamis Mushayt-Bishah-Al Junaynah 60 km northeast of Junaynah - 80 km due southeast from there - Hamdah - 140 km due east - 160 km due south - Yemen border - Zahran-Khamis Mushayt. See attached index map (fig. 5).

2. The area of the survey is approximately 55,000 km^2. There shall be approximately 1 station per 100 km^2. Station spacing shall be on the average 10 km on a rectangular grid. A minimum spacing between stations of 5 km and a maximum of 15 km shall be observed. The minimum number of stations established in the survey area shall be 550.

3. 1:50,000-scale photographs and photomosaics shall be used for navigation and location in the field.

B. Time frame for project completion

1. The duration of the project from beginning of field work to submission of final report including maps and field data shall not exceed six months.

C. Survey personnel

1. The survey field crew shall include at least one field geophysicist experienced in gravimetry and the estimation of gravimetric terrain corrections in areas where detailed topographic maps are not available.

D. Instruments

1. Gravimeters shall be first order geodetic gravimeters with low drift rates and temperature compensation. Two gravimeters shall be available - one for survey use and one for retention in a base camp as backup in case of failure or damage to the gravimeter in use.

2. Altimeters shall be used for the determination of elevation. Two altimeters shall be read at each gravity station and a recording barograph shall be used at a nearby base station during survey periods to establish the barometric variation.

II. TECHNICAL SPECIFICATIONS

A. Field procedures

1. Prior to the survey, there shall be a discussion and planning session with USGS geophysicists to establish field procedures and methods of computation.

2. Gravimeter care and maintenance

   (a) The gravimeter in use shall be maintained "on heat" continuously throughout the field work period. Should a gravimeter "lose heat", the last station observed shall be reoccupied after the meter has been restored to its operating temperature and held at that temperature for a minimum of six hours.

   (b) Gravimeters shall be transported in aircraft-type anti-vibration mounts, either on a crew member's lap, tied to a padded seat, or on a 15 cm foam pad. Every effort shall be made to prevent severe shock or upset of the gravimeter. In the event of a shock, a station observed before the shock shall be reoccupied and the gravimeter read every 15 minutes until three consistent readings are obtained to determine the tare.

   (c) Weekly checking of gravimeter levels and sensitivity shall be performed.

   (d) Meter leveling screws shall be removed and cleaned weekly (daily in dusty conditions).

   (e) At the discretion of USGS geophysicists, gravimeters shall be calibrated over a calibration line provided by USGS before and after field work.

   (f) Should a gravimeter on loan to the contractor by USGS be damaged during the survey, the contractor will be responsible for its repair or replacement.

3. <u>Altimeter care and maintenance</u>

(a) Altimeters shall be transported in padded cases and always shaded from the sun. They shall not be subjected to shocks or upset.

(b) Altimeters shall be inspected daily for overall condition and performance. Instruments suspected of malfuction shall be replaced by backup instruments.

4. <u>Field observations at each station</u>

(a) Gravimeter observations shall be made to the nearest 0.01 mgal.

(b) Altimeter observations shall be made to the nearest meter. Relative humidity and air temperature determinations shall be made.

(c) Maximum standard error for any observed gravity measurement shall be ± 0.25 mgal. Typical standard error should be ± 0.05 mgal or less.

(d) Maximum standard error for any altimetric observation shall be ± 2.0 m.

(e) Station locations shall be pin pricked and identified on 1:50,000-scale photographs or photomosaics. Maximum error in location shall be ± 100 m.

(f) A check system shall be employed during reading of the gravimeter to ensure correct readings. After leveling, gravimeter shall be read, leveling checked, reading checked, temperature read, gravimeter reading checked, gravimeter locked, lights off, gravimeter reading checked. Checks shall be recorded in field note books.

5. <u>Field notes</u>

(a) Field notes shall be recorded in bound notebooks.

(b) Date, operator names(s), survey name, gravimeter identification and page namber shall appear on every page.

(c) At each station, information recorded shall include:

1) Station identification, meter reading and temperature, local time (accurate to ± 1 minute), and gravimeter checks.

2) Method of transport (landrover, helicopter, and so forth).

3) Station description (including sketches) sufficient to exactly reoccupy the station.

4) Terrain description for Hayford-Bowie zones A-C terrain correction estimates.

5) Accuracy of station location on photos or maps.

6) Altimeter readings, air temperature, psychrometric readings, and weather conditions.

7) Any pertinent remarks pertaining to behaviour of gravimeter or altimeters, shocks, and so forth.

(d) Any recopied field data must be accompanied by the originals.

6. Simultaneously with the field work, compilation of a simple Bouger gravity anomaly (SBA) map at a scale of 1:500,000 and Hayford-Bowie zones A-C terrain correction estimates shall be completed. Compilation of the SBA map shall not lag behind the field work by more than 3 days. Important anomalies defined by only one station and steep gradients appearing on the SBA map shall be verified and/or supplemented by additional field work.

7. Coding of the gravity data on computer forms, provided by USGS for the purpose, shall be completed. In addition to station identifications, latitude, longitude, elevation, date, time, and meter reading, this will include estimates of the uncertainty in the observed gravity, horizontal and vertical station location, and Hayford Bowie zones A-C terrain correction.

8. Any loop of stations shall close on a base station within 10 hours.

9. Drift readings will be made at any one spot where a stopover lasts one hour or more. One reading will be made on arrival and one on departure.

10. All base stations and lines will be initiated and terminated on USGS Kingdom Gravity Net stations 16, 17, and 32.

11. All field survey loops will be initiated and terminated on the base lines established in item 10 above.

12. Maximum standard error of closure of any loop after tidal corrections are made shall be ± 0.25 mgal.

13. Except when operating by helicopter, an average gravimeter drift rate greater than 1.5 mgal per month shall necessitate use of a better gravimeter. When the gravimeter is being transported between stations by helicopter, an average drift rate greater than 5.5 mgal per month shall necessitate use of a better gravimeter.

14. Station locations shall be marked by a cairn of stones or other marker so that they can be relocated.

15. During the course of the survey, any station that has been previously established shall be reoccupied, if convenient, in order to further control gravimeter drift. Normally, reoccupation of at least five percent of the total number of stations, approximately evenly distributed over the survey area, will be required.

16. Exchange of observers and/or gravimeters will not be made along any given line or loop.

17. Stations shall always be located so as to minimize terrain corrections.

18. When the survey area includes a portion of or abuts against an existing gravity survey area, a tie to that survey shall be made by exact reoccupation of at least three gravity stations of the existing survey.

19. Documentation shall be provided demonstrating the accuracy of clocks used in the survey to record times of gravimeter and altimeter observations. This documentation shall include comparisons of all clocks used to a suitable time standard such as a broadcast standard time signal (for example, BBC) at a minimum of weekly intervals during the survey period to insure an accuracy of ± 1 minute in all time measurements.

III. SURVEY DOCUMENTATION - to be provided by the contractor, shall be comprised of the following:

A. Field notes

B. Completed coding forms

C. Notes and computations including altimetric reductions, latitude-longtitude measurements, gravimeter drift and calibration, SBA reduction, and any other sheet of paper associated with the survey. All documents shall contain the date and initials of the author on every page.

D. Field compiled SBA maps (1:500,000 scale).

E. Stable base SBA map on transparent material at 1:500,000 scale, including station locations and identification, latitude-longitude grid at five-minute intervals, SBA contours, and labeling information.

F. Original photographs, and/or photomosaics with the station locations used in the field.

G. A brief report describing the progress and details of the project, preliminary interpretation, and any special notes or remarks.

IV. MONITORING PROCEDURES

A. The contractor shall be subject to visits on the job by USGS Geophysicists from time to time for the purpose of evaluation of the quality of the field work, possibly including independent remeasurement of a random sample of stations, and amending the survey work if necessary.

V. MATERIALS, and so forth, to be furnished by USGS

A. Two sets of photographs and photomosaics of the survey area.

B. Two first-order geodetic gravimeters.

C. Available gravimetric data in the survey area.

VI. AMENDMENTS

A. Any portion of the contract shall be subject to amendment by mutual consent of the contractor and USGS.