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CRUSTAL STRUCTURE OF KUWAIT: CONSTRAINTS FROM GRAVITY ANOMALIES

By

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ABSTRACT

Interpretation of free air and Bouguer gravity anomaly maps provide new information about the crustal structure of Kuwait and surrounding areas. A new interactive program for IBM-compatible personal computer (PC) was used to prepare five geologic cross-sections from modeling of gravity profiles. The modeling was constrained by deep boreholes drilled for oil exploration. The cross-sections extend to depths of about 6,000 m, which was sufficient to portray the various Phanerozoic units throughout Kuwait.

The cross-sections provide definition of north to northwest trending anticlinal structures. Examples are the prominent positive anomalies associated with the Kuwait and the Dibdibba arches. These types of flexures had major influence on the accumulation of petroleum in the Arabian Gulf area. Follow-up regional and local geophysical studies, including magnetic, gravity, seismic, electrical, and radiometric surveys, are recommended to further our understanding of the crustal structure of Kuwait.

INTRODUCTION

The State of Kuwait is located in the northeastern part of the Arabian Peninsula at the northwestern end of the Arabian Gulf. Kuwait covers has an area of approximately 17,181 km^2 borders Iraq on the north and west and Saudi Arabia on the southwest (fig. 1). Our objectives were to interpret country-wide gravity anomaly data in order to provide new qualitative and quantitative information about the crustal structure and subsurface geology. For our study, three gravity anomaly maps of Kuwait were prepared, a free-air gravity anomaly map and two Bouguer anomaly maps; the gravity data were reduced at densities of 2.20 g/cm^3 and 2.67 g/cm^3. In addition, five profiles across Kuwait were modeled to enhance interpretation of subsurface structure. Several previous gravity studies of Kuwait relevant to this study have been reported (Bou-Rabee, 1986; Bou-Rabee and Blakely, 1993; and Warsi, 1990.

An interactive program for IBM compatible personal computers (PCs) was used to model the five gravity profiles. The gravity models extend to nearly 6,000 m below the surface and allowed reasonable estimates of depths of Cenozoic, Cretaceous, Jurassic, Triassic and Paleozoic sequences throughout Kuwait. The models provide estimates of depths to key stratigraphic units and a perspective of the structures penetrated by deep boreholes drilled for oil exploration. Shallow wells provided information on depth to the Dammam Formation, a limestone of Late Eocene age, which was used as a reference for modeling of the gravity profiles. The modeling further elucidated major geologic structures which included elongated anticlines and brachyanticlines associated with north to northwest trends of the Kuwait and Dibdibba arches. These flexures and other similar

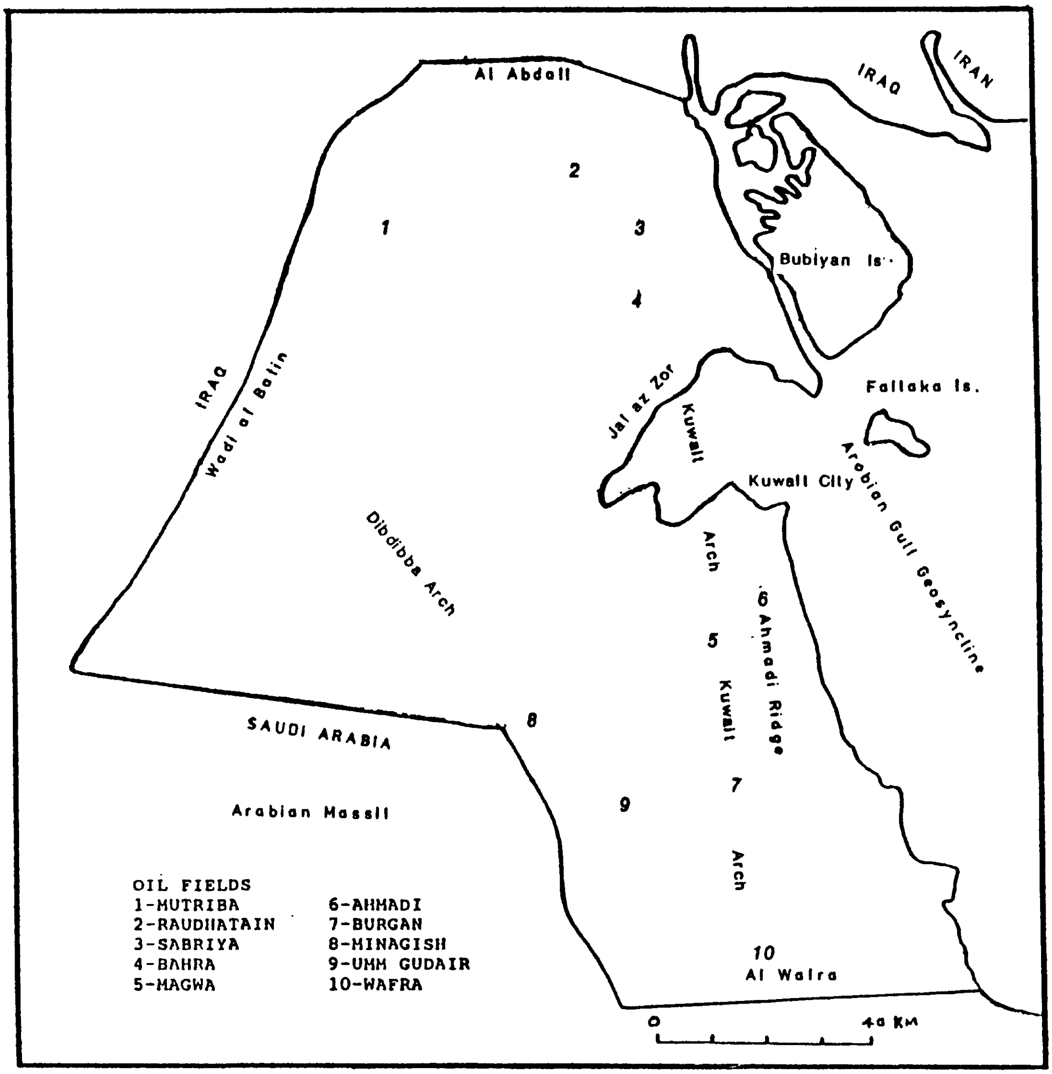


Figure 1. Index map of Kuwait showing geographic names and oil field locations (1-10).

well-known arches, such as the Ghawar arch in Saudi Arabia and the Qatar arch in the United Arab Emirates, had major influence on the distribution of oil fields in the Arabian Gulf region. The structures may have originated from movement of the Hormuz salt of Infracambrian age coupled with reactivation of basement faults (Bou-Rabee, 1986; Warsi, 1990).

GEOLOGY

Kuwait lies on the eastern foreland of the Arabian Shield and on the west flank of the Arabian Gulf geosyncline (fig. 1). The regional dip is to the northeast at about 2 m per km (Bou-Rabee, 1986). This regular dip is interupted by the Kuwait and Dibdibba arches and other smaller structures, which are present at the Raudhatain, Umm Gudair, and Minagish oil fields (fig. 1). These structures are very gentle, and no dips over 3° have been identified. Low dips and similarity of lithology make correlation of rock units difficult. Subsurface information indicates that these structures have been developing almost steadily since Middle Cretaceous time, and they may be as old as Late Jurassic age (Bou-Rabee, 1986). The evidence indicates that the structures have been uplifted due to horizontal compression, especially during pre-Miocene times. The Kuwait arch in the vicinity of Ahmadi ridge, in particular, appears to be the result of horizontal compression in post-Eocene times and is probably related to the Zagros Orogeny (Bou-Rabee, 1986).

Since Triassic time the Kuwait region appears to have occupied an intermediate position between the Arabian Gulf geosyncline to the northeast and the Arabian massif to the southwest. Rocks ranging in age from Eocene to Recent are exposed within the boundaries of Kuwait. Drilling has shown that the region is underlain by about 6,000 m of sedimentary rocks. Ages range from Triassic to Pleistocene, including up to 1,500 m of Jurassic strata, up to 3,300 m of Cretaceous strata, and up to 1,500 m of Eocene strata.

The stratigraphic column for this report is shown in figure 2. The Miocene-Pleistocene sedimentary section is represented by arenaceous beds with an areally localized and vertically limited evaporite beds of middle Miocene age. The evaporites thin to the southwest toward the desert of Iraq and pinch out in north Kuwait. The Eocene section is represented by a limestone sequence broken by a thin but very widespread anhydrite interval. The top of the Dammam limestone proved to be a reliable horizon to use as a reference for the gravity modeling (fig. 3).

Upper Cretaceous rocks are predominately limestone with subsidiary marls and thin shales. This lithology continues into the upper part of the Middle Cretaceous section. The lower part of the Middle Cretaceous and most of the Lower Cretaceous is predominately sandstone, with intervening shale horizons, and at least two well-developed limestones. The sand content of this

SYSTEM	SERIES	STAGE	GP.	FORMATION	LITHOLOGY	THICKNESS (FT.)
	RECENT		KUWAIT	SURFICIAL DEPOSITS		
	PLEISTOCENE			DIBDIBBA		150-1200
TERTIARY	PLIOCENE MIOCENE			LOWER FARS		
				GHAR		
	OLIGOCENE	LUTETIAN	HASA	DAMMAM		600-800
	EOCENE	YPRESIAN		RUS		350-450
	PALEOCENE	THANETIAN MONTIAN		RADHUMA		1500-1800
CRETACEOUS	UPPER	MAAS-TRICHTIAN	ARUMA	TAYARAT		660-1150
				QURNA		60-285
		CAMPANIAN		HARTHA		0-900
				SADI		30-1080
		SANTONIAN		KHASIB		100-850
		CENOMANIAN	WASIA	MISHRIF		0-255
				RUMAILA		0-460
				AHMADI		165-420
				WARA		0-220
	LOWER	ALBIAN		MAUDDUD		0-430
				BURGAN		915-1250
		APTIAN	THAMAMA	SHUAIBA		135-360
		BARREMIAN		ZUBAIR		1161-1480
		HAUTERIVIAN VALANGINIAN		RATAWI		320-590 275-695
		BERRIASIAN		MINAGISH		535-1170
				MAKHUL		400-900
JURASSIC	UPPER	TITHONIAN		HITH		230-960
		KIMMERIDGIAN		GOTNIA		800-1400
		OXFORDIAN CALLOVIAN		NAJMAH		200-350
	MIDDLE	BATHONIAN BAJOCIAN		SARGELU		850-950
	LOWER	TOARCIAN		MARRAT		1900-2000
TRI-ASSIC	UPPER	RHAETIAN CARNIAN		MINJUR		850-1100
	UPPER MIDDLE	LADINIAN AHISIAN		JILH		1200-1600
PER-MIAN	L. TRIASSIC U. PERMIAN	SCYTHIAN TATARIAN		SUDAIR		500-650
	PERMIAN	KAZANIAN		KHUFF		1500-2000

Figure 2. Regional stratigraphic chart showing ages of sedimentary rock units ranging from Permian to Recent. Sources of data are Kuwait Oil Company, Arabian American Oil Company, Arabian Oil Company, and Getty Oil Company.

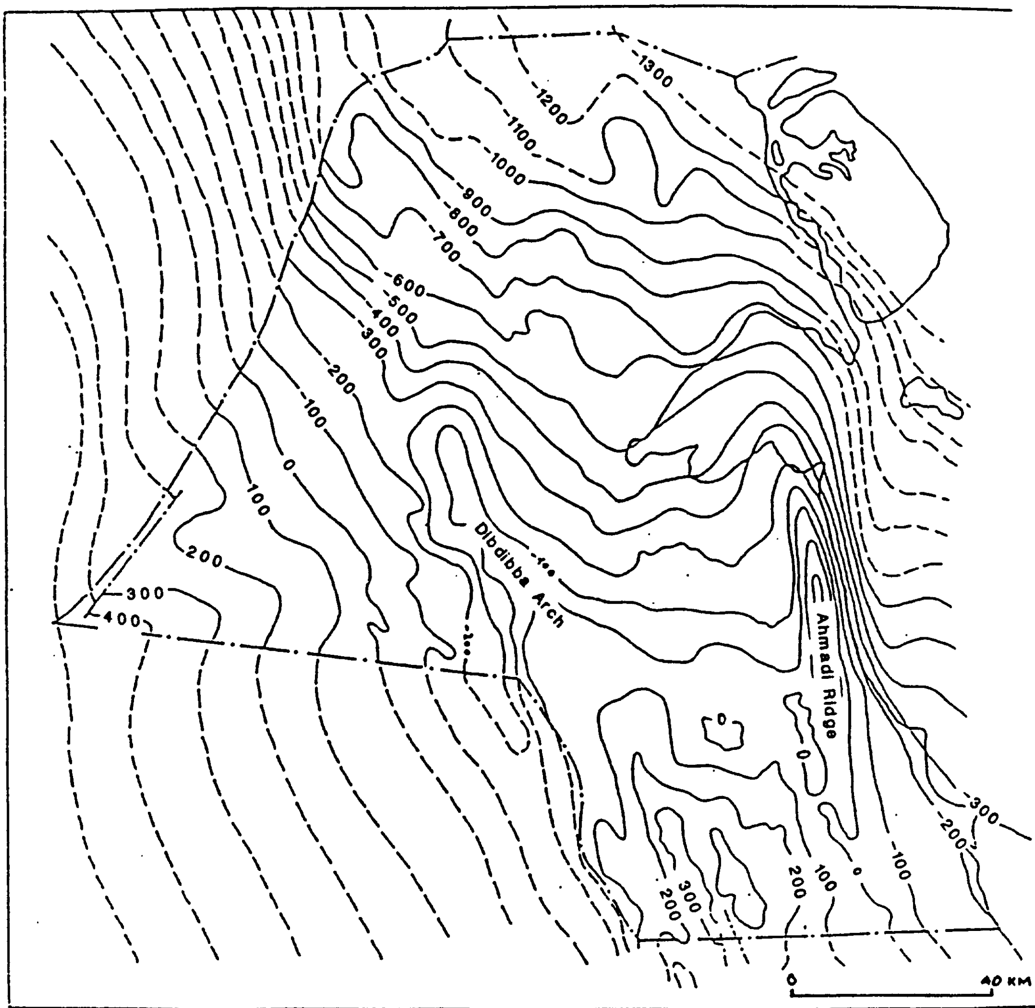


Figure 3. Map of Kuwait showing structural contours on top of Dammam Formation. Contour interval 100 ft (30 m).

sequence increases substantially southward toward Burgan (fig 1), where it becomes approximately 75 percent of the section. In northern Kuwait, sandstone comprises only 30 percent of the Middle Cretaceous rocks. The lowermost part of the Lower Cretaceous is represented by a limestone and shale sequence. The Jurassic rocks in southeastern Kuwait are predominantly limestone with a thick (400 m) anhydrite-salt-evaporite unit. Sedimentary rock of probable Triassic age are composed of shales and sandstones.

A major break in the above succession occurred during late Eocene and Oligocene times, with a possible minor break in Early Cretaceous (pre-Maestrichtian), and another clearly recognized break at the end of the Middle Cretaceous (Post-Cenomanian-Turonian). All intervals above Middle Cretaceous rocks show a progressive thinning across the crest of drilled structures in Kuwait, indicating that nascent folding and uplift has persisted since that time. Because no well has yet penetrated the Paleozoic in Kuwait, Paleozoic stratigraphy is poorly understood. Below the Sudair Formation (Triassic age), the Khuff Formation of Permian age (fig. 2) consists of 460-610 m of limestone with some clastic to carbonate shelf deposits (Murris, 1980). A description of Triassic through Cenzoic aged rocks is summarized in the appendix.

TOPOGRAPHY

Kuwait has a desert topography of low to moderate relief (fig. 4). The gently undulating topographic surface rises gradually from the shore of the Arabian Gulf toward the southwest. Elevations range from sea level at the shoreline to about 300 m at the extreme southwestern corner of the State. The Jal az Zor escarpment is the most significant topographic feature; other features include the Ahmadi ridge paralleling the east coast of Kuwait, small hills at the Burgan field, and the valley of Wadi al Batin along the western border (fig 1.). The Jal az Zor escarpment has a remarkably straight course. The local relief reaches about 130 m, and the base of the scarp is covered by loose sediments sloping uniformly toward the bay (Milton, 1967). The escarpment appears to correspond to subsurface structure, and its straightness suggests an origin related to faulting (fig. 4). The linear depression of Wadi al Batin, with an average width of 8 to 11 km and relief as great as 70 m, also may reflect deep-seated faulting.

In the northern and western parts of Kuwait the surface is covered by widespread gravel deposits. Parallel gravel-capped ridges trend northeastward and, although only a few meters in altitude above the general level of the surface, are very conspicuous and characteristic features of this area. Apart from the hills and ridges mentioned earlier, the southeastern quarter

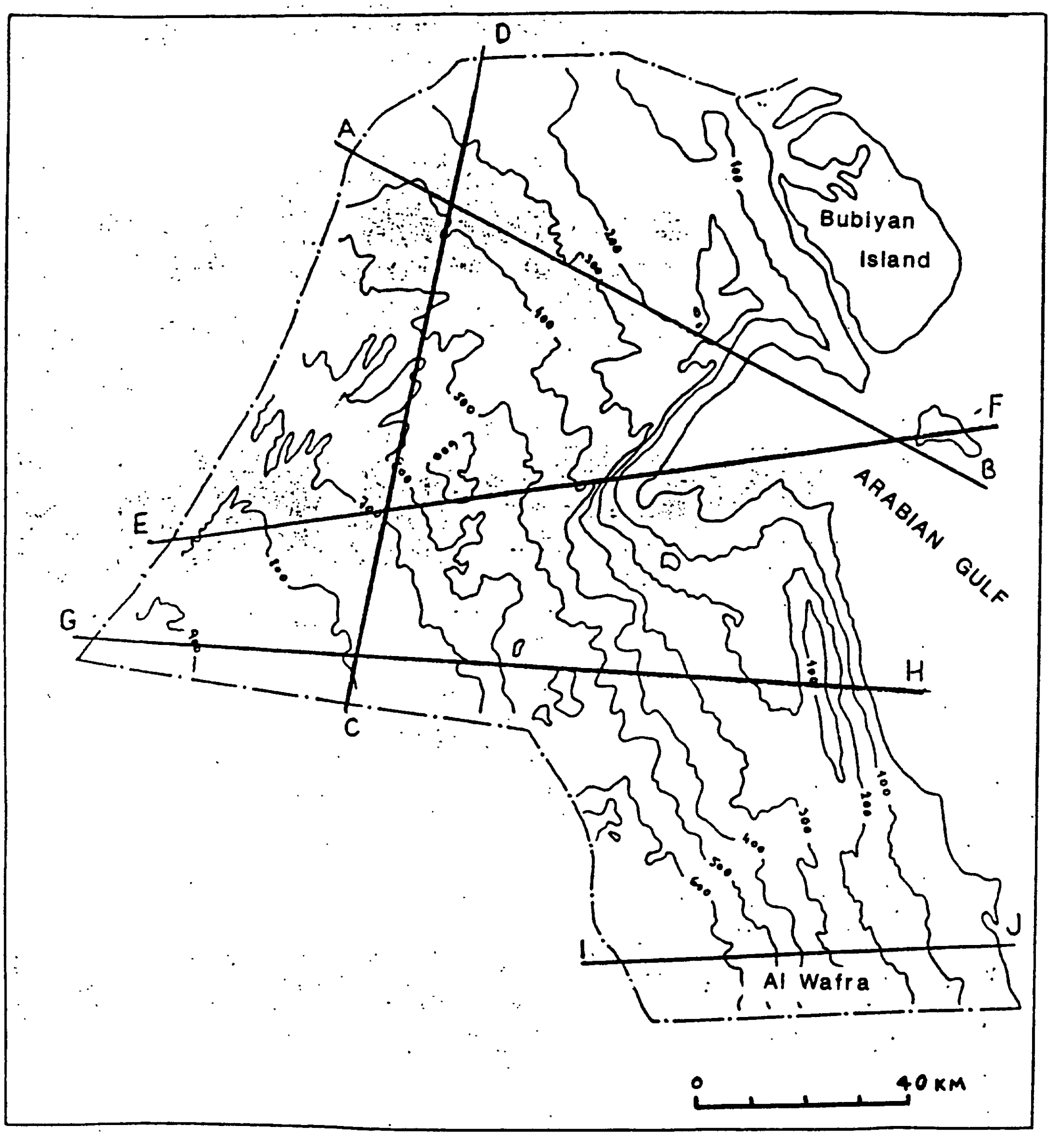


Figure 4. Topographic map of Kuwait with locations of gravity profiles and geologic cross sections from modeling. Contour interval 100 ft (30 m).

of Kuwait is low-lying and nearly flat. Northeastern Kuwait has low-lying muddy shores and several offshore islands, the largest of which is Bubiyan Island. This area is believed to be the site of deltaic and estuarine deposition by the Tigris-Euphrates River system (Milton, 1967). None of the islands, which at the surface are mainly silt and clay with some wind blown sand, rise above 3 m in elevation. Surrounding these islands are areas of extensive mud flats.

INTERPRETATION OF GRAVITY ANOMALY DATA

Information about crustal structure and subsurface geology of Kuwait was obtained from interpretation of Bouguer and free-air gravity anomaly maps and from geologic cross sections derived from modeling of five gravity profiles that extend across the State. The basic data are from gravity measurements taken at 1,574 locations in Kuwait. Distribution of observations is relatively close spaced along roads and trails. However, most parts of Kuwait are adequately covered for the purposes of this study (fig. 5).

Free gravity air anomaly map

The Free-air gravity anomaly map principally reflects the topography of the study area (fig. 6). Intensities range from -36.0 to less than 1.0 mGal and generally increase both southward and westward. The Wadi al Batin and Jal az Zor escarpment are well expressed in the map. The Ahmadi ridge is expressed as a steep gradient along its eastern flank. Near Wafra, a gravity high may reflect a small anticline on the west flank of the Kuwait arch.

Bouguer gravity anomaly maps

Two Bouguer gravity anomaly maps of Kuwait were prepared using reduction densities of 2.20 g/cm^3 and 2.67 g/cm^3 and (figs. 7 and 8). Because of the relatively low topographic relief, no terrain corrections were made. For this study, we selected the map reduced at a 2.67 g/cm^3 density as most representative of the average crustal density. For detailed studies of near surface sources, it can be argued that a lower reduction density is more appropriate since the surface sedimentary rocks (i.e., the Kuwait Group) have densities of about 2.20 g/cm^3 (fig. 2). However, a comparison of the two maps reduced at 2.67 g/cm^3 and 2.20 g/cm3 show that the position and shape of Bouguer anomalies are nearly identical since most of the topography of Kuwait is subdued.

Intensities of the Bouguer anomalies reduced at 2.67 g/cm^3 vary from -46 mGal in the northern part of the State near the Iraq border to -16 mGal in eastern Kuwait (fig. 8). The gravity field is dominated by two elongated positive anomalies separated by a deep gravity depression.

The most significant feature of the gravity field is the broad gravity high (labeled A) which appears to be related to an

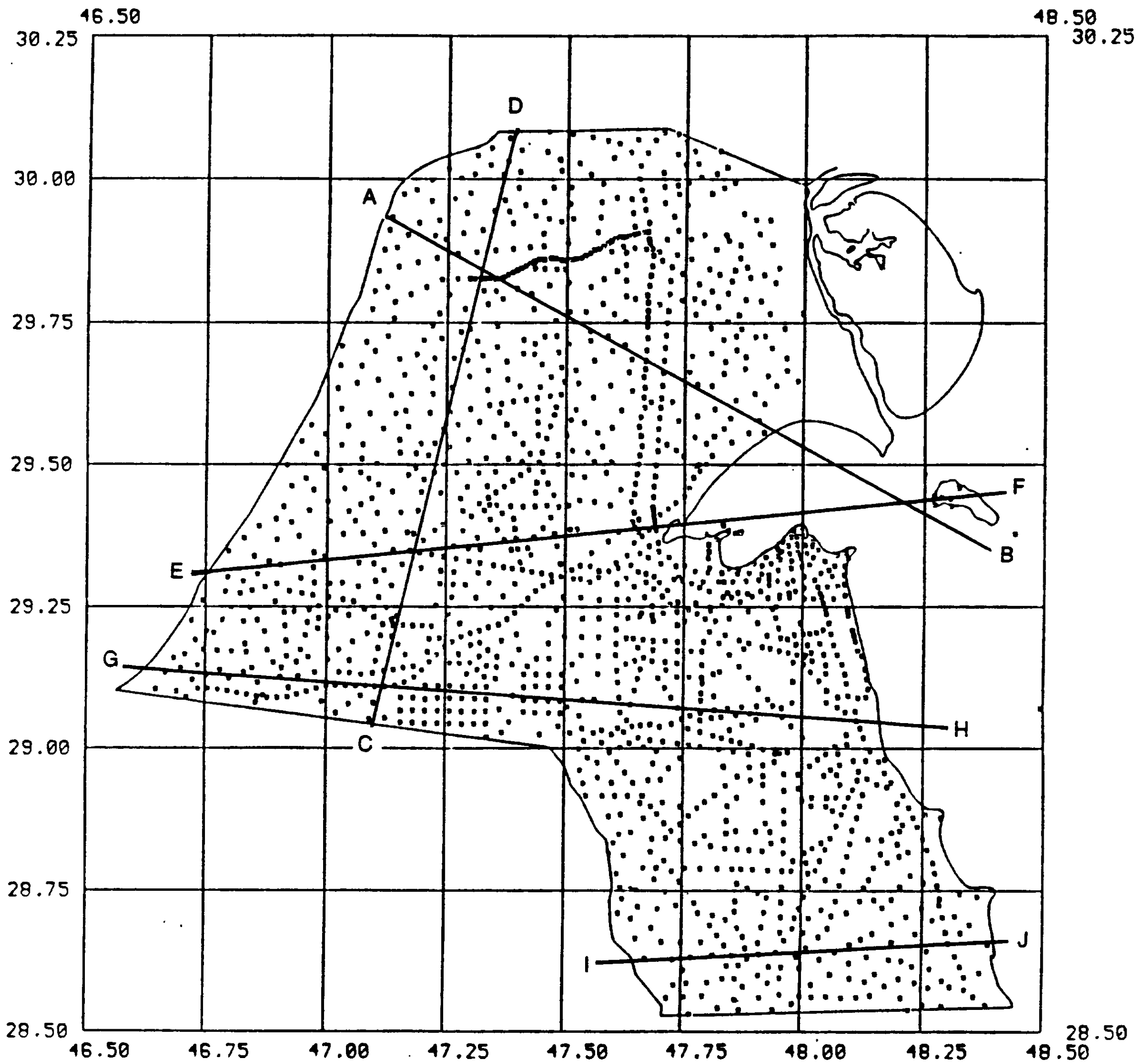


Figure 5. Locations of gravity measurements in Kuwait and positions of gravity profiles and geologic cross sections from modeling. Grid in 0.5 degree units of north latitude and east longitude.

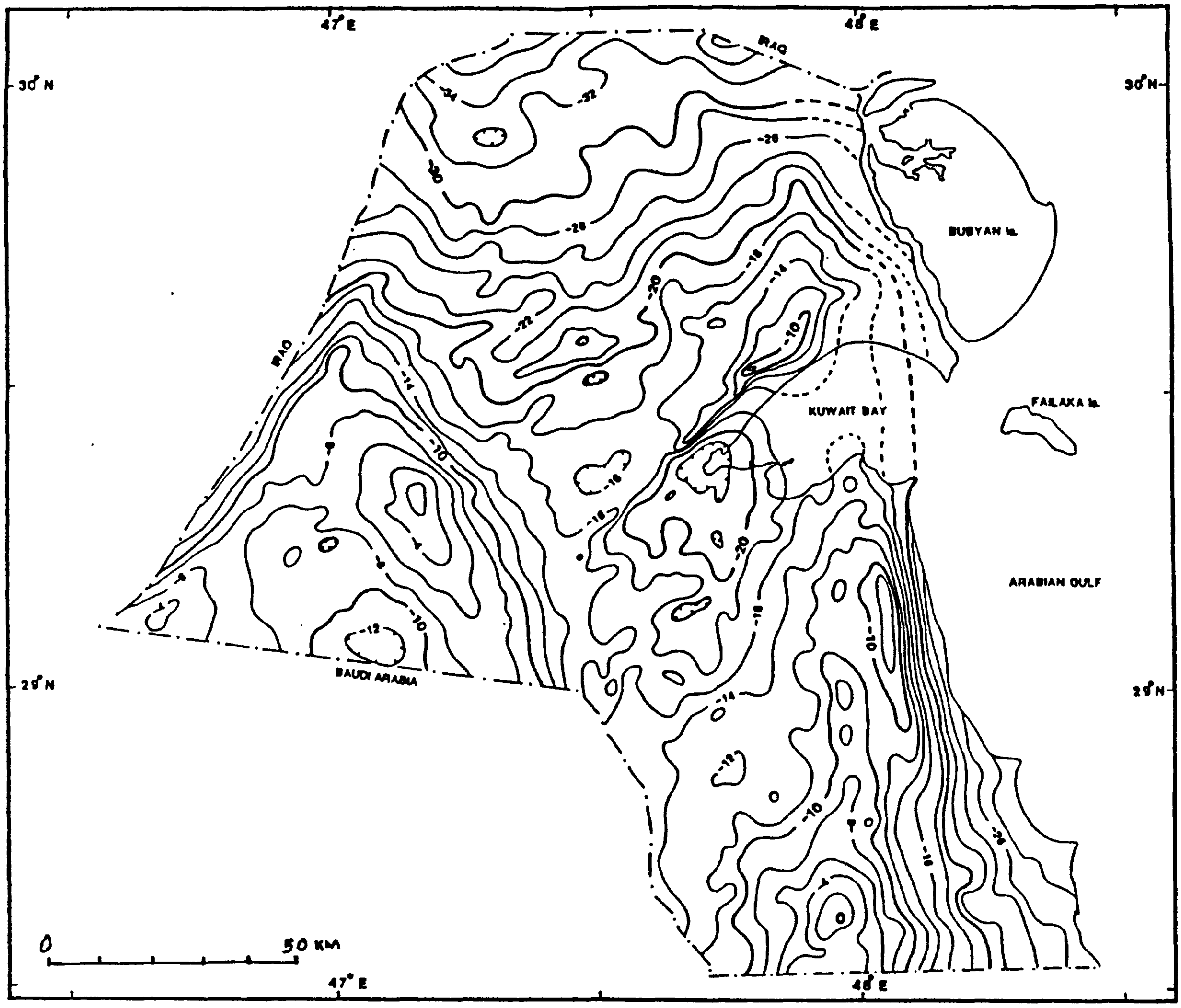


Figure 6. Free air gravity anomaly map of Kuwait. Contour interval 1 mGal (modified after Warsi, 1990).

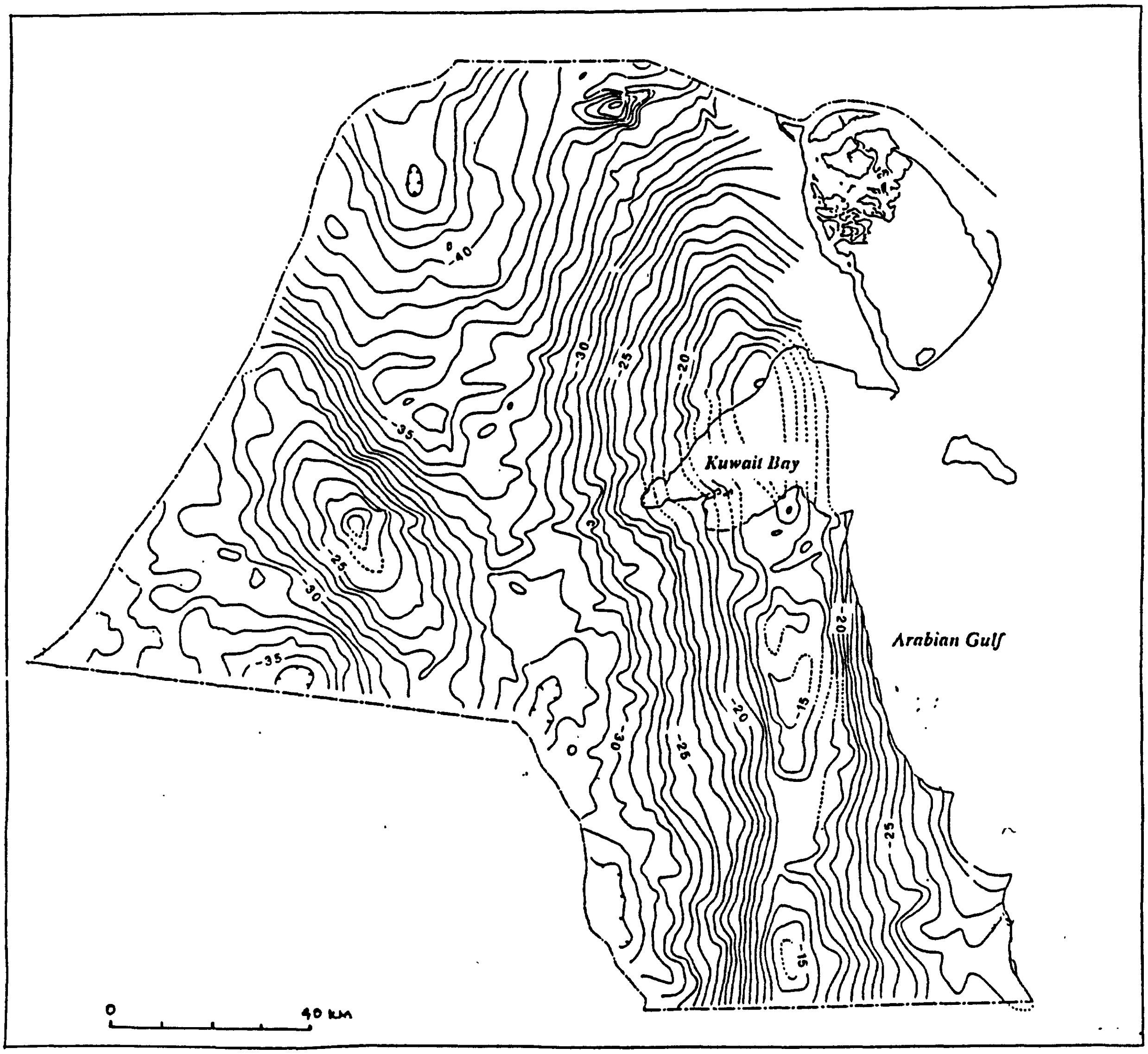


Figure 7. Bouguer gravity anomaly map of Kuwait. Reduction density 2.20 g/cm^3. Contour interval 1 mGal.

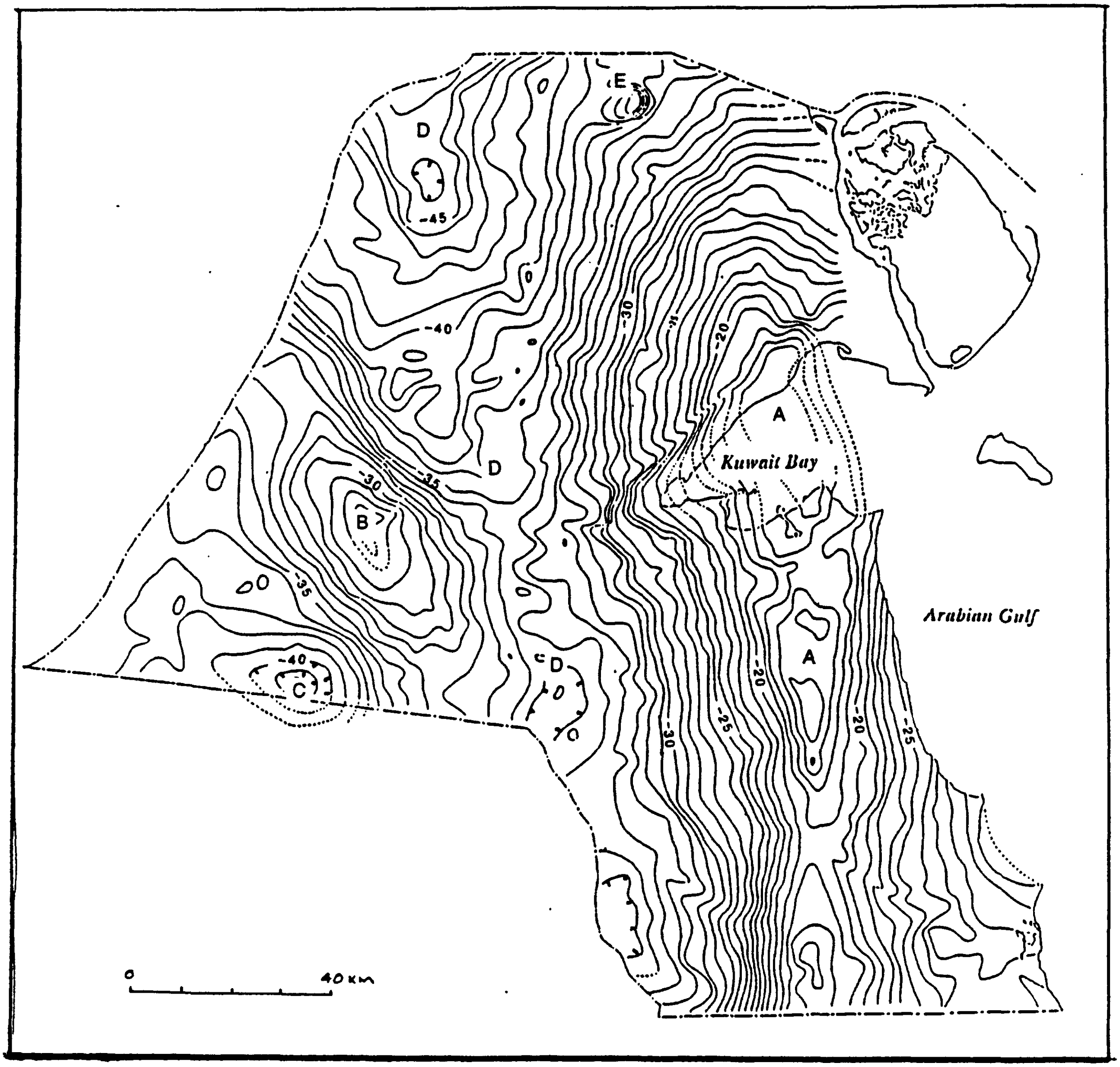


Figure 8. Bouguer gravity anomaly map of Kuwait. Reduction density 2.67 g/cm^3. Contour interval 1 mGal. A - E: Locations of gravity anomalies discussed in text.

asymmetrical north-south brachyanticline or perhaps a series of anticlinal structures which make up the Kuwait arch. This anomaly strikes north-south and broadens to the north. It extends for about 175 km across Kuwait Bay and into northeastern Kuwait where its source plunges beneath increasing thicknesses of sedimentary rocks. An important characteristic of this positive anomaly is that its maximum axis, although nearly parallel, does not follow the topographic relief of Ahmadi ridge, but is shifted nearly 10 km to the west.

Another prominent positive anomaly (labeled B) in the southwestern part of Kuwait, referred to as the Dibdibba arch (Warsi, 1990), has a maximum value of -27 mGal and lateral extent of about 75 km. From previous modeling this anomaly was attributed to a major brachyanticline elongated northwest-southeast (Bou-Rabee, 1986). South-southwest of the northwest trending Dibdibba positive anomaly, a gravity low (labeled C) in southwest Kuwait suggests the presence of a small basin of low-density sedimentary rocks that may extend into Saudi Arabia. To the east, the Dibdibba anomaly is separated from the larger positive anomaly associated with the Kuwait arch by a gravity trough (labeled D). This wedge-shaped north-northwest trending trough is caused by an intervening sedimentary basin. The basin widens and deepens to the north with gravity intensities generally decreasing from south to north in response to a combination of the gentle northeasterly dipping crystalline basement and the increasing northeasterly thickening of low-density sedimentary rocks of the Kuwait Group. In northern Kuwait, just southwest of Abdali, the source of a distinctive negative anomaly (labeled E) with several closed contours is unknown.

The Bouguer anomalies show no evidence of anomalous mass beneath Wadi al Batin, which suggests that this valley is not controlled by structure, or that, if a fault is present, it juxtaposes lithologies of little or no density contrast.

We propose that the Jal az Zor escarpment anomaly is an expression of a strike-slip fault that may have accommodated movement of small crustal plates, and that movement on the proposed strike-slip fault may have caused the opening of Kuwait Bay. Northeast-trending subsurface faults found in Kuwait Bay support this hypothesis (Bou-Rabee, 1986).

Gravity modeling

Geologic cross sections were made from computer modeling of gravity profiles that extend across Kuwait (figs. 4 and 5). The cross-sections are modeled to depths of nearly 6,000 m, which is sufficient to portray Middle to Upper Paleozoic and Mesozoic sequences throughout Kuwait. Due to a lack of density measurements, estimated density values were assigned in the modeling and are considered only a first approximation. Densities values used for this study were estimated on the basis of rock types, probable pressure and temperature, and depth of burial. Future investigations should include compilation of rock densities obtained from measurements of drill hole core samples and from borehole density logs.

The modeling was done using a 2.5-dimensional gravity computer program based on the formulation of Rassmusen and Pedersen (1979). Since the stratigraphic units are sub-horizontal for long distances, the models are essentially two-dimensional. Unfortunately little is known about the rocks below 2 to 5 km. One proprietary borehole drilled in the Burgan area reportedly reached the contact between Cretaceous and Jurassic beds at a depth of 2,910 m, the top of Triassic at 4,410 m, and bottomed at 4,620 m. The contact between the Kuwait Group and the Dammam Formation was established on the basis of well data and structure on top of Dammam Formation (fig. 3). Other depth information used to adjust the sections was taken from reports that discuss the crustal geology of Kuwait (Owen and Masr, 1958; Milton, 1964).

Calculated geologic cross sections

The geologic cross-sections were derived from modeling five gravity profiles, A-B, C-D, E-F, G-H, and I-J (figs. 9-13). The results provide qualitative and quantitative information, such as dimensions of structures and depths to key beds found in anticlines or brachyanticlines, such as those associated with the Kuwait arch and Dibdibba arch (fig. 1). Approximate depths picked to marker beds at specified km distances along each geologic cross section are listed in the text. Profile A-B This profile extends for 130 km from the northwest part of Kuwait southeastward across Kuwait Bay to Failaka Island (fig. 9). Bouguer gravity anomaly intensities along this profile increase from -46 mGal at its northwestern end to a maximum of -16 mGal over Kuwait Bay. The geologic cross-section shows a gently undulating stratigraphy. Maximum sedimentary rock thickness occurs at distance 15 km along the profile where the Kuwait Group has a thickness of about 300 m. The base of the Dammam Formation was modeled at 800 m, the base of the Rus Radhuma Formation is at 1,850 m, Cretaceous beds bottom at 3,050 m, and Jurassic-Triassic beds extend to depths of 5,300 m. Continuing to the southeast along the profile at 80 km, the thicknesses decreases over the Kuwait arch, a prominent gravity high. Depth values modeled are 120 m for the Kuwait Group, 300 m for the Dammam Formation, 550 m for the Rus and Radhuma Formations, 1550 m for Cretaceous beds and 3,600 m for the Jurassic-Triassic beds.

Profile C-D This profile extends approximately north - south with a length of 120 km (fig. 10). Gravity anomaly intensities along the profile include a negative anomaly of -40 mGal near the Saudi Arabia border, a positive anomaly associated with the Dibdibba arch (-28 mGal), and a negative anomaly near the Iraq border (-46 mGal). The depths modeled at the base of key stratigraphic horizons of the Dibdibba arch, at 40 km distance along the profile, are as follows: Kuwait Group 150 m, Dammam

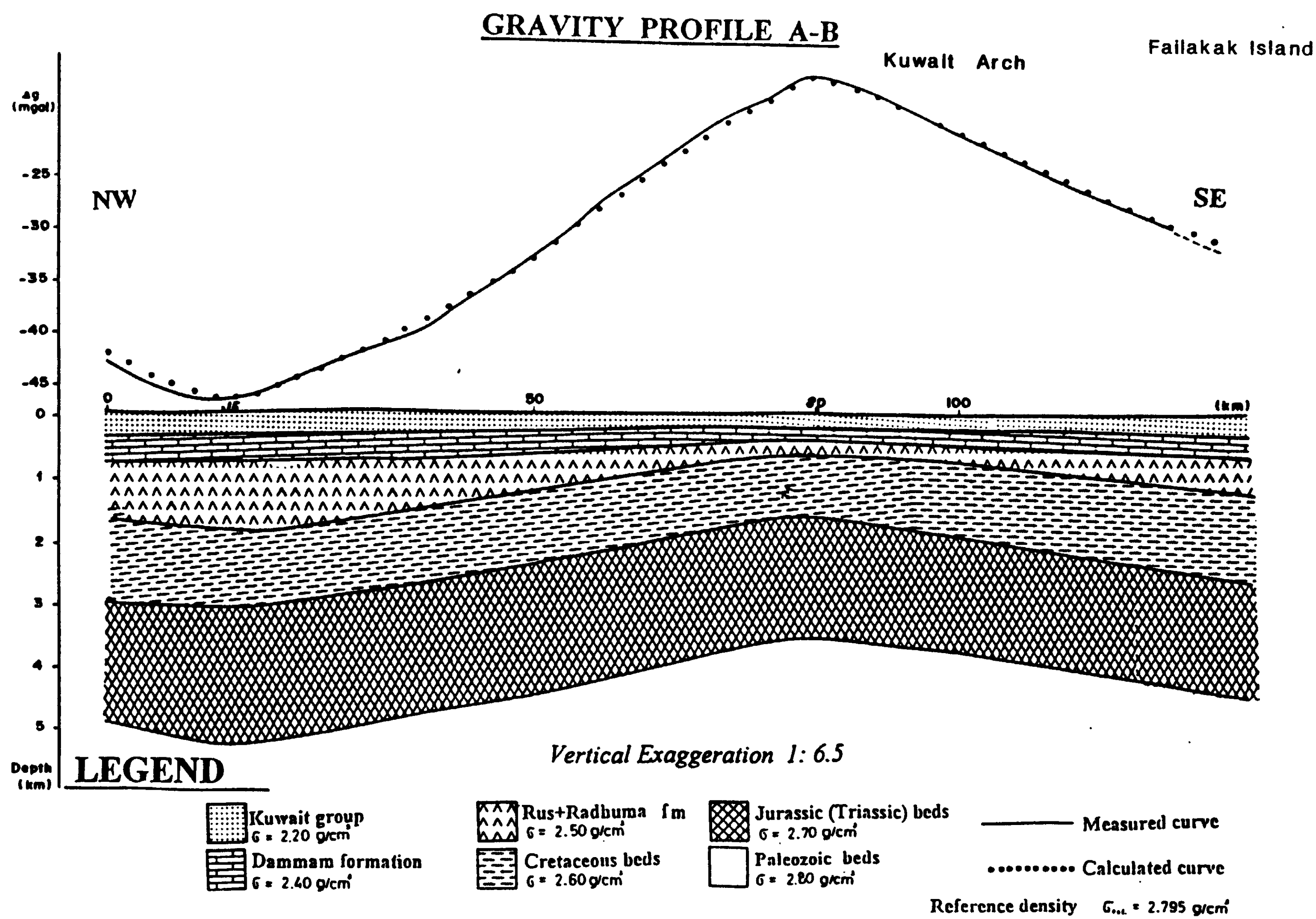


Figure 9. Bouguer gravity profile A-B and modeled geologic cross section.

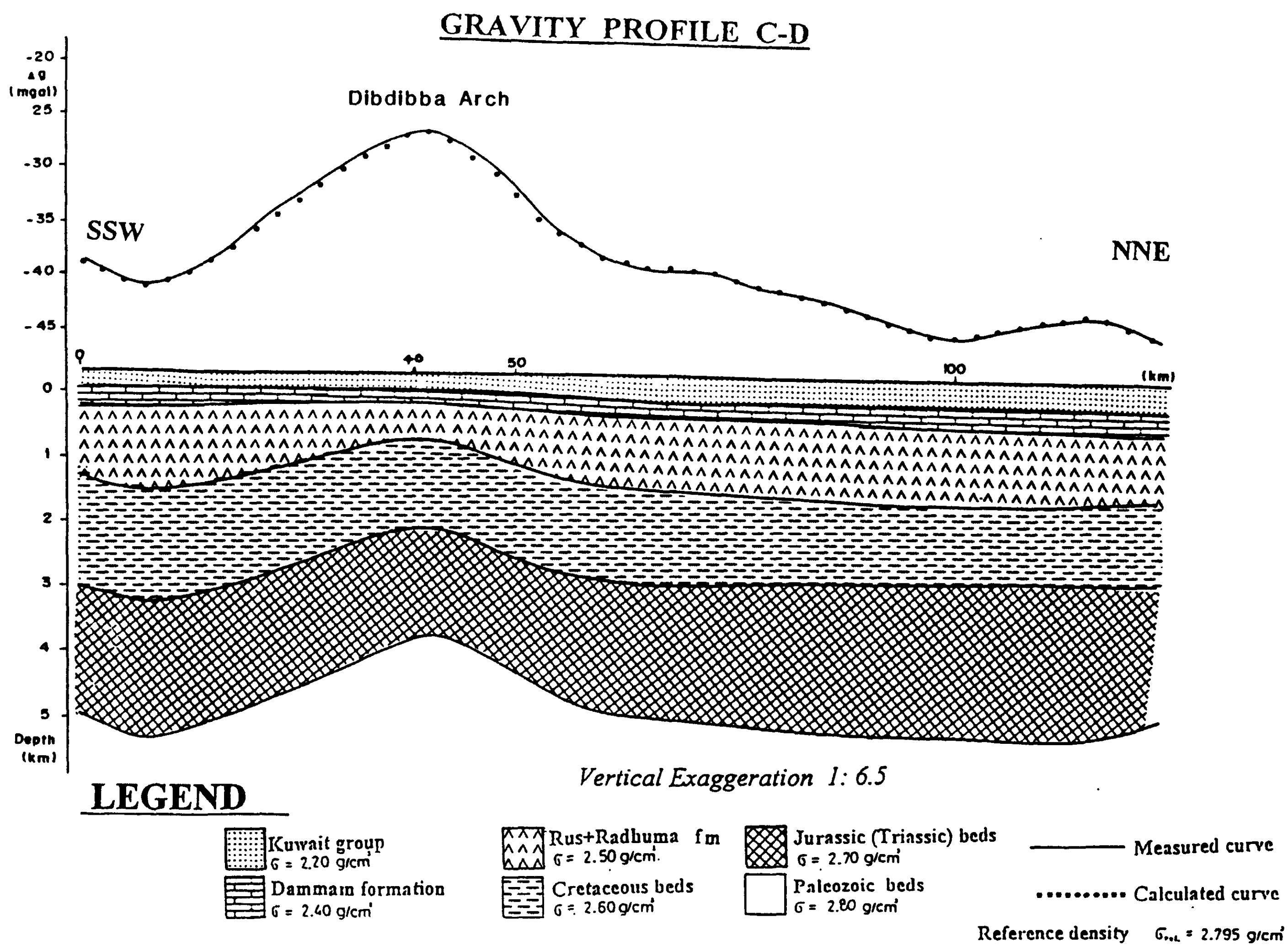
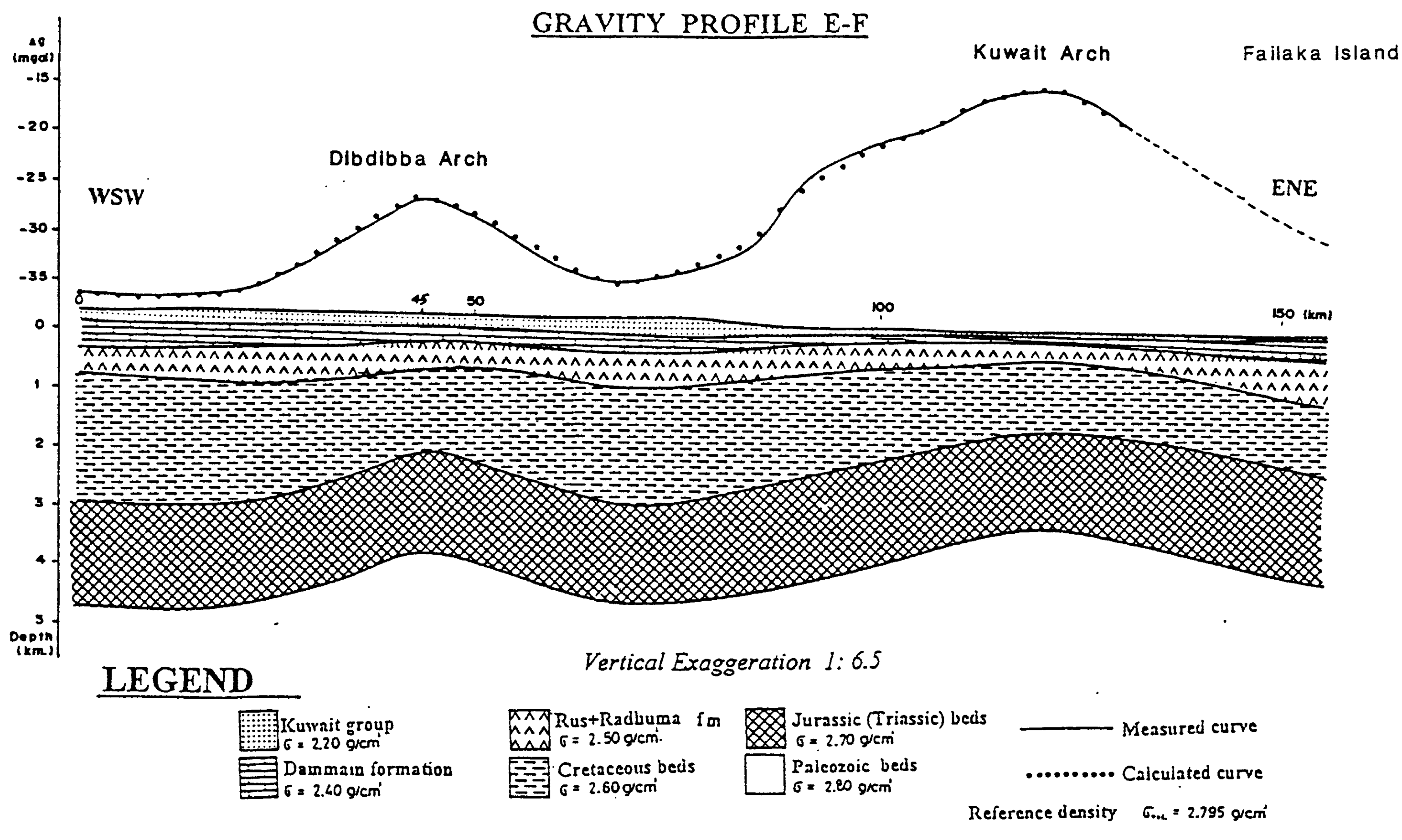
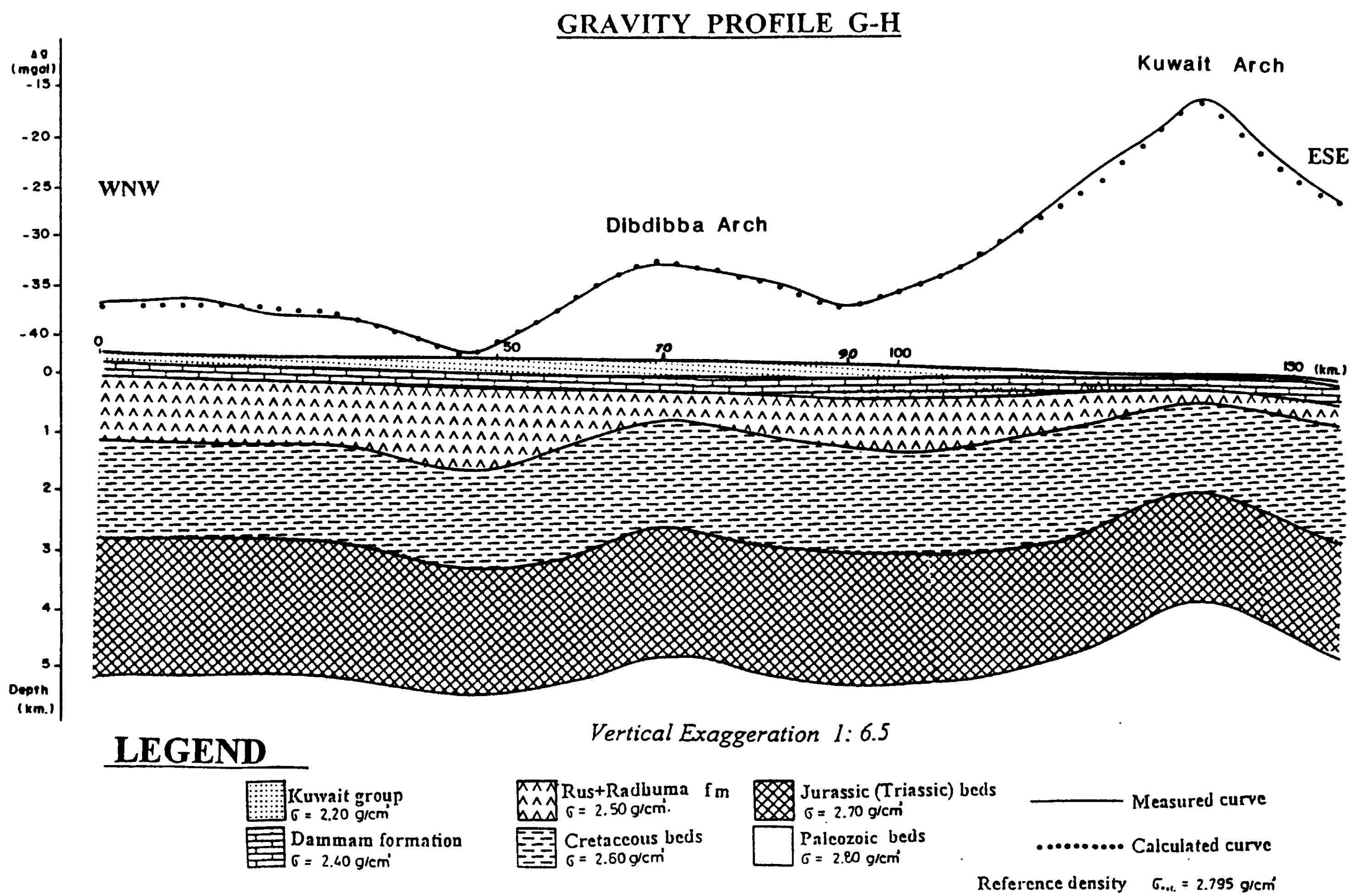


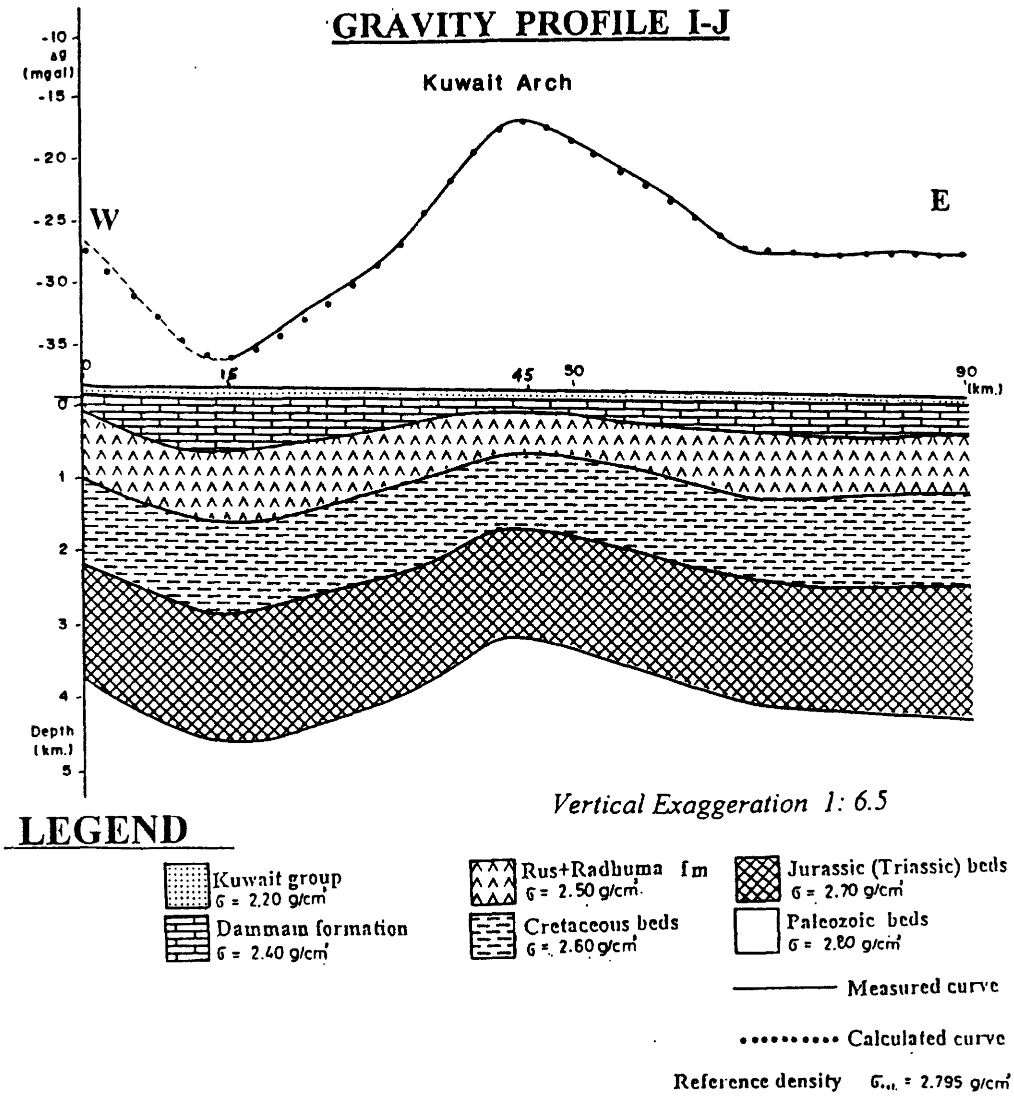
Figure 10. Bouguer gravity profile C-D and modeled geologic cross section.



11. Bouguer gravity profile E-F and modeled geologic cross section.



12. Bouguer gravity profile G-H and modeled geologic cross section.



13. Bouguer gravity profile I-J and modeled geologic cross section.

Formation, 400 m, Rus and Radhuma Formations, 900 m, Cretaceous beds, 2,350 m, and Jurassic-Triassic beds, 4,050 m. To the north t 100 km along the profile, these values increase to 400 m, 700 m, 1,900 m, 3,600 m and 5,450 m, respectively.

Profile E-F The longest profile E-F, extends approximately 155 km to the east-northeast (fig. 11). It starts at Wadi al Batin, crosses the positive anomaly associated with the Dibdibba arch, the gravity trough to the east of the arch, the positive anomaly associated with the Kuwait arch beneath Kuwait Bay, and ends near Failaka Island. Intensity values range from -37 mGal at the beginning of the profile to -16 mGal over Kuwait Bay. The depth of the Dammam formation decreases from 600 m near the Iraq border to 400 m beneath the positive anomaly associated with the Dibdibba arch at about 45 km along the profile (Bou-Rabee, 1986). The depth again increases to 700 m at the gravity trough in the central part of the profile (70 km distance). Beneath the maximum values of gravity, the depth of the Dammam Formation decreases to 220 m. The top of Cretaceous beds occur at 1,000 m, 850 m, 1,200 m, and 500 m, at distances along the profile of 0, 45, 70 and 120 from the Iraq border. The depth values of the base of the Cretaceous are 3,200 m, 2,250 m, 3,150 m, and 1,800 m. The depth values of the base of Jurassic-Triassic beds are 5,000 m, 3,950 m, 4,900 m, and 3300 m, at the above distances along the profile.

Profile G-H This profile is 155 km long and trends from west to east across Kuwait (fig. 12). It extends from an area of low gravity intensity near the Saudi Arabia border, across the southeast end of the positive anomaly associated with the Dibdibba arch at 70 km, and to a maximum of -15 mGal over Ahmadi ridge. The depth of the Kuwait Group from west to east along the geologic section is, 150 m at 50 km, 270 m at 70 km, 215 m at 90 km. Kuwait Group rocks have been eroded away at the top of Ahmadi ridge where the underlying Dammam Formation is exposed. At the east end of the section, the thickness of the Kuwait Group is estimated to be 50 m. From the west-southwest end at distances of 0 km, 50 km, 70 km, 90 km, 135 km, and 150 km along the profile, the depths to the base of Dammam Formation were modeled to be 400 m, 530 m, 450 m, 600 m, 190 m, and 430 m. At the same locations along the profile, the top of the Cretaceous is estimated to be 1,530 m, 1,900 m, 930 m, 1,420 m, 330 m, and 700 m. The base of the Cretaceous picked at the same points along the profile were 50 m, 3,600 m, 2,730 m, 3,200 m, 1800 m, 2,700 m, and the base of Jurassic-Triassic is estimated to occur at depths of 5,450 m, 5,730 m, 4,850 m, 5,430 m, 3,700 m, and 4,700 m.

Profile I-J This profile is 90 km long and crosses the Wafra area from west to east across the southern part of Kuwait (fig. 13). Bouguer gravity anomaly values range from -36 mGal on the west to -27 mGal at the coast. The main feature of this profile is the positive anomaly which is the continuation of the main south-north elongated positive anomaly associated with the Kuwait arch. The top of Dammam was found at a depth of about 150 m in the western part and decreases eastward to 70 m near the coast. Depth were picked along the section from west to east at 0, 15, 45, and 90 km. The depth of the base of Dammam Formation taken at the above distances are as follows: 500 m, 1,000 m, 400 m, and 500 m. Depths to the top of the Cretaceous are 1,200 m, 1,900 m, 900 m, and 1,300 m. Depths to the base of the Cretaceous are 2,400 m, 3,150 m, 1,800 m, and 2,500 m. The base of Jurassic-Triassic was picked at depths of 3,850 m, 4,950 m, 3,300 m and 4,300 m.

CONCLUSIONS AND RECOMMENDATIONS

This report describes qualitative and quantitative interpretations of gravity anomaly data for Kuwait, which adds to our knowledge of the crustal structure and regional geology of the country and its surroundings. For the first time, geologic cross sections across Kuwait have been calculated from gravity modeling. The result has been to enhance our interpretations of the stratigraphy and structure of the upper 5-6 km of the crust. Physical property data is not yet available and could only be approximated. Hence our interpretations should be considered as a first step. The interpretations provide greater detail about the structure and stratigraphy of geologic features associated with the Kuwait and Dibdibba arches. These structures are primarily elongated anticlines with northern or northwestern trends and are typical of structures associated with important oil fields in the Arabian Gulf area.

The top-priority geophysical investigation which we recommend is a new aeromagnetic survey of Kuwait of sufficient resolution to 1) provide information about depth of burial, structure, and petrology of the Precambrian crystalline basement and 2) further refine our understanding of the lithology and structure of layered stratigraphic rocks that occur above the basement complex. In addition, in some areas, detailed gravity measurements, 3-6 observations per km^3, are warranted, particularly, the area of the Jal az Zor escarpment. Improving knowledge of the tectonic origin of this escarpment and the structure at Wadi al Batin are important elements of the crustal studies of Kuwait. The small negative anomaly near Abdali should be verified with additional gravity control. Future gravity and magnetic surveys and interpretations must be supported by measurements of density and magnetic susceptibility of both exposed and drilled rock units. Paleomagnetic investigations also should be evaluated as an aid to studying the geologic evolution of the region. Other geophysical investigations, including seismic, electrical, and radiometric measurements, are recommended for follow-up studies in our continuing effort to better understand the crustal structure and stratigraphy of Kuwait, and for applications in geologic hazards and environmental problems.

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APPENDIX

Thicknesses and depths to tops of stratigraphic units are given to the nearest 5 m and should be considered approximate.

TRIASSIC SYSTEM

A complete section of Triassic rocks has been penetrated by a few wells in northern and southern Kuwait. The section is represented by three known formations: the Sudair, Jilh, and Minjur Formations.

Sudair Formation. The Sudair Formation ranges in thickness from about 465 m in the north to about 380 m in the south. Lithologically, the Sudair is composed of gray to brown, moderately hard, microcrystalline, argillaceous, dolomitic limestone, with shale.

Jilh Formation. The thickness of the Jilh Formation ranges from about 300 m in the south to about 240 m in northern Kuwait. The Jilh is divided into two units, a lower unit of argillaceous dolomite, with soft chalky white anhydrite, calcareous gray-green fissile to sub-fissile shale, and a thick bed of anhydrite; an upper unit similar to the lower but without the thick layer of anhydrite.

Minjur Formation. The Minjur Formation ranges in thickness from about 290 m in southern Kuwait to about 300 m in northern Kuwait. The Formation consists of littoral continental sandstone with minor thickness of conglomerates and shales representing a major regression at the end of the Triassic.

JURASSIC SYSTEM

Five formations of Jurassic age have been penetrated by wells. The total thickness of the Jurassic rocks varies from 1215 m to 1300 m. This variation in thickness is attributed mainly to the presence of evaporites within the Upper Jurassic Gotnia Formation. The general thickening of this sequence is toward the east-northeast.

Marrat Formation The thickness of the Marrat Formation, the lowest of these beds, ranges from about 580 m in southern Kuwait to about 610 m in northern Kuwait. The Marrat consists of upper and lower units of limestone and dolomite.

Sargelu Formation The Sargelu Formation consists of dark gray, calcareous, carbonaceous shale with occasional plant remains. Intercalations of oolitic limestone occur in the lower and upper part of the formation. The thickness ranges from 260 m in the south to 315 m in the north.

Najmah Formation The Najmah Formation consists of dark argillaceous limestone with interbedded, locally bituminous, calcareous, black shale, containing well preserved ammonite fossils and some bivalve shells. The thickness of this formation ranges from about 60 m in the southern part to about 105 m in northern Kuwait.

Gotnia Formation The Gotnia Formation consists of mainly anhydrite, white to clear crystalline halite layers, interbedded with fossiliferous, light to dark gray, argillaceous anhydrite, soft shale, and limestone. The thickness ranges from about 240 m in the south to about 425 m in the north.

Hith Formation The Hith Formation consists mainly of anhydrite interbedded with some limestone and shale. The thickness ranges from 70 m in southern Kuwait to about 100 m in northern Kuwait.

CRETACEOUS SYSTEM

Cretaceous sedimentary rocks in Kuwait, which contain the main oil reservoirs of the country, range in thickness from about 1830 m in the southwest to about 3,040 m in the northeast.

Thamama Group

The Thamama Group is divided into five formations:the Makhul, Minagish, Ratawi, Zubair, and Shuaiba Formations.

Makhul Formation The Makhul Formation is the lowest formation in the Thamama Group, it ranges in thickness from about 140 m in northern Kuwait to about 300 m in southern Kuwait. The formation consists of hard, dark brown, cryptocrystalline argillaceous limestone, occasionally dolomitic, and interbedded with marl and silt in the lower part of the section.

Minagish Formation The type-section of the Minagish Formation is located in Burgan well-113 in Burgan field of southeastern Kuwait where it is about 305 m thick. Lithologically similar to the Makhul Formation, the Minagish consists of hard, dark gray dense carbonates, mostly oolitic limestone. The Managish Formation ranges from about 320 m thick in southern Kuwait up to about 355 m in northern Kuwait.

Ratawi Formation The Ratawi Formation is composed mainly of interbedded shale and limestone. The Ratawi Formation thickens northward, but at a greater rate than the Minagish Formation. The Ratawi ranges from about 150 m thick in southern Kuwait to about 285 m in northern Kuwait.

Zubair Formation The Zubair Formation ranges from about 350 m thick in the south to about 450 m thick in the north. The lithology is mainly sandstone, with some intercalation of shale sequence with minor limestone.

Shuaiba Formation The thickness of the Shuaiba Formation ranges from about 60 m in southern Kuwait to about 80 m in northern Kuwait. Lithologically, it consists of coarsely crystalline, porous, and cavernous limestone with a highly dolomitized sequence; rare thin shale occurs locally.

Wasia Group

The mid-Cretaceous Wasia Group has been divided into five formations in southern Kuwait, and into six formations in northern Kuwait. All the production to date from the Greater Burgan oil field has been developed from the Wasia Group.

Burgan Formation The Burgan Formation consists of approximately 90% sandstone and 10% shale. The thickness of the Formation is about 365 m in the south to about 390 m in northern Kuwait.

Mauddud Formation The Mauddud is limited to a single limestone body with a thickness that ranges from a few meters at Um Gudair, to about 10 m at Burgan, and to more than 90 m in northern Kuwait.

Wara Formation The Wara Formation consists of glauconitic sandstone and siltstone with interbedded gray shale in the upper part and gray shale with a large sand body in the lower part. Thicknesses range from about 45 m in southern Kuwait to about 90 m in northern Kuwait.

Ahmadi Formation The Ahmadi Formation is an impervious shale which forms the cap rock over the Burgan, Magwa and Ahmadi fields. The Ahmadi ranges in thickness from about 5 m in southern Kuwait to about 150 m in northern Kuwait.

Magwa Formation The Magwa Formation is predominantly of limestone and is divided into two members, which are shown as formations in figure 2. The lower Rumaila Member is composed of of fine-grained, marly limestone and marl of deep water facies; these pass downward into fine-grained, white, chalky limestone; the thickness of this member ranges from near zero on the crest of the Burgan high on the Kuwait arch to about 100 m over the rest of Kuwait. The upper Mishrif Member is composed from top to bottom of fine-grained, limonitic, freshwater limestone; dense, fractured, styolitic limestone with algal limestone, gastropods, and shell fragments, and detrital, porous, shell, foraminiferal limestone grading down to marly limestone. This member is about 75 m thick in northern Kuwait and much thinner or not represented over structurally high areas of southern Kuwait.

Aruma Group

The Aruma Group is divided into five formations, Khasib (Mutriba), Sadi, Hartha, Qurna, and Tayarat.

Khasib (Mutriba) Formation The Khasib (Mutriba) Formation consists of white to gray, dense, detrital limestone, locally glauconitic, with an intercalation of shaly horizons near its base. The thickness of this unit ranges from 285 m in northern Kuwait to about 25 m in southern Kuwait.

Sadi Formation The Sadi Formation consists of fossiliferous limestone with few intercalations of shales and dolomites. The thickness of the formation ranges from about 10 m in southern Kuwait to about 305 m in northern Kuwait.

Hartha Formation The Hartha consists of an organic-rich, detrital limestone with some dolomite; shales and marl intercalations occur, particularly near the top. The thickness of the Hartha ranges from about 275 m to near zero over structurally high areas.

Qurna Formation The Qurna Formation consists of limestone, commonly argillaceous, locally dolomitic; a few intercalations of marly beds occur with some shales. The thickness of the formation ranges from about 20 m in southern Kuwait to about 85 m in northern Kuwait.

Tayarat Formation The Tayarat Formation consists of brown and dark gray, granular, crystalline, dolomitic, and locally anhydritic limestone and white limestone interbedded with minor quantities of thin, black, bituminous, pyritic shales. Thicknesses range from about 200 m in the south to about 350 m in the north.

TERTIATY SYSTEM

Rocks of Cenozoic age are composed of the Hase and Kuwait Groups which range in age from Paleocene to Recent.

Hasa Group

The Hasa Group is composed of three Formations: the Dammam, the Rus, and the Radhuma.

Radhuma Formation Radhuma Formation was named for the Umm-er-Radhuma water well in Saudi Arabia. The formation consists of mostly anhydrite, and dolomitic and marly limestone. Thickness ranges from about 510 m in the south to about 545 m in the north.

Rus Formation The Rus Formation consists of alternating beds of anhydrite and limestone. Regionally, the Rus in Kuwait varies in thickness from about 105 m in the south to about 135 m in the north.

Dammam Formation The type section of the Dammam Formation for Kuwait is in Burgan well, number 10, in southern Kuwait. It consists of 180-240 m of white-gray, porous, dolomitized limestones, nummulitic limestones, and soft, chalky limestone. The formation ranges in thickness from about 120 m in southwestern Kuwait to about 255 m in northeastern Kuwait. The formation has been locally subdivided into three members on the basis of lithology; from top to bottom, these are:

Member 3 - shaley, chalky, porous limestone with hard, siliceous limestone at top.

Member 2 - chalky, locally shaley limestone with thin siliceous limestone with beds at the base.

Member 1 - dense, dolomitic limestone with a lower fossiliferous (numulitic) dolomitic limestone, thin anhydrite beds and green shale in the lower part.

Kuwait Group

The Kuwait Group forms the surface outcrop over the entire country, except where overlain by unconsolidated Recent and sub-Recent sediments ranging from gravel and sands to fine-grained coastal deposits. The exposed stratigraphic sequence includes conglomerates, sandstones, sandy limestones, claystones, marls, sands, and gravel and ranges in age from Miocene to Holocene. They show marked increase in thickness, from a few meters at Ahmadi to about 425 m in northeastern Kuwait. In northern Kuwait, this group is divided into three formations, based on presence of an intermediate evaporite horizon: 1) the Ghar Formation (sand and gravel), 2) the Lower Fars Formation (evaporites), and 3) the Dibdibba Formation (sand and gravel). No subdivision is possible in southeastern Kuwait where the succession is made up of sands and fine gravel referred to generally as the Kuwait Group.

Ghar Formation The Ghar Formation lies between the Lower Fars Formation and the Dammam limestone and consists mainly of marine to terrestrial sands, silts, and gravel. Thickness increases from the southwest, reaching about 180 m in northern and northeastern Kuwait.

Lower Fars Formation The Lower Fars Formation consists mainly of anhydrite, gypsum, clay, marl and shallow water limestone. The formation is absent in the south and the thickness of the unit ranges from about 60 m west of Kuwait to about 110 m to the north.

Dibdibba Formation The Dibdibba Formation consists of fluviatile sequence of ungraded, crossbedded sands and gravels with intercalations of sandy clays, sandstones, conglomerates, and siltstones. The maximum thickness of the Dibdibba Formation occurs in northeastern Kuwait where it reaches 185 m; the formation is not recognized in the southwestern corner of Kuwait.

RECENT

Surficial rocks of sub-Recent to Recent age consist of eolian sand, residual deposits, playa deposits, desert plain deposits, and sabkha deposits.