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Stratigraphy and Structure of Eastern Syria Across the Euphrates Depression

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ABSTRACT

A crustal-scale geotransect across the northern Arabian platform, oriented north-south in eastern Syria, reveals an alternating series of basement uplifts and basins separated by predominantly transpressional fault zones above an effectively uniform crust. Four major tectonic provinces are crossed along a 325 x 100 km corridor that extends from the Iraqi border in the south to the Turkish border in the north: the Rutbah uplift, the Euphrates depression, the Abd el Aziz structural zone, and the Qamichli uplift. These features are the manifestations of reactivated Pre-Cenozoic structures that responded to forces acting along nearby Arabian plate boundaries, particularly Cenozoic convergence and collision along the margins of the northern Arabian platform, i.e., the Bitlis suture and the East Anatolian fault in southern Turkey and the Zagros suture in Iran and Iraq.

The database for this study consists of 3000 km of industry seismic reflection data, 28 exploratory wells, geologic, and Bouguer gravity maps. The deep crustal structure and, in part, the basement geometry along this transect are inferred from two-dimensional modeling of

Bouguer gravity, whereas the shallow (about 8 km) structure is constrained primarily by well and seismic data.

Features of the geotransect reveal:

1. A relatively uniform crustal column approximately 37 km thick with only minor crustal thinning beneath the Euphrates. Crustal thinning may be slightly more pronounced beneath the Euphrates (about 35 km) to the southeast of the transect where the Bouguer gravity anomaly is slightly higher.

2. Along the Euphrates depression, ongoing subsidence, which began during Late Cretaceous time, resulted in the deposition of at least 3 km of Late Cretaceous and Cenozoic rocks. The structural complexity of the Paleozoic and most of the Mesozoic sedimentary sections along the transect contrasts markedly with a relatively simple, flat-lying Cenozoic section along most of the transect. A notable exception is the Abd el Aziz uplift, where Cenozoic rocks are strongly deformed.

3. While Euphrates subsidence continued throughout the Cenozoic, the east-west trending Abd el Aziz structure began to be inverted into a fault-bounded tilted block since the Miocene, perhaps as a response to the last episode of intense Miocene collision along the nearby Bitlis and Zagros suture zones.

Introduction

The Arabian plate was separated from the African plate in the early to mid-Miocene along the Red Sea rift. The plate is bounded by the major plate boundaries of the Middle East (Fig. 1). The northern and eastern boundary is marked by the Bitlis suture, the left-lateral East Anatolian fault, and the Zagros fold belt. The western boundary includes the Red Sea rift in the southwest and the left-lateral Dead Sea leaky transform fault system along the Levantine margin to the northwest. Syria is located on the northern flank of the Arabian plate, and the diverse structural and stratigraphic evolution of the Syria region reflects the complex interactions between these

Cenozoic plate boundaries and pre-Cenozoic structures (e.g., Beydoun, 1977; Lovelock, 1984; McBride et al., 1990; Best et al., 1990; Chaimov et al., 1990, 1992; Al-Saad et al., 1992).

This paper presents a north-south crustal transect that traverses eastern Syria for approximately 325 km from the Iraqi border in the south to the Turkish border in the north (Figs. 1 and 2). The surface geology of Syria east of the Euphrates river is composed of mostly undeformed Neogene and Quaternary rocks, with little old sedimentary section exposed; however, the Neogene and Quaternary surface rocks overlie a structurally complex system of alternating basins and uplifts. Seismic reflection data and well control highlight a dramatically thickened Mesozoic and Cenozoic section in the NNW-trending Euphrates and N. Abd el Aziz depressions. Thinner sedimentary section, however, is present across the Abd el Aziz and Qamichli uplifts. The Euphrates graben/fault system developed by extension/transtension following a period of extensive uplift and erosion during Jurassic and early Cretaceous times (Koopman, 1986). Additionally, transpressive movements at the end of the Late Cretaceous and into the Tertiary resulted in a widespread increase in vertical movement along many of the pre-existing graben faults (Koopman, 1986), thus forming the horst and graben structures in this province as well as local upwarping of the overlying sedimentary sequence in broad hydrocarbon-bearing anticlines.

Data

The data base for this transect consists of geologic maps, exploratory well information, seismic reflection data, and gravity and aeromagnetic data within a 100 km wide corridor along the transect. The shallow structure (<8 km) of the crustal cross section is constrained by over 3000 km of seismic reflection data and 28 exploratory wells. The deep crustal structure is interpreted from two-dimensional modeling of Bouguer gravity data.

The entire seismic reflection database of Syria includes more than 100,000 km seismic data acquired and processed by many different contractors between 1974 and 1990. Hence, the seismic data vary in quality. These seismic data were tied directly to ten exploratory wells (see

Figs. 2 and 3), and supplemented by 18 wells within the 100 km width of the transect. The sedimentary section along the transect has been separated into four layers: Cenozoic, Mesozoic, Paleozoic, and basement layers. These distinctions are related to observed reflectivity on the seismic sections and to density distributions from well logs.

Low amplitude reflectivity characterizes the predominantly clastic Paleozoic section, however, four sub-horizontal regional reflectors that deepen northeastward towards the Euphrates depression are prominent on seismic profiles from the Rutbah uplift (Fig. 4). The upper three reflections, designated "A, B, and C," correlate with Paleozoic unconformities interpreted in wells, whereas the deepest reflection, "D", is interpreted as an equivalent to the infracambrian Burj limestone of Jordan. The "D" reflection is a multicyclic event that is regionally continuous with a slight dip to the north and northeast; the reflection deepens abruptly across faults beneath the El Madabe step and Euphrates depression, reaching a maximum observed depth of approximately 7.5 km. The "C" reflection is interpreted as the top of the Ordovician section at a depth of about 2.7 km on the Rutbah uplift, deepening to about 3.3 km toward the Euphrates depression (Figs. 4 and 5). "B" is interpreted as the top of Carboniferous (Fig. 4), and based on well logs "A" represents the top of the Paleozoic section in the Rutbah uplift and the base of the Cretaceous section beneath the El Madabe step and Euphrates depression (Fig. 4). This dual identification of the "A" reflection is due to the variable regional distribution of Triassic and Jurassic rocks.

Reflections from Mesozoic and Cenozoic rocks diverge gradually toward the Euphrates depression. The high reflectivity of the Mesozoic and Cenozoic sections derives from unconformities, such as where Lower Cretaceous rocks overlie Late Triassic strata and where Late Triassic, in turn, overlie Carboniferous, as well as from thickly bedded marine carbonates (mainly Mesozoic) and continental clastics (mainly Cenozoic). The total thickness of the Mesozoic and Cenozoic sedimentary section in the Euphrates depression reaches about 4 km.

Structural and Stratigraphic Overview

As observed on a geologic map of Syria, the region west of the Euphrates river is more structurally complex, i.e., the Palmyrides mountain belt, than the region east of the river. However, the relatively monotonous Neogene/Quaternary deposits on the surface mask a series of basins and uplifts with well developed, intervening transition zones. The transect traverses from south to north: the Rutbah uplift, El Madabe transition zone, the Euphrates depression, Derro-Al Baida high, the Abd el Aziz structural zone, Abd el Aziz depression, and the Qamichli uplift (Fig. 2). While many changes occur in the deformation style, they are generally minor in a vertical displacement sense. Thus, stratigraphy and age of unconformities and not structure (strictly speaking), especially in the Euphrates depression, reveal the most complete geologic evolution of the region. For this reason, much of the study deals with the detailed stratigraphic relationships in the sedimentary record and the inferences that can be drawn about past depositional settings based on such observations. A brief description of the structure and sedimentary cover encountered along the transect from south to north is included below, followed by a more detailed discussion of depositional settings in eastern Syria.

Rutbah uplift

The Rutbah uplift in Syria is the continuation of a broad, basement-cored upwarp of predominantly Paleozoic rocks centered in Iraq. Its northern nose occupies southern Syria, and is the starting point for the transect. Cretaceous and Paleogene deposits (1-1.5 km thick) veneer the thick Paleozoic sediments of its northwestern flank in Syria. The total thickness of the Phanerozoic section is at least 6-7 km, estimated from the depth of the deepest prominent reflector of the seismic data. This reflection is interpreted to be from a dolomitic section equivalent to the Burj limestone (Infra-Cambrian age) (horizon D in Fig. 4), which is recognized on many seismic lines in the region, and is different in character from the Ordovician reflectors, and could be correlated with Khanaser well data to represent lower Cambrian sequence. The

Rutbah uplift is not strongly deformed; however, the northeastern and eastern flanks of the Rutbah uplift are marked by a faulted transition zone into the Euphrates depression. This zone, called the El Madabe step, is marked by the Al Faydat fault zone (see Fig. 2), a near-vertical, normal fault that penetrates the entire sedimentary section.

Euphrates depression

North of the El Madabe step the transect obliquely traverses a series of minor anticlines and horst and graben features that characterize the structural framework of the Euphrates depression. The Euphrates depression in a NNW-trending asymmetric half graben system that deepens to the east and is marked by a thickened section of marine upper Cretaceous rocks (approximately 2.5 km) and continental Neogene and Quaternary rocks (about 1 km) (Fig. 4) (SPC & Al Furat Petr. Co., unpublished regional reports 1976-1988). The base of the Cretaceous in the Euphrates depression is faulted down 3.5 km relative to the adjacent eastern platform. The eastern side of the depression is bounded by the Al Furat (i.e., Euphrates) transcurrent fault zone, which extends in a series of nearly vertical faults for 640 km from the Iraqi border in the southeast to the Turkish border in the northwest. The Euphrates graben/Al Furat fault (i.e., the Euphrates depression) becomes more pronounced in the complex region where they intersect the NE-trending Palmyride mountain belt, northwest of Der Azzour (Fig. 2). However, the depression changes to a graben system toward the southeastern border of Syria.

The effect of upper Cretaceous/Cenozoic thickening causes a depression of the Paleozoic section. Seismic data tied to available well logs show that the top of the Carboniferous deepening to about 4.5 km and the Cambrian section deepening to about 7.5 km beneath the depression. Faults subparallel to the Al Furat fault cut the central part of the depression into a series of horsts and grabens. Subtle low-amplitude folds occur throughout the depression.

Two major unconformities in the Euphrates depression are observed between the Carboniferous and the Late Triassic, and between the Late Triassic and Early Cretaceous. The entire Jurassic section is missing within the depression (Figs. 3 and 4).

Systems of faults, some deeply penetrating, separate the Euphrates depression from the Derro-Al Baida high and Rawda uplift along the northern and eastern margins, respectively. North of the Euphrates depression the transect crosses the Derro and Al Baida highs (Figs. 2 and 5), two "steps" in a transition zone similar to the El Madabe step, but stepping up out of the northern side of the depression. The Derro high may represent the northeastern extension of the Palmyra fold-thrust belt into the Sinjar trough region, but the exact relationship of the Palmyra fold belt to the Sinjar trough is not yet known (Figs. 2 and 4). The southern flank of the Derro-Al Baida high is complicated by a northeast-trending faulted zone, whereas the northern flank is bounded by a north dipping reverse fault that forms the southern limit of the Abd el Aziz structural zone (Figs. 2, 5, and 6). Quaternary volcanism produced local basalt flows above some of the deeper penetrating faults (Palmyride trend) and along the northwestern Al Furat fault where it cuts the western side of the Derro high (Fig. 2), also indicating a deeply penetrating fault.

The prominent seismic reflectors associated with Paleozoic rocks beneath the Euphrates depression shallow as they approach the Al Baida high, with the Cambrian section at 5.5 km in the Derro high (Fig. 5) and 4.5 km in Al Baida; the Ordovician and Silurian unconformities also shallow to the north.

Abd el Aziz structural zone

North of the Derro-Al Baida zone is the Abd el Aziz uplift, a doubly-plunging asymmetrical anticline. During Mesozoic time, it was a small sedimentary basin that inverted in the Neogene, and forms the northwestern edge of the folded Mesozoic Sinjar trough (Figs. 2 and 6). The overall structure of Abd el Aziz is controlled by a south dipping reverse fault (perhaps a wrench fault) (Ponikarov, 1967; Lovelock, 1984; Hickman, 1988; SPC unpublished regional reports, 1976-1988). Northeast-trending, left-lateral strike-slip faults, clearly visible on satellite images, dissect the Abd el Aziz structure (Ponikarov, 1967; Lovelock, 1984; Trifonov, 1986; Hickman, 1988). Upper Cretaceous beds are exposed in the highest part of the structure and are cut by a major reverse fault zone along the crest dipping to the south that brings anomalous blocks of Carboniferous rocks to the surface. Regional north-south compression associated with the convergence of Arabia with Turkish/Eurasian blocks, produced folding, reverse faulting, and left-lateral strike-slip faulting (Fig. 6). The deformation in the area is of the order of 1-2 km vertical movement and appears to be rooted in the basement (Lovelock, 1984; Hickman, 1988).

The Mesozoic subsidence and Neogene inversion of Abd el Aziz (Lovelock, 1984; Trifonov, 1986; Dunham, 1988; Hickman, 1988) and the Sinjar trough are strikingly similar to that of the Palmyride mountain belt (e.g., McBride et al., 1990; Chaimov et al., 1990).

A major south-dipping reverse fault separates the Abd el Aziz structure from the north Abd el Aziz depression. This depression strikes east-west and is situated between the southern slope of the Qamichli uplift (equivalent to the Mardin uplift of southern Turkey) and the northern flank of the Abd el Aziz high (Fig. 6). To the east the depression is continuous with the Sinjar trough (SPC unpublished regional reports 1976-1988). With no well drilled in the north Abd el Aziz depression, sedimentary thicknesses are interpreted from seismic data. Regional geologic studies and seismic surveys reveal a Mesozoic-Cenozoic depression filled with 6-7 km of Phanerozoic sediments that have been relatively unaffected by the Neogene compression that inverted the Palmyride trough and Abd el Aziz structure. These rocks are deformed slightly by east-west trending (Sinjar trend) faults. Regional interpretation of the seismic data indicates that late Upper Paleozoic, late Upper Triassic and Jurassic rocks are absent from the depression, whereas the Cretaceous-Cenozoic section thickens (Figs. 6 and 7). The depression was not significantly deformed during about the past 20 Ma (Trifonov, 1986; Hickman, 1988). As across most of eastern Syria, continental to lacustrine/shallow marine Neogene rocks up to 500 meters thick cover the area.

Qamichli uplift

The Qamichli uplift, at the northern end of the transect, represents the southern flank of the Diyarbakir (Mardin) uplift of southern Turkey. A complex system of NE-trending faults, inferred to penetrate into the basement, deform Mesozoic and Paleozoic rocks and separate the Qamichli uplift from the north Abd el Aziz depression to the south. Displacement across the faults reaches only a few tens of meters. In addition, there are many small faults with northerly trends that dissect the eastern nose of the uplift (Ponikarov, 1967; Lovelock, 1984; SPC unpublished regional reports, 1976-1988).

Approximately 4.5-5.5 km of Phanerozoic rocks, mostly Lower Paleozoic, are indicated from well control in the area (SPC unpublished regional reports 1976-1988). In the Qamichli well No. 1 approximately 1 km of Cenozoic rocks and 850 meters of Mesozoic rocks are found unconformably overlying Ordovician section. A slightly thicker section (~2.25 km) of Mesozoic and Cenozoic rocks was penetrated by the Affendi well No. 1, located on the southern slope of the uplift.

Geological and geophysical data show that the Qamichli uplift was first deformed in the early Paleozoic. Deformation has continued in Miocene and Quaternary time (Grunau and Rigassi, 1984). The more intensive movements in the uplift took place in the late Lower Paleozoic, with uplift of the basement during that time (Rigo de Righi and Cortesini, 1964; Ala and Moss, 1979; Dewey et al., 1986). Other phases of uplift occurred during the Late Triassic to Early Cretaceous, evidenced by missing Upper Triassic-Jurassic and early Lower Cretaceous rocks, i.e., Lower Cretaceous rocks overlie the Middle Triassic section (Fig. 3). There was an anigmatic Late Jurassic - Early Cretaceous rifting episode which affected especially northern and northeastern segments of the Arabian plate (e.g., Gorur et al., 1991; Robertson and Searle, 1990). This rifting event possibly led to uplift in southeast Turkey and in the Qamichli region in Syria.

Depositional Setting

Although some available publications have described exposed Phanerozoic lithology in Syria in exhaustive detail (e.g., Ponikarov, 1966), the following is the most up-to-date analysis of lithology, facies changes, and major unconformities in eastern Syria, including data from recent seismic reflection surveys as well as information from many wells which were not available to past studies. Some of these new interpretations contradict decades old published descriptions of Syrian stratigraphy. In order to support the interpretations presented in this paper, selected examples of seismic data along the transect will be provided. The following descriptions are derived mainly from data in eastern Syria, but much of the general analysis regarding past depositional environments is equally applicable to the rest of the northern Arabian platform.

The thickness of the sedimentary section in Syria averages 5-7 km with a 10 km maximum in some deep basins (e.g., the Palmyrides) (Seber et al., 1992; Best et al., 1993). This estimate is based on over 200 wells tied to seismic reflection and refraction data. As there are relatively few deep wells in Syria, information on the Paleozoic is the least known. The completeness of the sedimentary section varies from region to region. In the Rutbah and Qamichli uplifts the sedimentary section is mainly composed of Lower Paleozoic rocks 3.5-4.5 km thick, whereas in the Euphrates depression and Abd el Aziz structural zone, Mesozoic and Cenozoic rocks predominate, with thicknesses of greater than 4 km. This is one of the main distinguishing characteristics of the geology of Syria, and it indicates that subsidence in the different tectonic provinces of Syria was not synchronous (Ponikarov et al., 1967; Beydoun, 1977 and 1981; Lovelock, 1984; SPC unpublished regional reports, 1976-1988).

Five major depositional sequences in eastern Syria have been identified on the seismic reflection profiles (Fig. 7). The first stage is marked by deposition of shallow to open marine sandstone and shale of Cambrian (inferred), Ordovician, and Silurian ages, with thicknesses ranging from 1.5-5 km. The top of this sequence is unconformable, with no Devonian rocks identified in Syria to date. The second depositional stage is marked by Carboniferous and

Permian, 1.2-3 km thick sandy shale and carbonates that overlie the lower Paleozoic section with slight angular unconformity. The third, Triassic and Jurassic, stage is marked by an increase in carbonates and evaporites, which attain a maximum thickness of 2 km in the Sinjar trough. The fourth stage, Cretaceous through Paleogene, is composed of carbonate rocks with sandy shale at the base and varies in thickness from 0.5-1.5 km. The base of this section is an unconformity atop Triassic-Jurassic rocks throughout most of Syria, but atop Paleozoic rocks on the Rutbah uplift. The fifth stage is represented by shelf and shallow water carbonates, lagoonal deposits, continental sands and conglomerates of Neogene and Quaternary age with cumulative thicknesses increasing eastward from 1 km to 1.5 km (see Figs. 4 and 8).

Precambrian

Within Syria, depth to basement and thickness of the Phanerozoic section varies for different tectonic provinces. The deepest basement, and, hence, the thickest sedimentary section, lies along the Palmyride-Sinjar trough trend, roughly northeast-southwest, through central Syria (Seber et al., 1992) (see Fig. 2). No Precambrian section has been penetrated in any well, so information about the Precambrian within Syria is inferred locally from outcrops in northwest Syria in the Bassit ophiolite complex and regionally from near the Gulf of Aqaba in Jordan and the Arabian shield in Saudi Arabia. These Precambrian rocks include metamorphosed shale, amphibolite gneiss, quartzite and marble. Diversity of the section, as evidenced by the Arabian shield, precludes any definitive conclusions about the possible composition of basement beneath Syria. Gravity modeling suggests that several different crustal blocks may form the northern Arabian platform (Best et al., 1990).

Paleozoic

The lower Paleozoic of central and eastern Syria is composed of shallow marine sandstone and shale punctuated by several regional unconformities. More than 2.5 km of Cambro-

Ordovician clastics were penetrated in the northwest (Khanaser well No. 1) (Al-Saad et al., 1992), while more than 2.3 km of Ordovician alone was found in the Swab well No. 1 to the southeast (see Fig. 4) (SPC unpublished regional reports, 1976-1988). In a time period from Late Silurian to Permian, broad, subaerial uplifts formed in northern and southern Syria, resulting in the preservation of a thick (0.75 km) lower Silurian section in central Syria consisting of clastics and grabtolitic black shale, and the erosion or non-deposition of any Devonian rocks (Gvirtzman and Weissbrod, 1984; Lovelock, 1984; SPC unpublished regional reports, 1976-1988).

Identification of Late Paleozoic rocks in some wells is controversial; a sequence of clastics and carbonates is interpreted to represent lower Carboniferous and Permian rocks. However, no Permian rocks are identified along the transect or in eastern Syria except in very local sub-basins of the Euphrates depression (SPC unpublished regional reports, 1976-1988). As no Devonian rocks are recognized in Syria, Carboniferous rocks unconformably overlie clastics believed to be of a Silurian age. Carboniferous rocks crop out in only one small exposure in the Abd el Aziz high of northeastern Syria. In the subsurface, thick, variegated Carboniferous claystone and sandstone, interbedded with limestone, were encountered in the Swab and Markada wells in southeastern and eastern Syria, respectively. Wells and seismic data show Silurian and Ordovician rocks unconformably overlain by up to 1 km of Carboniferous rocks.

On the Qamichli uplift at the northern end of the transect (see Fig. 2) the Middle Triassic unconformably overlies the Upper Ordovician. Rocks of Silurian through middle Triassic age are missing in the Qamichli and Affandi wells either due to erosion or non-deposition, depending upon the area considered (Ponikarov, 1967; Garfunkel and Derin, 1984; Gvirtzman and Weissbrod, 1984; Lovelock, 1984; Al Labown, 1988; SPC unpublished regional reports, 1976-1988). This unconformity also cuts out the Triassic in Turkey where the Lower Cretaceous section overlies Ordovician rocks (Kanun-1 well, Fig. 3). Regional isopach maps of the Upper Paleozoic indicate the development of a major depocenter throughout central Syria wherein Carboniferous marine shale, sandstone, siltstone and shaley sand interbedded with limestone accumulated. This depocenter extends from the Sinjar trough across the Euphrates depression (Fig. 8) (Beydoun, 1981; SPC unpublished regional reports, 1976-1988).

Mesozoic

Mesozoic rocks crop out only in the crests and cores of the anticlinal and faulted arches of the Palmyride mountain belt, the coastal ranges and the Abd el Aziz high, in addition to most of the wells in Syria. The Mesozoic section consists of carbonates with interbedded evaporites, clastics and marls. Thick clastic sequences (2-4 km) are present in the Lower Cretaceous and Upper Triassic sections (SPC unpublished regional reports, 1976-1988) and form the main oil reservoirs within the Euphrates depression.

By Early to Middle Triassic time, subsidence initiated in the Sinjar trough (Lovelock, 1984; SPC unpublished regional reports, 1976-1988), contemporaneous with that in the Palmyride trough. The northern part of the Euphrates depression and Derro-Al Baida high were higher during the Jurassic and Early Cretaceous. Wells along the transect indicate an eastward thickening of the Triassic section and a thinning toward the north and south. Triassic and Jurassic deposits are absent in southeast Syria and along the transect (Fig. 4) (SPC unpublished regional reports, 1976-1988).

Over the studied area and most of Syria a shallow, restricted marine and lagoonal environment characterized Triassic times. Wells to the north (Derro-2) and south (Thayyem 103) along the transect encountered Triassic rocks of varied lithology, including dolomite, anhydrite, minor amounts of shale and very minor terrigenous clastics. The Triassic section thickens from 150 m to 1000 m (Fig. 3) and changes facies northward from continental clastics to dolomite to deeper water dolomite and shale. Most of the Triassic evaporites were deposited during the Late Triassic along the basin margin (Garfunkel and Derin, 1984).

The available information can be interpreted to indicate a Late Triassic to Early Cretaceous marine regression that inhibited the preservation of Jurassic sediments in the east and caused deposition of deltaic sandstone and conglomerate of late Neocomian age there. A marine transgression ensued during Aptian-Albian time. The southwestern corner of Syria and the Aleppo plateau and Rutbah uplift were probably all emergent during this time (Ponikarov, 1967; Lovelock, 1984; (SPC unpublished regional reports, 1976-1988). Shallow marine to continental clastics were deposited in southeast Syria, while farther north shallow water carbonates and evaporites formed (Fig. 8).

Another regression began in the late Turonian and peaked in the Campanian and early Maastrichtian, exposing Cenomanian-Turonian carbonates to percolating fresh waters and weathering processes, thus giving rise to the karstic surfaces that, when exposed, inhibit the acquisition of good seismic reflection data. In the Late Cretaceous a thick section of limestone, marl and calcareous marl was deposited in the Palmyride and Sinjar troughs.

Well correlations and seismic reflection data indicate that subsidence accelerated in the Late Cretaceous in the Euphrates depression, possibly as a response to rotation of Arabia from Africa. This was followed by moderate Paleogene and Miocene compression that overprinted the extension and produced flexures over the earlier Late Paleozoic rift structures (Fig. 8). The compression also produced strike-slip movement along the main Al Furat fault (Ponikarov, 1967; Beydoun, 1977; Ala and Moss, 1979; Lovelock, 1984; Hempton, 1987). The renewed Late Cretaceous transgression that continued into the Cenozoic covered the remaining paleo-highs and pre- Triassic strata.

Cenozoic

The transition from Mesozoic to Cenozoic was marked by widespread transgression. Paleogene and Lower Neogene rocks were deposited in open and at times restricted seas and consist predominantly of carbonates and evaporites. The Upper Miocene and younger section is more terrigenous in comparison, but contains some marine strata. Late Miocene and Pliocene basalt flows were common (see Fig. 2). Paleogene rocks crop out in most of the southern part of the study area and are present in all the wells drilled in the region. During the Paleogene, carbonate deposition persisted throughout the regions of active subsidence. The Paleocene section consists of marl and calcareous shale, indicating that an open sea environment had been established by about 60 Ma. In the Eocene the sea slowly retreated, and the depositional setting became more restricted, resulting in the deposition of marl and chalky limestone. A lagoonal facies, which consists of micrite with sponges and algae, was deposited during the Oligocene, signaling the return to a shallower, near shore marine environment.

A minor transgression occurred in early Neogene time, resulting in the deposition of Lower Miocene evaporates with salt, limestone, and clay, indicative of a lagoonal environment. Middle Miocene rocks, mainly marly carbonates, indicate a shelf environment. A regression in the Middle Miocene resulted in a "transition zone" of anhydrite, shale and limestone from the Middle Miocene rocks to the Upper Miocene lagoonal deposits.

The final retreat of marine conditions from Syria took place in the Late Miocene. Pliocene deposits consist of conglomerates and non-marine sandstone, and Pleistocene sediments consist of recent alluvial and lacustrine clastics with marls in the local valleys and depressions. Late Miocene, Pliocene and Pleistocene tectonism gave rise to deep-seated structures which controlled much of the volcanic activity that blanketed some areas with basalt flows (Figs. 2 and 8) (Dubertret, 1970).

Although the surface geology and parts of the buried sedimentary section, especially the Mesozoic, are superficially monotonous, the detailed lithology, thickness variations, and facies changes described above and shown schematically in Fig. 8 highlight the differential subsidence and uplift history of eastern Syria during the Phanerozoic.

Geophysical Observations and Modeling

The shallow sedimentary cover along the transect (<8 km) is well constrained from wells and seismic reflection profiles. Modeling of the Bouguer gravity anomalies in eastern Syria helps to constrain the structure and nature of the deeper section, from the top of the basement to the base of the crust.

Gravity data and modeling

The Bouguer gravity map of Syria was compiled in 1975 by the Bureau d'etudes Industrielles et de Cooperation de l'institut Francais du Petrole (BEICIP, 1975) from 19 different existing gravity surveys acquired from 1948 to 1972. Based on borehole information, an average reduction density of 2.53 g/cm^3 was used for calculation of the Bouguer anomalies. Along the transect Bouguer gravity values vary from -6 mGal in the Derro high to about -40 mGal north of the Abd el Aziz structure (see Fig. 9).

Two-dimensional gravity modeling of the Bouguer data was carried out using the U.S. Geological Survey Hypermag program (Saltus and Blakely, 1983). The program calculates the anomalies generated by a simplified crustal model with relative density contrasts between polygonal model bodies. The shallow structure (<8 km) of the model is reliably constrained by available seismic reflection and well data. A simplified gravity model along the transect (Fig. 9) was constructed, and its calculated gravity profile demonstrates a good correlation with the observed gravity values. The model demonstrates that the whole crust can be treated as a relatively uniform section, with no large scale lithologic or crustal thickness discontinuities evident deep in the crust. Simple variations in depth to basement give rise to most of the observed variations in Bouguer gravity along the transect. A slight crustal thinning from 37 km south and north of the Euphrates depression to 35 km beneath it can account for the subtle change in the long wavelength Bouguer gravity anomaly over the Euphrates depression. Although the above model is not a unique one, it is the most simple and geologically reasonable and still explains the observations.

Magnetic data

The aeromagnetic data in Syria were acquired from 1958 to 1959 by a Soviet scientific group (Filatov and Krasnov, 1959). Flight lines were run in a series of surveys, each perpendicular to the strike of recognized surface structure in a region. The flight altitude was 200 meters. Three main magnetic features are identified along the transect: a value of 100 gammas to the south between the Rutbah uplift and Euphrates depression; a high value of 150 gammas associated with the Derro and Al Baida highs; a broad low of -100 gammas associated with early depression of the basement beneath the Abd el Aziz structural zone.

Because of the relative lack of pronounced magnetic anomalies along the transect and the lack of information on susceptibility values, we do not provide a crustal model that explains the observations. Such a model would be a highly non-unique one. However, the following general observations of the magnetic field in eastern Syria can be made:

1) The low intensity, quiet magnetic field is consistent with the thick sedimentary cover of the Rutbah uplift.

2) A zone of high magnetic intensity over the El Madabe step punctuates the northward gradation from low intensity in the Rutbah uplift to a higher intensity in the Euphrates depression.

3) The positive magnetic anomaly over the Derro and Al Baida highs is probably associated with basalt flows and relatively shallow basement.

4) The lack of a pronounced positive anomaly over the Abd el Aziz uplift could indicate a relatively non-magnetic basement there; however, a positive anomaly associated with the Qamichli uplift may indicate thin sediments covering a shallow and more strongly magnetized basement.

Interpretation of the Crustal Cross Section

The interpreted crustal cross section (Fig. 10) reveals a relatively simple crustal structure. Important characteristics of the cross section include the following:

1) Gravity modeling indicates a relatively uniform crustal thickness of approximately 37 km. A slight crustal thinning to 35 km is possible beneath the Euphrates depression.

2) Thicknesses in the Phanerozoic sedimentary section, interpreted from seismic reflection data and exploratory well information, correlate with variations in depth to the basement inferred from interpretation of Bouguer gravity anomalies.

3) Some faults may penetrate the whole crust, based on their persistence through time as zones of crustal weakness, and the requirement of some relatively deeply penetrating basalt conduit.

4) Initial late Mesozoic - early Cenozoic subsidence of the Euphrates graben/fault system (i.e., the Euphrates depression) caused marked thickening of the sedimentary section in the Euphrates depression.

5) Minor Paleogene and especially Neogene transpression slightly inverted some of the existing normal-faulted structures in the Abd el Aziz zone. This zone has Mesozoic and Cenozoic history parallel that of the Palmyrides.

The tectonic evolution of the Euphrates system, the main geologic feature of eastern Syria, included a long-lived depression with very minor superimposed inversion (Fig. 8). The Mesozoic and Cenozoic Euphrates depression may have been preceded by an old, possibly Proterozoic suture (e.g., Best et al., 1990). The Silurian marked the first stage of subsidence in eastern Syria, followed in the Permian by a resurgence of subsidence and perhaps an episode of fault-controlled rifting along the Al Furat fault zone. As the southeast "toe" of the Arabian plate (i.e., Oman) rotated counterclockwise to close the Neo-Tethys in the Late Cretaceous, right-lateral strike-slip motion and slight compression took place along the Al Furat fault zone. With continued subsidence of the Euphrates system into the Neogene came the inversion of Abd el Aziz in the north and the Palmyrides to the west possibly as a response to the last episode of collision between the Arabian and Eurasian plates.

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Figure Captions

Fig. 1. Generalized tectonic map of the Arabian plate with location of the transect in eastern Syria. DSF=Dead Sea fault.

Fig. 2. Generalized tectonic map of eastern Syria showing key structural features and location of data discussed in text. Location of transect marked by bold solid line within a 100 km wide corridor (dashed lines). Seismic reflection profiles and well control (solid circles) used to construct the interpretive crustal cross section are shown. Tens of thousands of kilometers of seismic reflection data and over 200 wells supplemented the discussion in text.

Fig. 3. Well correlation diagram along the transect. Vertical exaggeration is approximately 40. Note thickened Triassic and Cretaceous at the Thayyem 103 location in the Euphrates depression.

Fig. 4. Example of the seismic reflection character of the Paleozoic section on a portion of line PS 417A. See Fig. 2 for line location.

Fig. 5. Example of seismic reflection data across the Derro high, line PS 11. Profile runs parallel to and just east of the Euphrates River. See Fig. 2 for line location.

Fig. 6. Example of seismic reflection data across Abd el Aziz mountain, line UN 310. Note undeformed sedimentary basin rocks to the north. See Fig. 2 for line location.

Fig. 7. Example of seismic reflection data in the north Abd el Aziz depression, approaching the Qamichli uplift, line KB-13. Sedimentary section is predominantly Paleozoic rocks. See Fig. 2 for line location.

Fig. 8. Cartoon depicting crustal evolution of eastern Syria along the transect (left column) and regional facies variations in the Phanerozoic section, with estimated thicknesses in meters.

Fig. 9. Gravity model used to constrain the structure of the mid to deep crust along the transect. Gravity values are in units of g/cm^3. The observed Bouguer gravity data can be modeled by a simple crustal model with very minor crustal thinning beneath the Euphrates depression. "Major" anomaly variations can be explained by changes in basement depth, i.e., sediment thickness. See text for discussion of other data used to constrain this model.

Fig. 10. Interpretative north-south cross section across eastern Syria, from Turkey to Iraq, based on all available well information, seismic reflection data, gravity and magnetic data and geologic maps.