Structure and Evolution of the Petroliferous Euphrates Graben System, Southeast Syria[1]

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ABSTRACT

The northwest-trending Euphrates graben system is an aborted intracontinental rift of Late Cretaceous age that has subsequently been hidden by Cenozoic burial. Approximately 100 km wide, the system comprises an extensive network of grabens and half grabens extending some 160 km from the Anah graben in western Iraq to the Palmyride fold belt in central Syria, where it becomes more subdued. The youngest prerift rocks are presently at a maximum depth of about 5 km. Based primarily on interpretation of 1500 km of seismic reflection profiles and data from 35 wells, we mapped a complex network of numerous branching normal and strike-slip faults, generally striking northwest and west-northwest. Both branched and single-strand linear normal faults of generally steep dip, as well as positive and negative flower structures, are manifest on seismic sections. No single rift-bounding fault is observed; instead, a major flexure coupled with minor normal faulting marks the southwestern edge of the basin, with considerable variation along strike. To the northeast, deformation diminishes on the Rawda high near the Iraqi border.

The Euphrates graben system likely formed in a transtensional regime, with active rifting primarily restricted to the Senonian and with an estimated maximum extension of about 6 km. Minor Cenozoic inversion of some structures also is evident. Approximately 30 oil fields have been discovered in the Euphrates graben system since 1984. Recoverable reserves discovered to date reportedly exceed 1 billion barrels of oil and lesser amounts of gas. Light oil is primarily found in Lower Cretaceous sandstone reservoirs juxtaposed by normal faulting against Upper Cretaceous synrift sources and seals.

INTRODUCTION

Recent detailed studies on a number of continental rifts have shed considerable light on the architecture and evolution of these types of basins (e.g., Rosendahl, 1987; Morley, 1995). Continental rifts hosting major hydrocarbon accumulations include the North Sea (e.g., Stewart et al., 1992), Gulf of Suez (e.g., Patton et al., 1994), and many others. The Euphrates graben system in southeastern Syria is an aborted continental rift that also holds significant petroleum reserves, but a comprehensive analysis of its development has been unavailable before now in the public literature. In this study, we describe the structure of, and interpret the evolution of, the Euphrates graben system.

Much of the northern Arabian plate consists of a mosaic of relatively stable blocks, including the Rutbah uplift, the Aleppo plateau, and the Rawda (Khleissia) and Mardin highs, bounded by zones of persistent, episodic instability (Figure 1). Deformation in many of these unstable zones, including the Palmyride fold belt, Euphrates/Anah fault system, Azraq/Sirhan graben, and Sinjar and Abd El Aziz uplifts, can be traced back at least to the Triassic and possibly to the late Proterozoic (e.g., Best et al., 1993; Litak et al., 1997). Deformation within the mobile zones has varied through space and time, partly dependent upon the orientation of the zones, and apparently has reflected tectonic events at nearby plate boundaries (e.g., Chaimov et al., 1992; Barazangi et al., 1993). Recent studies of the Palmyrides have elucidated much of their tectonic history, from a possible Proterozoic suture

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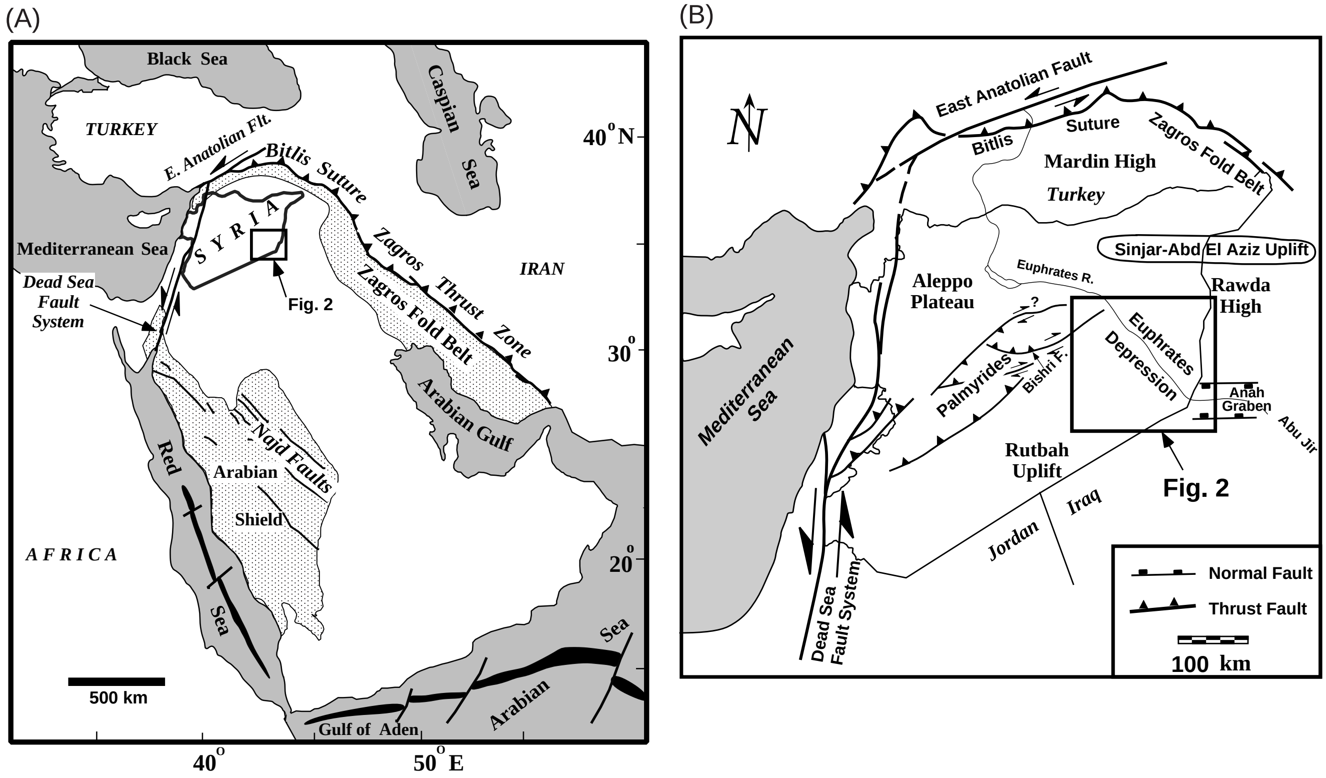

Figure 1—(A) Map showing simplified tectonic setting of the Arabian plate. (B) Map showing location of study region and nearby tectonic features. Location of the area shown in Figure 2 also is shown.

zone (Best et al., 1990) to a Mesozoic aulacogen (Ponikarov, 1967; McBride et al., 1990; Best et al., 1993), to the Late Cretaceous and Cenozoic inversion and uplift (e.g., Al-Saad et al., 1992; Chaimov et al., 1992; Searle, 1994).

Lovelock (1984) briefly described the Euphrates graben and "Al-Furat fault" in a review of regional tectonic elements. Sawaf et al. (1993) presented a crustal-scale cross section across eastern Syria. In two recent papers, Alsdorf et al. (1995) described the junction between the Palmyrides and the Euphrates depression, and Litak et al. (1997) discussed the first-order structures and regional tectonic framework along the length of the northwest-trending Euphrates (Al-Furat) fault system throughout Syria. Brew et al. (1997) used seismic refraction and other data to determine depth to metamorphic basement and to examine upper crustal structure in eastern Syria.

Late Cretaceous rift structures are best developed in southeastern Syria, herein referred to as the Euphrates graben system. These structures, now buried by up to 2.5 km of Cenozoic sedimentary rocks, are largely responsible for the considerable oil reserves that have been discovered in the region during the past decade (de Ruiter et al., 1995). In the context of both continental rifting and regional tectonics, this study focuses on the structural and geologic evolution of the Euphrates graben system and its subsequent burial and partial inversion during the Cenozoic.

DATABASE

The principal data for this study include 1500 km of seismic reflection profiles and information from 35 exploratory wells (Figure 2) covering an area of approximately 13,000 km^2. These data are a subset of a considerably larger database provided by the Syrian Petroleum Company as part of an ongoing cooperative joint project with Cornell University. Seismic data were collected by a variety of contractors throughout the 1980s, and most of the lines are migrated. An array of vibrators provided the source for most of the data, although explosive sources were used on several lines in the Euphrates River valley. Seismic data were interpreted in paper-record form. Stratigraphic tops were available for all wells, and various logs and lithologic information were available for several wells, including sonic logs for six wells. The sonic logs

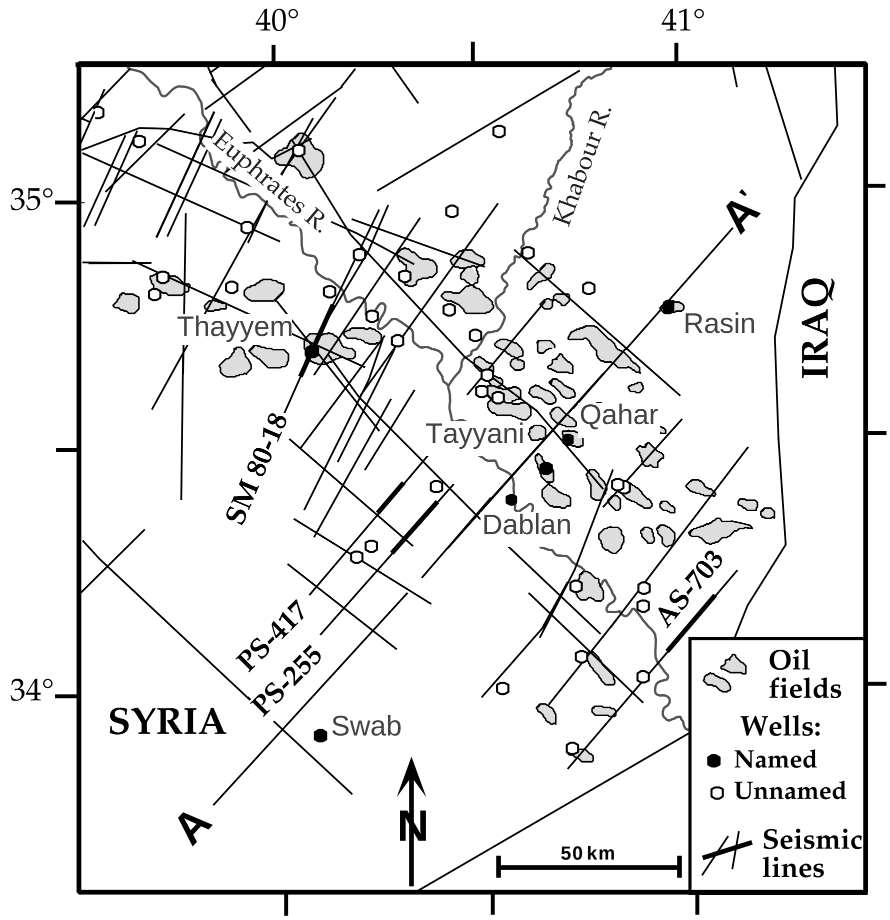

Figure 2—Database map of southeastern Syria showing location of oil fields, wells, and seismic profiles. See Figure 1 for area location. Line AA′ denotes line of cross section in Figure 5. Bold portions of seismic lines are shown in Figures 6, 7, 9, and 13.

were digitized to produce synthetic seismograms and velocity information for depth-time conversion to facilitate well ties to the seismic data.

Stratigraphy and Seismic Character

The stratigraphy of southeastern Syria records a clastic-dominated Paleozoic section more than 4 km thick underlying Triassic–Neogene carbonates and evaporites interbedded with lesser amounts of shale and sandstone (Figure 3). The stratigraphy of eastern Syria is described in some detail by Sawaf et al. (1993), and lithostratigraphic charts have been published by Lababidi and Hamdan (1985); therefore, we concentrate on the major packages of rock and their seismic signatures. Based on refraction and wide-angle reflection data, Seber et al. (1993) and Brew et al. (1997) estimated the minimum thickness of the entire sedimentary section to be over 8 km on the Rutbah uplift. The Paleozoic section is generally poorly reflective with a few prominent exceptions (Al-Saad et al., 1992). A strong, continuous, multicyclic reflection from the Middle Cambrian Burj limestone is the deepest regionally correlatable event (McBride et al., 1990; Sawaf et al., 1993), disappearing below 4 s beneath the deepest part of the Euphrates graben system. Brew et al. (1997) determined basement depth beneath the Euphrates graben system to be around 9 km. On some seismic lines, the Burj marker is discordant with reflections observed below it, which may represent Proterozoic sedimentary rocks [as suggested by Seber et al.(1993)] beneath an Eocambrian (Pan-African) unconformity. Good regional reflections from the top of the Upper Ordovician Affendi and Lower Ordovician Swab formations can be ascribed to sharp shale/sandstone and sandstone/shale discontinuities, respectively. More than 3400 m of Ordovician section is penetrated in the Swab well (location shown in Figure 2). The poorly reflective Silurian Tanf Formation, up to 750 m thick, contains a sandstone unit underlying organic shales thought to represent a good potential source rock (Beydoun, 1991). No Devonian rocks have been recognized in Syria, but the unconformity (D on Figure 3) has little structural relief, making its seismic identification problematic. Lower Carboniferous rocks of the Markada Formation are penetrated in several wells. These

Figure 3—Generalized stratigraphic column for eastern Syria.

Age			Formation	Maximum Thickness (m)	Description	Notes
Quaternary			Bakhtiary	1000	conglomerate w/ sandstone	Minor reactivation; transpression
Tertiary	Pliocene		Upper Fars		sandstone w/ shale	
Tertiary	Miocene		Lower Fars	700	anhydrite, gypsum, sh.	
			Jeribe	125	dolomitic lmst. w/ anhyd.	
			Dibbane	250	anhydrite over halite	
			Euphrates	200	limestone & marly ls.	Mapped horizon on Figure 11
	Oligocene		Chilou	500	limestone & marly ls.	
	Eocene		Jaddala	600	marly ls.& limestone	
	Paleocene		Kermav (Aliji)	600	marl & marly shale	Mapped horizon on Figure 10
Cretaceous	Upper	Maastricht. / Campanian	Shiranish	1600	marl & argil. limestone	A
		Santonian	Soukhne/Massive	700	marl over cherty lmst.	Main phase of rifting
		Coniacian	Derro	150	red congl. sandstone	
		Turonian / Cenomanian	Judea	1200	dolomitic ls.w/ anhydrite	B
	Lower		Rutba	500	sst. over some basalt	Mapped horizon on Figure 4
Triassic	Upper		Sarjelu	700	dolomite w/ shale	C
			Allan/Muss	150	dolomite w/ shale	
			Adaya	150	shale, anhyd. & dolomite	
			Butma	300	dolomite w/ shale	
	Middle		Kurrachine Anhydrite	400	anhydrite	
			Kurrachine Dolomite	800	dolomite w/ some ls.	
	Lower		Amanous Shale	250	shale	
Permian			Amanous	750	sandstone	
Carboniferous			Markada	1200	sst. w/ some dolomite	D
Lower Silurian			Tanf	750	shale w/ interbed. sltst	
Ordovician			Affendi	1000	sandstone w/ shale	
			Swab	1000?	shale w/ minor sst.	
			Khanasser	1500?	sandstone	
Cambrian			Sosink	750+	quartzitic sandstone	
			Burj	150+	dolomite limestone	
			Zabuk	?	quartzitic sandstone (?)	

rocks are up to 1 km thick and consist mainly of interbedded sandstones and shales; these rocks are generally less reflective than the overlying section. Locally, however, a dolomite marker forms a prominent seismic horizon. The Upper Carboniferous, Permian, and Lower Triassic section is generally absent in the study area (Sawaf et al., 1993).

The Triassic–Santonian section in eastern Syria is dominated by carbonates and evaporites, with lesser amounts of shale, chert, and an areally restricted Lower Cretaceous sandstone. This sandstone, the Rutba Formation, was most likely deposited in a deltaic environment and is an important hydrocarbon reservoir in the area. Marked thinning of the Upper Triassic section onto the Rutbah uplift is noted on several seismic lines and is attributed to the emergence of the uplift during this time (Sawaf et al., 1993). Jurassic carbonates attain a thickness of over 800 m in the Bishri and Sinjar areas (and considerably more along the Levantine margin), but are missing in the Euphrates area, as is the Neocomian section. This Early Cretaceous unconformity (C on Figure 3) is nearly concordant with underlying Triassic rocks, and may represent a regional uplift that eroded Jurassic and (partially) Triassic rocks, or may represent simply a prolonged hiatus (Best et al., 1993). Several wells also encounter a thin section of basalt in the Lower Cretaceous and lower Upper Cretaceous. These volcanic rocks are found in a number of wells throughout Syria and probably are related to regional extension rather than the onset of the Euphrates graben sensu stricto. Because of its lithologic heterogeneity, the entire Triassic–Lower Cretaceous section often forms a distinctive zone of high-amplitude reflections that ranges in seismic thickness up to several hundred milliseconds.

Due to the presence of several unconformities, the completeness of the Cretaceous section differs greatly from well to well. The late Campanian–Maastrichtian Shiranish Formation is present throughout the area, although its thickness varies dramatically. This formation primarily consists of marl having poor seismic reflectivity; strong local reflections within the Shiranish interval are likely due to interbedded limestone or sandstone. The Shiranish Formation overlies either the Upper Cretaceous Soukhne or Judea, the Lower Cretaceous Rutba, the Triassic Serjelu (Mollussa F), or the Carboniferous Markada formations (Figure 3). The Coniacian Derro Formation, unconformably bounded at both top and base, is present in only eight of the available wells. The base Coniacian unconformity (B on Figure 3) probably signals the onset of rifting in the Euphrates graben (Lovelock, 1984), and generally exhibits the most pronounced discordance of any Cretaceous unconformity in the study area. In addition, a seismic discordance of lower relief, but considerable extent, is apparent in several areas within the Shiranish itself. This upper unconformity (A on Figure 3) appears to be especially notable in the northwestern part of the study area, and is here interpreted as the synrift/postrift boundary.

Paleogene rocks (Chilou, Jaddala, and Kermav formations) grade upward from marl and calcareous shale to limestone, and underlie the lower and middle Miocene evaporites of the Dibbane, Jeribe, and Lower Fars formations (Figure 3), deposited in open or sometimes restricted seas (Sawaf et al., 1993). Less than about 400 m of upper Neogene and Quaternary continental clastics (Upper Fars and Bakhtiari formations) are exposed at the surface over much of the study area. The low-amplitude, discontinuous seismic reflections of these units contrast sharply with the strong continuous reflections of the underlying Miocene evaporites.

STRUCTURAL DEVELOPMENT OF THE EUPHRATES GRABEN SYSTEM

Seismic Interpretation

A time-structure map on the base of the Upper Cretaceous (the Rutba Formation over most of the study area) illuminates the extent and style of deformation of the Euphrates graben system (Figure 4). Sonic logs were available for at least portions of six wells; these logs were digitized to produce synthetic seismograms that were tied to the nearest seismic lines. The resulting velocity information was used to tie in stratigraphic tops from the additional 29 wells in the study area. Where necessary, wells were projected up to several kilometers to the nearest available seismic line by considering seismic character and structural trends. Data quality varies, with mapping generally most reliable in the southwestern part of the study area, and less reliable in the deeper parts of the graben system. Where strike lines are sparse, fault correlations are made on the basis of similar seismic expression and consistency of structural levels.

Deformation is distributed over a wide area among many closely spaced faults; only the larger or more continuous faults are shown. Faults generally trend northwest to west-northwest, with only minor branches and transfer zones of differing orientations. The rift axis generally coincides with the Euphrates River valley, with the deepest part just north of the junction with the Khabour River (Figure 4). This map documents two sets of fault domains. In the north and northwest, faults strike west-northwest, with several large normal faults typical of a classical graben. In the south and southeast, however, faults strike more northwest, with more diffuse deformation and near-vertical flower-type structures suggesting strike-slip motion (e.g., Harding, 1985). Deformation is transferred in a step wise fashion toward the southeast, with down-to-the-north fault motion transferred from the Deir Azzor fault to the Thayyem fault, and eventually to the El Ward fault (Figure 4). The El Ward fault exhibits progressively less throw to the southeast, becoming more of a hinge or flexure. Several faults (notably the El Ward fault) exhibit a convex shape in map view. This pattern is unusual in continental rifts, with the "ideal" half graben of Rosendahl (1987) being of concave arcuate shape; however, similar faults have been reported in the Suez rift by Patton et al. (1994). We found no evidence for major transverse structures such as those reported in the East African rift (e.g., Rosendahl et al., 1986).

The general structure of the Euphrates graben system is illustrated by a seismically derived cross section (Figure 5). Relatively steep (>70°), planar normal faults are approximately symmetrically distributed around a central graben. Many of these faults clearly offset or disrupt the Cambrian Burj Formation between 3 and 4 s, corresponding to approximately 5–8 km (Figures 5, 6), indicating that they penetrate deep into the section, probably into Precambrian basement. Basement depth along this cross section is between approximately 6 and 8.5+ km (Brew et al., 1997). Faults are spaced irregularly about every 5 km, and are mostly depicted here as single faults with occasional synthetic or antithetic faults; however, only major faults are shown, and observed disruption of seismic data suggests numerous additional minor faults. With few exceptions, faults do not extend upward into the Tertiary section, constraining the main phase of active extension to the Late Cretaceous. From the

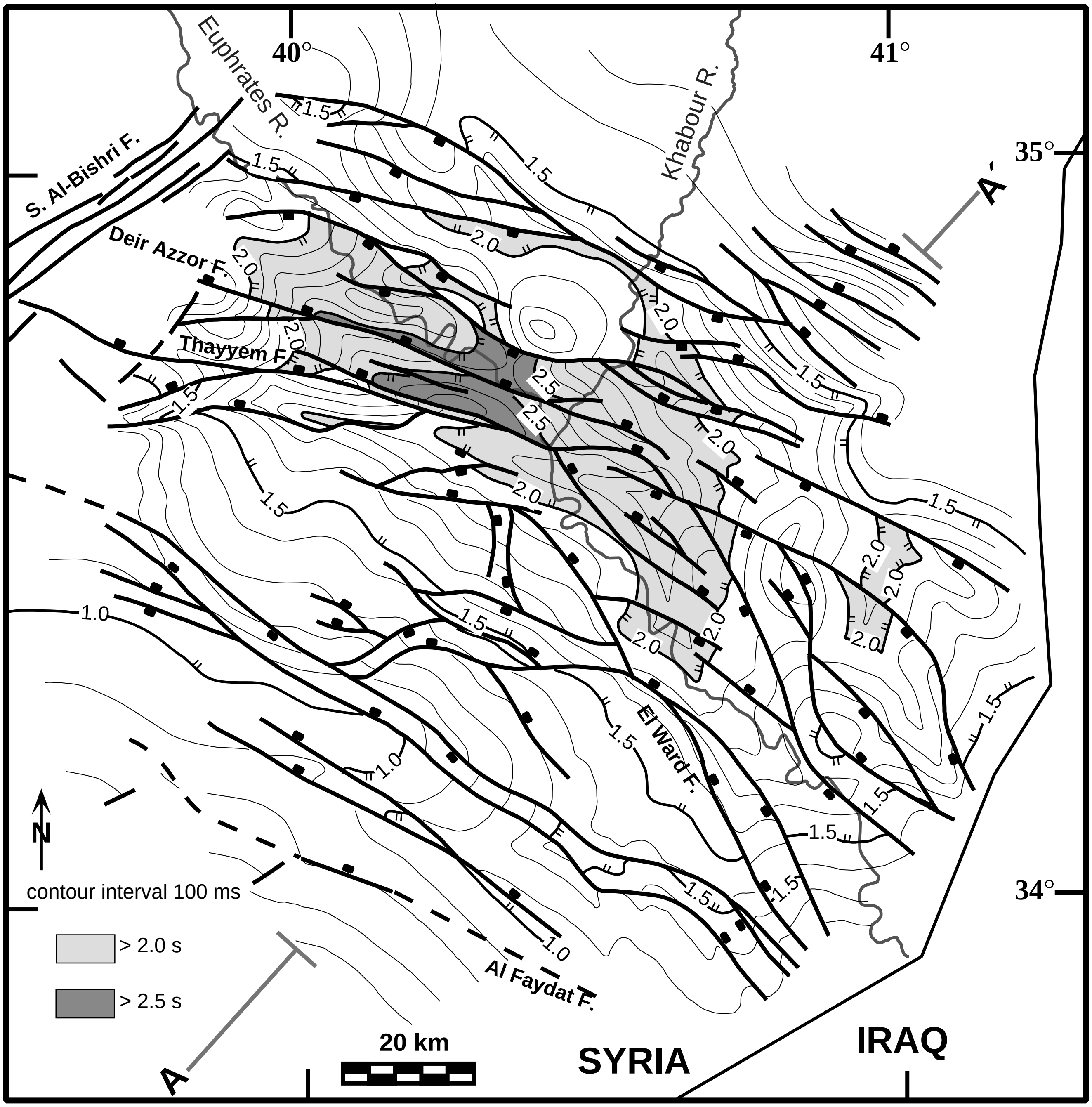

Figure 4—Time-structure map of the base Upper Cretaceous horizon, in seconds two-way traveltime. Large west-northwest–striking normal faults (Deir Azzor, Thayyem) dominate in the northwestern part of the area, whereas numerous northwest-striking normal and strike-slip faults abound near the Iraqi border, with no single fault dominant. Seismic and well control shown in Figure 2. AA′ denotes line of cross section shown in Figure 5.

relatively undeformed section of the Rutbah uplift to the southwest, minor down-to-the-northeast faulting is apparent in front of a flexural feature where Upper Cretaceous and Tertiary rocks begin to thicken fairly abruptly (Figure 5). This "edge" of the Euphrates graben system is sometimes referred to as the El Madabe step (Sawaf et al., 1993). The deepest part of the main graben occurs just east of the Euphrates River, where the dominant fault dip changes from northeast to southwest. This central

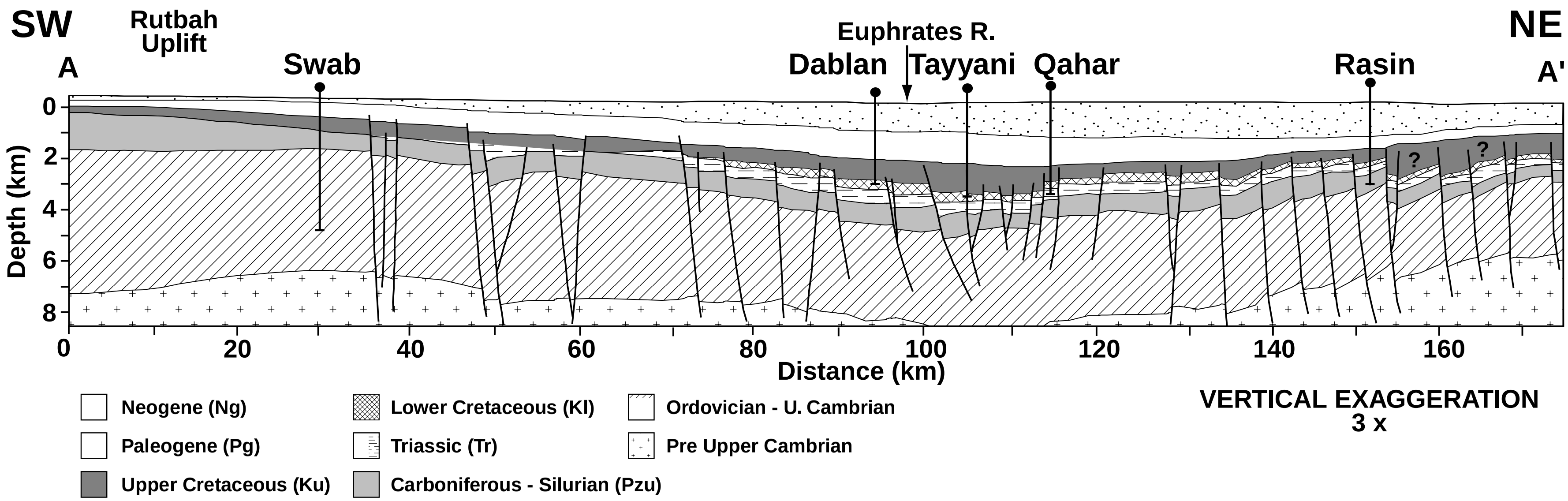

Figure 5—Structural cross section across the Euphrates graben system based on seismic interpretation constrained by well data. Location shown in Figures 2 and 4.

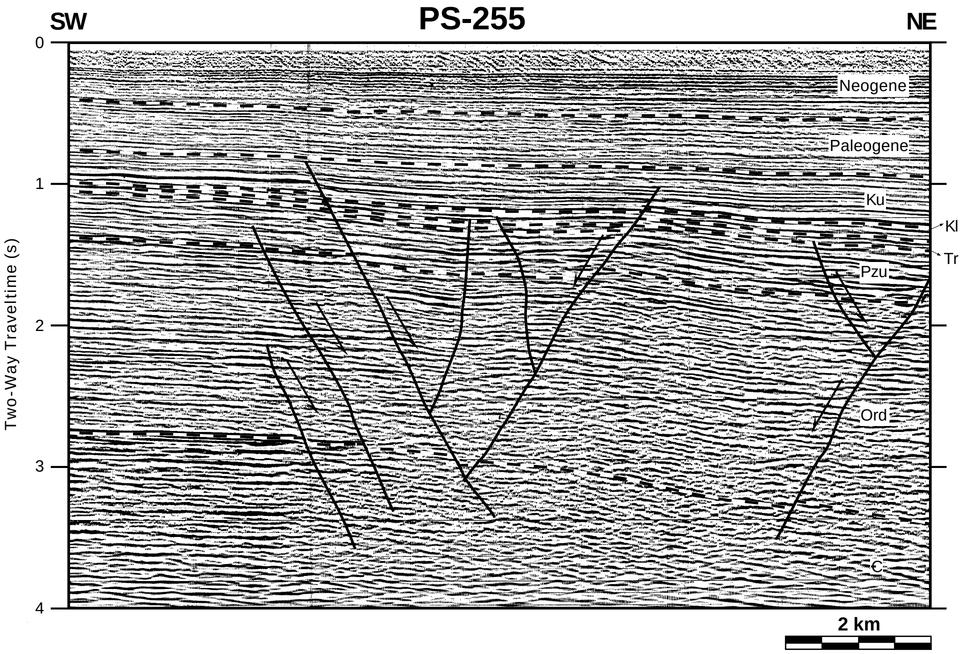

Figure 6—Seismic example of southwestern edge of Euphrates graben system. Pzu = rocks of Paleozoic age younger than Ordovician. See Figure 2 for location. Abbreviations are explained in Figure 5.

graben area approximately coincides with the main oil-producing trend of the Euphrates play (Figure 2). The northeastern portion of the transect displays a series of southwest-dipping half grabens bounded by northeast-dipping planar normal faults (Figure 5). A local structural high at Lower Cretaceous levels occurs near the Rasin well. Based on limited data (see Figure 2), we interpret the area northeast of this local high as another zone of Late Cretaceous normal faulting between the Euphrates River and the Rawda high; however, Paleogene rocks continue to thin over this secondary graben, in contrast to the central part of the Euphrates graben system. A southwest-dipping monocline can be dated to the Neogene (Figure 5). The monocline approximately coincides spatially with the underlying half grabens, suggesting minor Neogene reactivation of the earlier structure.

In the vicinity of the El Madabe step the Coniacian unconformity (B on Figure 3) is most clearly

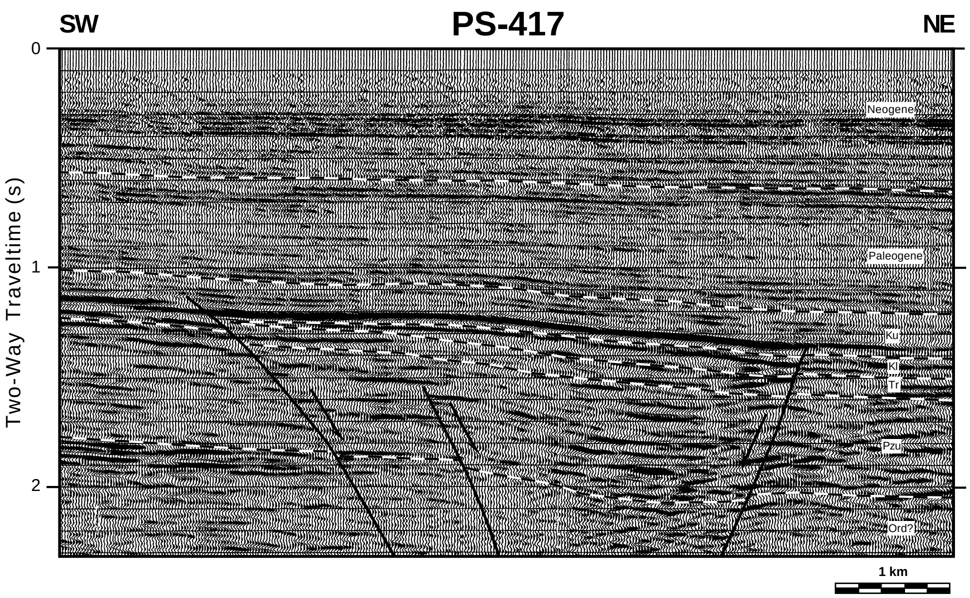

Figure 7—Seismic example of Coniacian unconformity (B on Figure 3) truncating Lower Cretaceous rocks at transition from Rutbah uplift to Euphrates graben system. Pzu = rocks of Paleozoic age younger than Ordovician. See Figure 2 for line location. Abbreviations are explained in Figure 5.

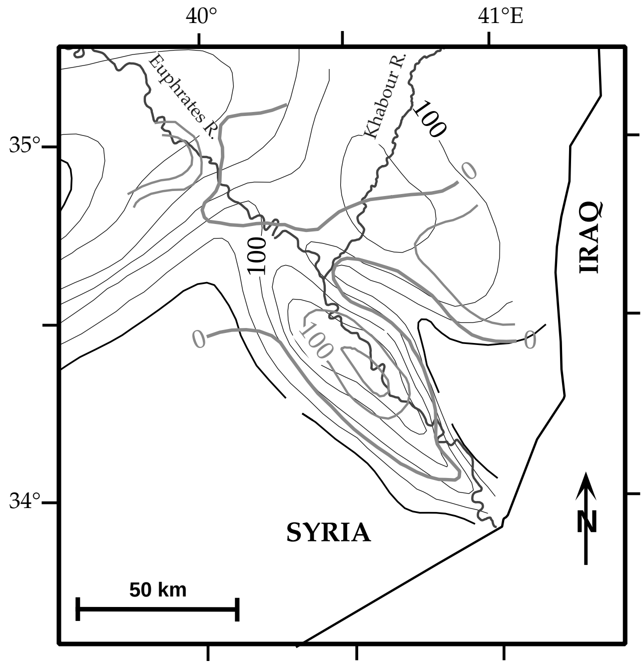

Figure 8—Isopach maps of the Lower Cretaceous Rutba (thin lines) and Upper Cretaceous Judea (heavy lines) formations (see Figure 3). The subcrop pattern suggests subsequent erosion along the graben flanks. Contour interval 50 m.

evident. This unconformity progressively cuts out Lower Cretaceous and then Triassic rocks to the southwest as it merges with base Cretaceous and Upper Triassic unconformities. In wells drilled farther to the southwest, the Rutba Formation, the principal reservoir in the area, is missing. This unconformity can be mapped on seismic reflection data in the area (Figure 6, 7). An isopach map of the Rutba Formation based on seismic and well data indicates thickening along the axis of the graben system (Figure 8). At least part of this thickening likely is due to erosion. The Cenomanian–Turonian Judea Formation pinches out closer to the graben axis than the underlying Rutba Formation (Figure 8), a subcrop pattern consistent with postdepositional erosion rather than onlap. This updip pinch-out of the reservoir raises the possibility of a combination stratigraphic/structural play in this area, a concept that, to our knowledge, has not been tested.

An excellent example of Euphrates structure is shown on line SM 80-18 (Figure 9). A major normal fault system drops Lower Cretaceous rocks approximately 500 ms (~1 km) down to the northeast. Footwall uplift, perhaps including a component of strike-slip faulting, is apparent beneath a clear unconformity. Because a sonic log is not available for the Thayyem well, the precise age of this unconformity is difficult to ascertain; however, well control indicates that the pre-Coniacian Judea Formation is thicker on top of this structure than in the downthrown fault block, signifying that the Judea has not been cut out by the unconformity. Thus, we interpret this unconformity (A on Figure 3) to occur within the Shiranish (Late Campanian–Maastrichtian) rather than the Coniacian. In fact, the Santonian–early Campanian Soukhne Formation is thinner on the structure than elsewhere, consistent with a post–early Campanian age for the unconformity. The major thickening, from 200 to 500 ms, occurs in the Campanian–Maastrichtian Shiranish Formation, dating the main phase of extension to that time. Occurring near the top of the Shiranish Formation as seen in Figure 9, the unconformity is likely of late Maastrichtian age (A on Figure 3), and may represent the boundary between the synrift and postrift sequences (Litak et al., 1997). Note also the slight rollover of Neogene reflections, with a northwestern (counterregional) dip suggesting minor inversion of this structure.

The overall postrift structure is illustrated by a generalized depth map to the top of Cretaceous rocks (Figure 10). This map, based primarily on well tops and guided by seismic data, shows a broad depression centered just east of the junction between the Euphrates and Khabour rivers, with a maximum depth exceeding 2600 m BSL. At the Oligocene level, the basin is much broader, with Neogene deposits (primarily the upper Miocene Lower Fars Formation) extending over much of eastern Syria (Figure 11). Subtracting these two maps yields an isopach map of Paleogene rocks, inferred to represent the postrift sequence (Figure 12). Note that the Paleogene and Neogene depocenters are offset somewhat. This offset may indicate that, although the existence of the Euphrates weak zone likely had some influence on the location of Neogene sedimentation, Neogene deposition may have been primarily controlled by other factors, which may include the Zagros collision and development of the Mesopotamian foredeep.

In the easternmost part of the study area, both positive and negative flower structures (Harding, 1985) are interpreted as indicative of strike-slip faulting (e.g., Figure 13). These faults also appear to have been active during the Late Cretaceous. Reactivation of these structures is commonplace and appears to be diachronous on different structures. Figure 13 depicts subtle deformation of Paleogene reflections; other structures evince growth during the middle Miocene (e.g., Figure 12) and Pliocene (Quaternary?). These structures bear considerable similarity to mild inversion structures noted in east Africa by Morley (1995). Cenozoic inversion in the Euphrates graben area is minor and results in minimal shortening.

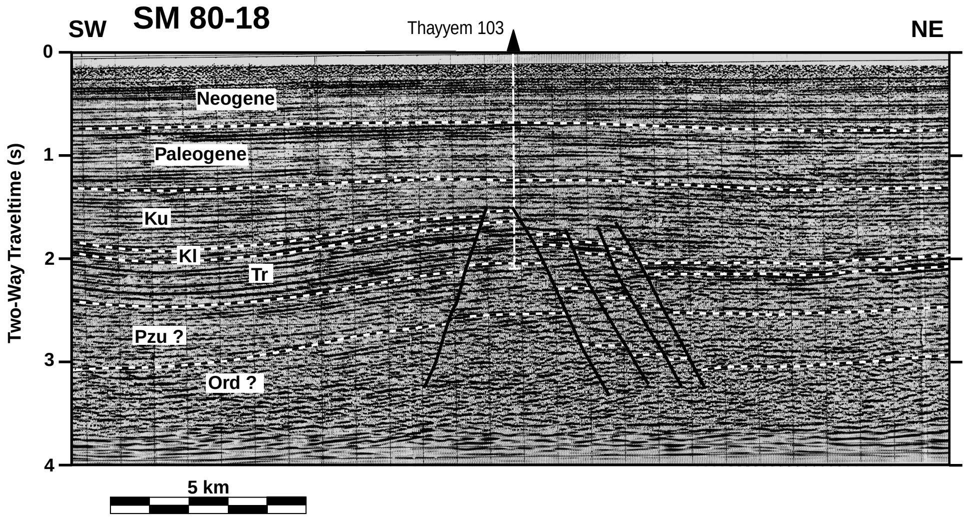

Figure 9—Seismic example showing Thayyem field and fault, an example of a major normal fault into a half graben. Note the marked unconformity within the Upper Cretaceous. Pzu = rocks of Paleozoic age younger than Ordovician. See Figure 2 for location. Abbreviations are explained in Figure 5.

Magnitude of Extension

The cross section in Figure 5 can be used to provide simple estimates of extension across the Euphrates graben system. Two methods are applied here, and both methods yield estimates of not more than 6 km total extension. First, line-length balancing at the base of the Upper Cretaceous results in an estimate of only about 0.9 km; however, line-length balancing commonly gives lower estimates of extension than do other methods. In this instance, the low estimate of extension primarily is due to the steepness of the faults, typically more than 70°, but their true attitude is poorly constrained by the seismic data (e.g., see Figure 10). Because the extension along a given fault varies as the cosine of the dip angle, slight changes in fault dip lead to significant differences in bed length measurements. Also, in presenting Figure 5 we did not consider many minor faults and splays that may accommodate additional extension, so by necessity these results represent a minimum estimate. Marrett and Allmendinger (1991) argued that small faults can account for a significant amount of the total strain across a fault system.

An alternative method is to calculate the extension directly from the excess sediment area. This method assumes that isostatic equilibrium was maintained throughout rifting, and that low-density synrift and postrift sediments are compensated by thinning of the crust and lithosphere. The isostatic balance is summarized by Turcotte (1983) in the following equation:

$$y_s = \frac{(\rho_m - \rho_c)}{(\rho_m - \rho_s)} y_{C0}(1 - \gamma_C) - 0.5\frac{\rho_m \alpha_m (T_m - T_0)}{(\rho_m - \rho_s)} \gamma_{L0}(1 - \gamma_L) \quad (1)$$

where y_s = the synrift sedimentary thickness, the first term on the right = the combined synrift and postrift thickness; the second term = the postrift accumulation. We wish to solve for γ_C, the crustal thinning factor, and γ_L, the lithospheric thinning factor. Absent evidence to the contrary, these terms are assumed to be equal. For many of the variables used in these terms, we have taken these commonly used values: ρ_m = the density of the mantle (3300 kg/m^3), ρ_c = the density of the crust (2750 kg/m^3), α_m = the coefficient of thermal expansivity of typical rocks (3×10^{-5}/K), T_m - T_0 = the difference in temperature between the surface and the mantle (1250 K), and y_{L0} = the initial lithospheric thickness (assumed to be 180 km).

The initial crustal thickness, y_{C0}, is taken as 37 km based on a seismic and gravity transect in southwestern Iraq that passes close to southeastern Syria (Alsinawi and Al-Banna, 1990), and on the gravity model of Sawaf et al. (1993) and Khair et al. (1997) in eastern Syria. The area of the synrift (Late Cretaceous below the postrift unconformity; A on Figure 3) section was measured from Figure 5, and found to be 50 km^2. For a rift zone 100 km wide, the measured areas correspond to average sediment thickness of 500 m. For the postrift (primarily Paleogene) thickness we also subtracted the average thickness of postrift-age sediments observed outside of the rifted area. This method yields a value of 625 m. The average density of the synrift and postrift sediments (ρ_s) is derived from the density log of the El Madabe NW-101 (about 15 km northwest of the cross section). The synrift density is 2.43 kg/m^3, and postrift density is 2.22 kg/m^3. An average value for the combined synrift and postrift sections, weighted in proportion to their thicknesses, is thus 2.313 kg/m^3.

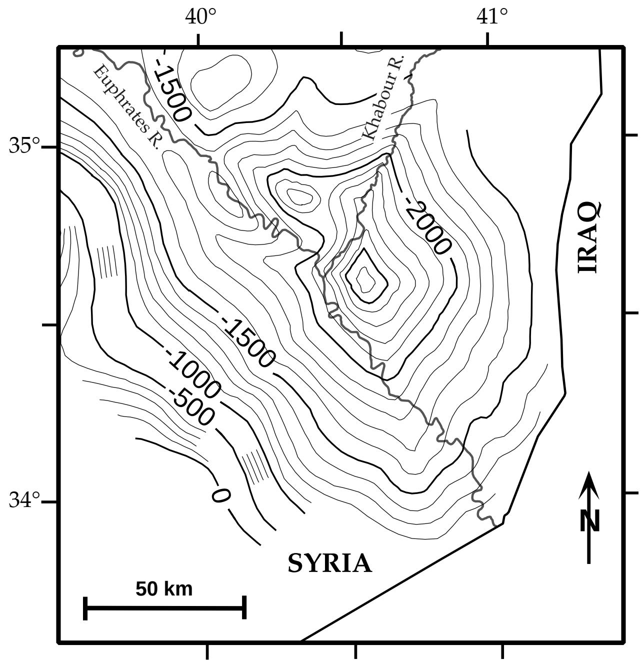

Figure 10—Generalized structure map, top of Cretaceous (see Figure 3). Contours in meters below sea level.

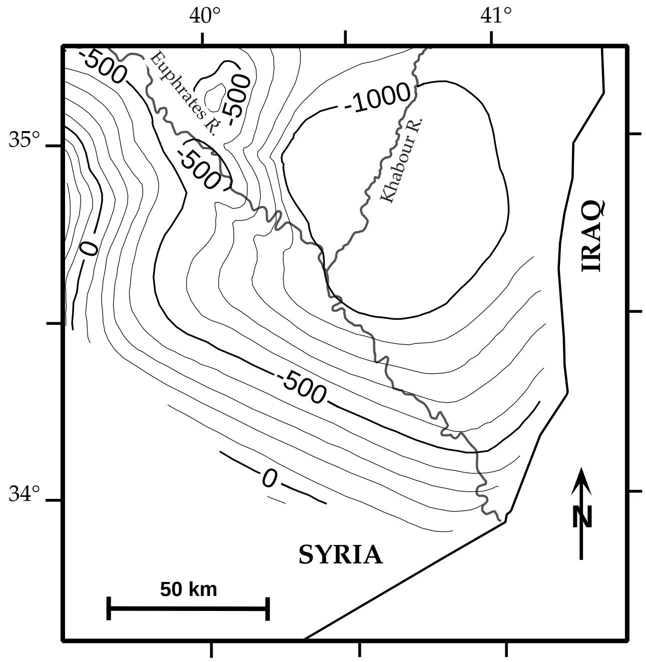

Figure 11—Generalized structure map, top of Oligocene (see Figure 3). Contours in meters below sea level.

Using the values in equation 1 yields a thinning factor of 0.946, corresponding to a stretching factor (β value of McKenzie, 1978) of 1.06. Thus, 6 km of stretching has taken place, thinning the initial 37 km crust to 35 km, and thinning the lithosphere approximately 10 km, from 180 km to 170 km. The second term of equation 1 also provides an independent assessment of the postrift thickness based on thermal subsidence after the end of rifting, which here yields an average postrift thickness of 604 m, compared to the observed value of 625 m. These calculations, although necessarily nondefinitive because they are based on certain assumptions (lithospheric thickness, mantle temperature, etc.), thus suggest that the Euphrates graben system underwent stretching of about 6 km, and subsequent thermal subsidence appears to have extended throughout the Paleogene.

The fact that lower and middle Miocene formations are thin or absent also suggests that postrift sedimentation effectively ceased before the Neogene. In addition, the late Miocene depocenter is offset somewhat to the northeast from the locus of rifting (compare Figures 10 and 11). Thus, the upper Miocene section probably is dominated by subsidence that may be associated with development of the Mesopotamian foredeep and the Zagros continental collision.

The amount of strike-slip along the Euphrates fault system is more difficult to quantify, and reliable estimates are not possible with the current data set; however, comparing the number, continuity, and apparent seismic disruption of the normal faults and faults interpreted to involve some strike-slip motion suggests that the magnitude of strike-slip displacement is not greater than the extensional displacement. Mapping of Lower Cretaceous reflections provides little evidence for significant strike-slip movement. In particular, the Euphrates fault system probably did not accommodate the nearly 60 km of offset necessary for the Abd El Aziz and Sinjar zones to represent the northeastward continuation of the Palmyrides (see Figure 1B), as suggested by Lovelock (1984).

DISCUSSION

Hydrocarbon Habitat

The trend of major producing oil fields in the Euphrates graben system occurs in a fairway approximately 40 km wide (Figure 2). This fairway is centered northeast of the Euphrates River near Iraq and trends northwest, becoming more west–northwesterly near the Khabour River. Inspection of the structure map (Figure 4) reveals that this productive trend follows the fault trends discussed, as well as the rift axis. In addition, the larger fields generally are located near the deepest

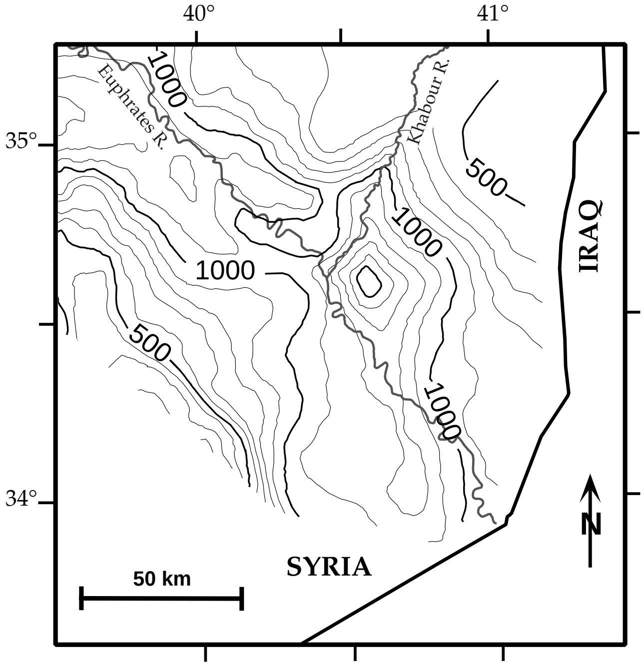

Figure 12—Isopach map of Paleogene rocks (see Figure 3), contours in meters.

part of the basin. This correlation suggests that the location of productive fields is largely governed by the thickness and maturity of synrift source rocks. The source rocks are principally the Soukhne and Shiranish formations, but others are documented in the Silurian Tanf formation (Figure 3), and possibly within the Carboniferous (de Ruiter et al., 1995).

The Thayyem oil field (Figure 9) is exemplary of oil-producing structures in the Euphrates graben system, albeit most structures are considerably subtler. The Thayyem was the first field discovered in the Euphrates play in 1985 (Beydoun, 1988; de Ruiter et al., 1995), and remains one of the most prolific fields. Primary production is from the Rutba Formation, with additional reserves in Miocene carbonates trapped in the inverted rollover structure. The Rutba reservoir is charged by Upper Cretaceous source rocks, principally the Soukhne and Shiranish formations, downthrown to the normal fault system. The thick Shiranish section also provides the seal both above and laterally, with closure achieved against the normal faults.

Most oil fields are similarly located on structural highs associated with normal faults and rely on upthrown closure against those faults. The Rutba sandstone is juxtaposed against the marly shales of the Shiranish Formation by even relatively small faults. Many fields of limited areal extent, but significant productivity, are due to the extremely numerous minor faults of the Euphrates system and the relatively undeformed sealing lithology that exists above good reservoir rocks. Trap integrity is somewhat of a concern only in the areas that have experienced significant reactivation in the northwestern part of the Euphrates fault system. In addition to the Shiranish Formation, the shaly Derro clastics have been proven to be good seals, and several reservoir/seal pairs have been documented in the Triassic carbonates and evaporites (Beydoun, 1991). Although the Rutba sandstone is the most prolific reservoir in the graben, other reservoir-quality rocks have been documented in the Triassic and Carboniferous, although more drilling is needed to fully assess Paleozoic lithology. Sealing of a Carboniferous reservoir might have to rely on interbedded shales or on being upthrown against the Upper Cretaceous carbonates. Proven recoverable reserves in the Euphrates area are estimated at well over 1 billion barrels of light, sweet oil and much lesser amounts of gas. Current production from the Euphrates is around 450,000 barrels per day (OAPEC Bulletin, 1996).

Cenozoic Reactivation

In contrast to the Palmyrides (e.g., Chaimov et al., 1990), Abd El Aziz-Sinjar uplift (Sawaf et al., 1993), and even the northwestern part of the Euphrates fault system (Litak et al., 1997), the Euphrates graben system in southeastern Syria has experienced relatively little inversion associated with the Cenozoic collision along the northern edge of the Arabian plate. Near the junction with the Palmyrides, several Late Cretaceous extensional structures appear to have been uplifted during the Neogene. In particular, an anticline along the Euphrates River near the main graben axis may be associated with reactivation of a Cretaceous normal fault (at approximately 34°45′N, 40°10′E on Figure 11), and probably accommodates some of the dextral transpression along the South Al-Bishri (Figures 1B, 4) and related faults of the Palmyrides [see Alsdorf et al. (1995) for more discussion of this area]. In contrast to the South Al-Bishri fault, however, there is no seismicity or topographic evidence for Quaternary inversion of this structure. Shortening associated with this structure is limited to a maximum of a few hundred meters, and probably less.

In the northwestern part of the Euphrates fault system, Litak et al. (1997) documented significant uplifts and clear instances of true inversion of normal faults. Such features are not apparent in southeastern Syria. Instead, Late Cretaceous faults seem to have been reactivated as positive flower structures or uplifted blocks (see Figure 13). These structures may be related to their proximity to the

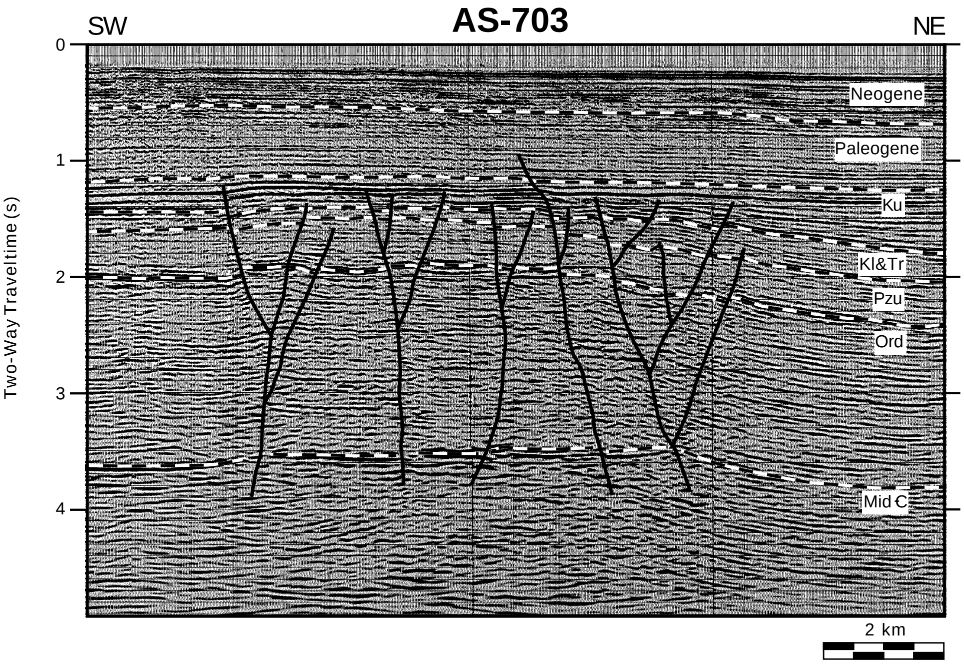

Figure 13—Seismic example showing uplifted block exhibiting apparent strike-slip faulting adjacent to half-graben (to northeast). Note slight upwarping of Paleogene reflections signifying minor Cenozoic reactivation. This structure is the site of a reported 1994 oil and gas discovery. Pzu = rocks of Paleozoic age younger than Ordovician. See Figure 2 for location.

east-trending Anah graben in Iraq (Dunnington, 1958; Ibrahim, 1979) and also accommodate minimal shortening. Upwarping of Pliocene reflectors can be noted on several structures. Strike-slip deformation also may occur along the northern edge of the Euphrates graben system where seismic control is relatively poor. (This end of the Euphrates graben and its relationship to the Abd El Aziz and Sinjar uplifts will be further explored in future research.) The presence of several linear segments of the Euphrates River and the general coincidence of its present course with the mapped fault trends suggest some Quaternary activity along those faults, especially in southeastern Syria (Ponikarov, 1967), but no significant Quaternary offsets are observed on the few seismic lines that cross the Euphrates River valley.

Regional Relationships

Northwest-trending structures are apparent all over the northern Arabian plate, from the Red Sea to the Zagros Mountains. Beydoun (1991) suggested that these structures might all be related to the late Proterozoic Najd fault system exposed in Saudi Arabia (e.g., Stoesser and Camp, 1985; Agar, 1987; Husseini, 1989). The Najd deformation may have imparted a deep-seated regional fabric that controlled the locus of later episodes of deformation. Lovelock (1984) conjectured that the Euphrates fault system, after an eastward step at the Anah graben, continued along the southeast-striking "Abu Jir" trend. Kader and Marouf (1994) discussed parallel structures farther east along the Tigris River that appear to have a remarkably similar history to the Euphrates graben system. These workers described flower structures, normal faulting, and graben formation active during the Campanian–Maastrichtian with minor late Neogene dextral transpression. Litak et al. (1997) attempted to further link the Najd fabric to the Sirhan graben and overlying basalt field in Jordan, and also suggested that the Euphrates fault system may represent a Proterozoic suture between the Rutbah and Rawda blocks. This conjecture is supported by the gravity modeling of Brew et al. (1997).

The fault trends mapped in this study generally are consistent with the exposed Najd faults, lending credence to those interpretations; however, as discussed, two fault populations of different characteristics and slightly different strikes can be distinguished. The northwest-striking faults in southeasternmost Syria are more nearly parallel to those of the Najd trend. Because they also appear to evince more strike-slip movement than the graben-type normal faults farther northwest, one interpretation is that these northwest-striking faults were oblique to the Late Cretaceous extension direction, whereas the graben-type normal faults may have been more nearly orthogonal to extension. This scenario implies that the west-northwest–striking faults initially may have formed in response to Late Cretaceous stresses rather than being reactivated Proterozoic faults. That is, Late Cretaceous intraplate strain may have been initially accommodated by the

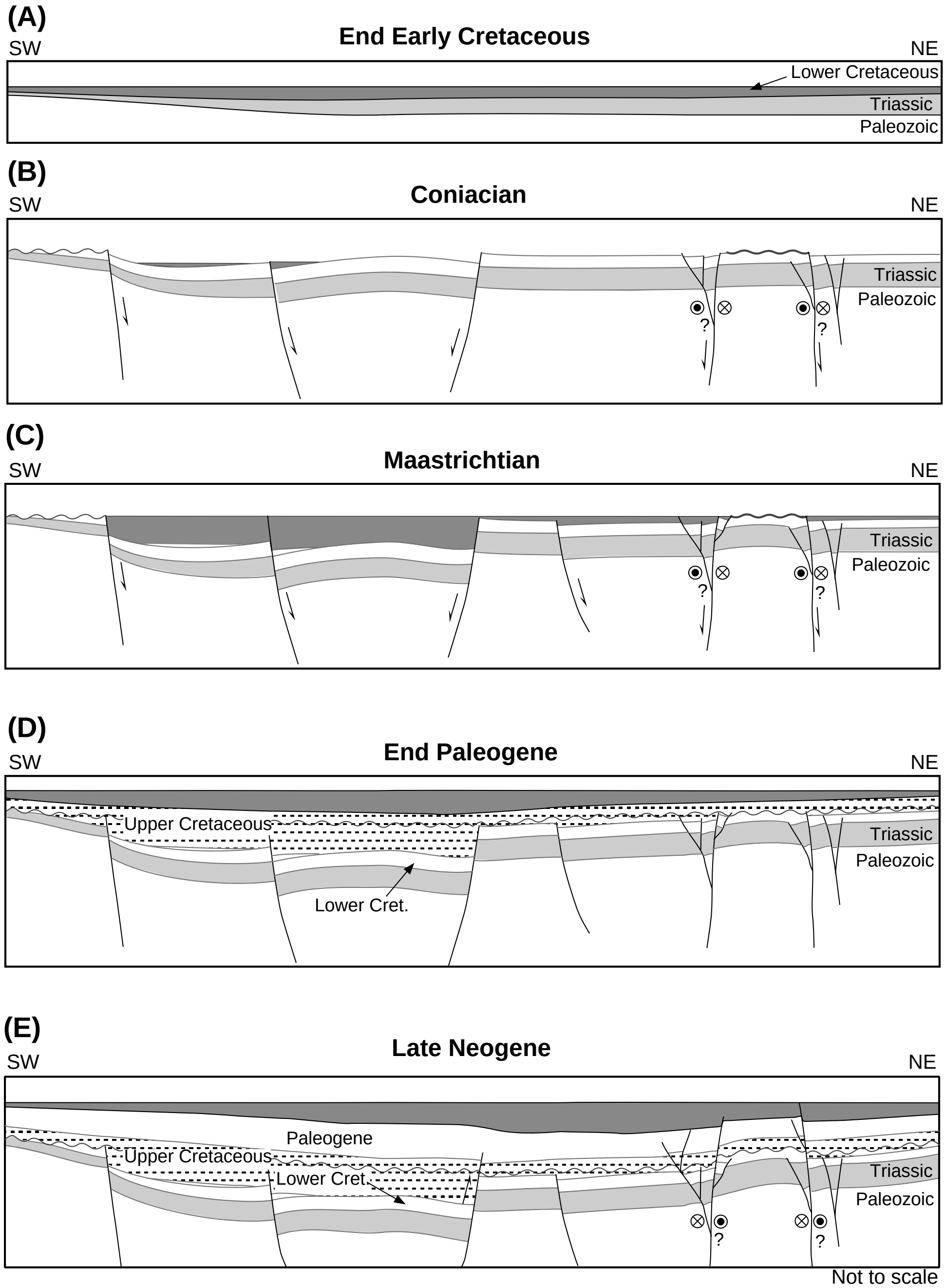

Figure 14—Series of schematic cross sections illustrating conceptual evolution of the Euphrates graben system. Darkest shaded area represents most recent sedimentation in each case.

Najd faults, but later broke through a new set of more favorably oriented structures. This interpretation would suggest that Late Cretaceous motion of the Rawda block relative to the Rutbah block was north–northeast rather than north as implied by Lovelock (1984) and Litak et al. (1997). Alternately, the change in fault orientation may reflect a change in the preexisting structures at the "corner" of the Rutbah block formed by the intersection of the Euphrates and Palmyrides trends.

Comparison With Other Rifts

At about 160 × 90 km, the scale of the Euphrates graben system in southeast Syria is roughly comparable to both the North and South Viking grabens (e.g., Beach et al., 1987), and to the half grabens of northern Lake Tanganyika (Rosendahl et al., 1986). The Euphrates graben system is slightly larger than the largest basins in the Rio Grande rift (e.g., Russell and Snelson, 1994), and about the same width, but one-half the length, of the Suez rift (e.g., Chénet et al., 1987). Thus, the Euphrates system probably would be classified as a rift unit in the nomenclature of Rosendahl (1987), although its aspect ratio is approximately one-half that of typical rifts. In this nomenclature, the combination of the Euphrates graben system and the Abu Jir zone, described by Lovelock (1984) as a transtensional structure, may represent a rift zone. The offset along the Anah graben might then form an accommodation zone between these two. Litak et al. (1997) demonstrated that Senonian extension, albeit much less pronounced, is also present along the Euphrates trend northwest of the Palmyrides, occurring at least as far north as the Turkish border.

Our extension estimate of about 6% ($\beta = 1.06$) is lower than that reported in the literature for most other continental rifts. Kusznir and Park (1987) compiled β values ranging from 1.1 to 1.3 in the Rhine graben to 1.55 to 1.9 in the North Sea central graben, with a representative average of 1.4–1.5. Using a variety of techniques, several workers have estimated extension in the Gulf of Suez ranging from 1.1 in the northern part (Colletta et al., 1988) to 1.65–1.7 in the southern part (Angelier, 1985) [see Patton et al. (1994) for compilation]. Bosworth (1995) recently estimated β for the central basin of the southern Gulf of Suez rift at 1.9–2.0, placing it as perhaps the most highly extended of failed continental rifts. The relatively low value for extension in the Euphrates graben system signifies that it was arrested at an early stage of development.

In contrast to the "classical" rift structure as seen in the East Africa rift (Rosendahl, 1987), the Euphrates graben system does not exhibit sharp edges characterized by major listric bounding faults. Instead, the southwestern edge of the Euphrates system is marked by several faults that become progressively smaller onto the edge of the Rutbah uplift (Figure 5). The northwestern part of the rift (near the Palmyrides) in particular has the gross morphology of a full graben; farther southeast, the southwestern margin is manifested by a steep-sided flexure with minimal throw across the associated fault (Figures 6, 7). This feature has the appearance of the updip end of a half graben, but does not correspond to a major southwest-dipping normal fault. Major transverse structures, such as those reported in the East African rift (Rosendahl, 1987), are not observed. Chénet et al. (1987) postulated that transverse faults in the Suez rift followed the trend of a preexisting crustal fabric. If Najd-type faults underlie the Euphrates graben system, the preexisting fabric is nearly orthogonal to the extension direction, perhaps explaining the lack of transverse structures. Listric faults are only clearly observed in the deepest part of the graben.

Although not ubiquitous, high-angle faults and deep-water sedimentation were argued by Morley (1995) to be common features at early stages of continental extension. Their presence here again suggests that the Euphrates rift aborted early on. On the northwestern margin of the Española basin in New Mexico, Baldridge et al. (1994) also noted numerous high-angle, planar normal faults accommodating minimal extension and distributed over a broad zone. Baldridge et al. (1994) interpreted that zone as an aborted rift boundary and suggested that this style of deformation may characterize the initial formation of rift basins, an inference consistent with our results. The cessation of rifting in the Euphrates graben may have been due to a change in the state of stress in the Arabian plate related to the Late Cretaceous convergence associated with ophiolite emplacement along the Arabian plate margin.

CONCLUSIONS

The Euphrates graben system in southeast Syria is an aborted continental rift that was primarily active in the Late Cretaceous. Following Lower Cretaceous deposition of the Rutba Formation (Figure 14A), extension began during the Coniacian with block faulting, development of a regional unconformity, and limited deposition of continental clastics (Figure 14B); however, the main phase of deformation occurred during the Campanian–Maastrichtian (Figure 14C), with extensive normal faulting and graben formation. Faulting essentially ceased by the Paleocene; a Paleogene thermal sag basin (White and McKenzie, 1988) overlies the graben system (Figure 14D). An additional phase of deposition in the upper Miocene overlies part of the Euphrates graben, but probably is primarily related to the Mesopotamian foredeep associated with the nearby Zagros continental collision. Minor late Neogene transpression reactivated some of the structures in response to the Zagros-Bitlis continental collision (Figure 14E). The area appears to be tectonically inactive at present.

The total amount of extension is minimal, probably not more than 6 km, but deformation is extremely widespread and complex considering the amount of extension. This may be partly due to the presence of a preexisting zone of weakness that served to distribute deformation across numerous preexisting faults. The amount of strike-slip displacement also is inferred to be minimal. Two distinct fault populations are noted: west-northwest–striking normal faults with relatively large throws in the northwestern part of the study area, and steeply dipping, northwest-striking flexures and strike-slip faults nearer to the Iraqi border.

Light oil and minor gas accumulations are found primarily in Lower Cretaceous clastic reservoirs upthrown to both large and small normal faults. The charge is believed to emanate from late Senonian synrift source rocks downthrown to the trapping faults. Larger fields occur in the deepest part of the basin, probably due to greater thickness and increased maturity of source rocks.

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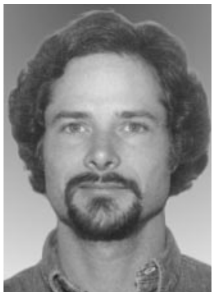
Robert Litak



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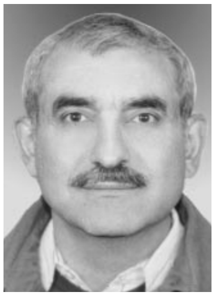

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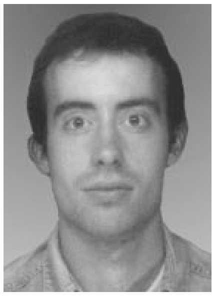

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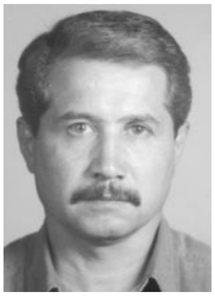
Tarif Sawaf



Tarif Sawaf is a senior geologist and associate head of the regional geologic department, Syrian Petroleum Company. His academic background includes a B.S. degree in applied geology from Damascus University, Syria. His professional experience includes seven years employment as a petroleum geologist with Sonatrach, Algeria, and he currently specializes in the subsurface and structural geology of Syria.

Anwar Al-Imam

Anwar Al-Imam obtained both a B.S. degree in 1965 and a Ph.D. in 1974 in applied geophysics from Moscow State University, Russia. He has worked as a lecturer in Damascus University, as director of the General Geological Survey of Syria, and as head of Geophysical Interpretation for the Syrian Petroleum Company. He also worked as a professor in the Institute of Earth Sciences in Oran in Algeria, 1990–1992. His interests include seismic interpretation and modeling.

Wasif Al-Youssef

Wasif Al-Youssef was the director of the Exploration Department, Syrian Petroleum Company, 1988–1997. Since 1972, he has held the positions of director, Service-Contract Department; director, Petroleum Studies Department; and chief of Petroleum Reservoir Engineering. Wasif received his diploma-engineering degree in petroleum geology in 1972, and his doctorate in petroleum engineering in 1993 from the Institute for Geology of Energy and Exploitation of Combustible Resources, Russia. Wasif has participated in numerous energy-related conferences as a speaker.