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Mesozoic–Cenozoic evolution of the intraplate Euphrates fault system, Syria: implications for regional tectonics

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Abstract: A lack of dramatic surface geological structures along the Euphrates River in Syria belie a complex tectonic history revealed by newly released seismic reflection and well data. We document the intraplate Euphrates fault system, characterize the variation in structural style along its 350 km length in Syria, and infer its Mesozoic–Cenozoic tectonic and deformational history. We then relate the deformation of the Euphrates system and other proximate intraplate structures to nearby Arabian plate boundary processes in order to develop a new model for the tectonic evolution of the northern Arabian plate.

Throughout most of Mesozoic time, the Euphrates area experienced minor deposition compared to the Palmyride trough to its southwest, and the Sinjar trough to its northeast. During latest Cretaceous time, however, significant sinistral transtension occurred along the length of the Euphrates fault system in Syria, with graben formation especially noteworthy in southeastern Syria. This episode was probably related to events at nearby plate boundaries, and may have reactivated a zone of weakness formed during Pan-African accretion of the Arabian plate. A Palaeogene sag basin formed over the graben system in southeastern Syria. Neogene continental collision along the northern and eastern Arabian plate boundaries caused minor reactivation of the Euphrates fault system in a dextral transpressional sense, in concert with significant inversion and the main phase of uplift of the nearby Palmyride and Sinjar mountains.

Keywords: Syria, Arabian Plate, intraplate processes, seismic profiles, deformation.

The northern Arabian plate comprises diverse structural elements and a variety of temporally and spatially differing structural styles. Although located in a primarily intraplate setting, the tectonic history of Syria has been profoundly affected by events along nearby plate boundaries (Fig. 1). The northern boundary of the Arabian plate represents a collision zone in southern Turkey often referred to as the Bitlis suture (e.g., Sengör & Yilmaz 1981; Hempton 1985). The northwest-trending Zagros collision zone is essentially an eastward continuation of the Bitlis zone, produced by continental collision between Arabia and Iran (e.g., Sengör & Kidd 1979; Berberian & Berberian 1981; Berberian & King 1981; Barazangi 1989). The emplacement of ophiolites during Late Cretaceous time along the northwestern, northern, and eastern margins of the Arabian plate indicates an initial episode of convergence at that time, the extent and nature of which remain controversial (e.g., Beydoun 1991). However, Tertiary island-arc-type volcanism in Iran implies that subduction of oceanic crust continued until Miocene time, when full-fledged continental collision began (e.g., Coleman-Saad 1978). Debate continues concerning the Cenozoic history of the Arabian/Anatolian boundary, with various workers favoring either continued convergence, subduction, and shortening (Yilmaz 1993) or strike-slip motion with periods including both extension and convergence (Karig & Kozlu 1990). Continuing convergence between the Arabian and Anatolian plates is now accommodated by a combination of thrusting along the Bitlis zone and left-lateral motion along the East Anatolian Fault as the Anatolian block ‘escapes’ toward the west (e.g., Sengör *et al.* 1985; Burke & Sengör 1986).

To the west lies the Dead Sea Fault System, a left-lateral ‘leaky’ transform fault extending from the Red Sea Rift at the Gulf of Aqaba in the south, through Lebanon and westernmost Syria to a complex triple-junction in southern Turkey. Offset documented along the fault system varies from about 105 km in the south to about 20 km in the north (Freund *et al.* 1970; Garfunkel 1981; Quennell 1984; Chaimov *et al.* 1990). The main phase of motion along the Dead Sea Fault System is thought to have commenced in Miocene time in concert with the opening of the Red Sea (e.g., Garfunkel 1981; Cochran 1983).

The Euphrates fault system is an area of significant intraplate deformation, extending over 350 km throughout Syria, but has received only limited scrutiny in the open literature. First mentioned by Lovelock (1984) as part of a regional synthesis, the Euphrates system has subsequently been a substantial topic of only three recent publications, all of which focussed on aspects of the graben system of southeastern Syria (Sawaf *et al.* 1993; Alsdorf *et al.* 1995; de Ruiter *et al.* 1995). This study complements considerable recent work in the nearby adjoining Palmyride fold belt (McBride *et al.* 1990; Best *et al.* 1990, 1993; Chaimov *et al.* 1990, 1992, 1993; Al-Saad *et al.* 1992; Barazangi *et al.* 1993; Seber *et al.* 1993; Salel & Séguret 1994; Searle 1994).

In this study, we use newly available seismic and well data to document the first-order deformation history of the Euphrates fault system in Syria. We then relate our observations and interpretations to published interpretations of other intraplate tectonic elements within and around Syria, and speculate on regional kinematics throughout Mesozoic and Cenozoic time.

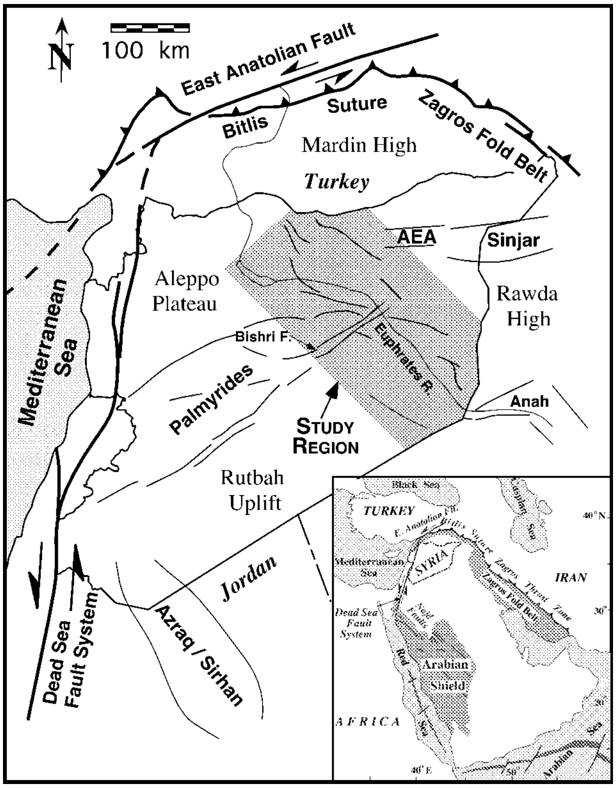

Fig. 1. Map showing location of study region and nearby tectonic features. Thin black lines represent significant faults or boundaries of mobile zone. Inset shows simplified tectonic setting of Syria within the Arabian plate. AEA, Abd El Aziz.

We argue herein that the complex pattern of intraplate deformation within Syria and surrounding areas can be considered in terms of episodic reactivation of long-lived weak or mobile zones between relatively strong or stable blocks. The reaction of these weak zones to changing stress conditions associated with plate boundary events has produced the mosaic now characterizing the structural styles of the northern Arabian plate.

Palaeozoic–Cenozoic tectonic history

The stratigraphy of Syria records a clastic-dominated Palaeozoic section underlying Triassic to Neogene carbonate rocks and evaporites interbedded with lesser amounts of sandstone and shale (Fig. 2). Up to several hundred meters of Upper Neogene–Quaternary rocks, primarily continental clastics, are exposed over much of the study area. Early Palaeozoic subsidence led to deposition of over 3 km of Cambro-Ordovician clastic sediments throughout most of Syria along an east-facing continental margin (Best *et al.* 1993). Isopachs of sediment thickness reveal a northeast-trending trough throughout Syria originating during Silurian time, with the thickest deposits of both Silurian and Carboniferous rocks occurring in the area of the present-day Palmyrides to the Sinjar area (Sawaf *et al.* 1988). However, significant erosion of Carboniferous sediments may have occurred on the Rutbah Uplift (Fig. 1) and adjacent areas. Devonian rocks are absent throughout Syria, indicating an unconformity of regional extent. In this study we note the existence of large Palaeozoic structures in north-central Syria which may denote the presence of more extensive late Palaeozoic deformation than previously reported.

Isopach maps based on well and seismic data (Sawaf *et al.* 1988) indicate that during the Permian, the Euphrates trend began to be established as the northeast edge of the developing Palmyride trough, separating it from deposition in the Sinjar area. Throughout most of Triassic through Cretaceous time, a northwest-trending ridge along the Euphrates formed between the Palmyride and Sinjar troughs, with the entire area forming a structural saddle.

During Late Cretaceous time, an episode of collision along the northern and eastern margins of the Arabian plate is evidenced by widespread ophiolite emplacement, although Yilmaz (1993) did not consider this event to represent continent-continent collision. According to Chaimov *et al.* (1992), this event occurred penecontemporaneously with initial inversion and modest uplift in the southwestern Palmyrides as inferred from seismic stratigraphic relationships. Field evidence has been cited by Salel & Séguret (1994) as confirming the latest Cretaceous timing of initial Palmyride uplift. Opening of the Euphrates graben system in southeastern Syria also took place during Late Cretaceous time (Sawaf *et al.* 1993; Alsdorf *et al.* 1995). During Miocene time, significant plate boundary tectonism included opening of the Red Sea, initiation of the main phase of motion along the Dead Sea fault system, the Zagros continental collision and formation of the associated Mesopotamian foredeep, and accelerated convergence between the Arabian and Eurasian/Anatolian plates. These events were accompanied by the onset of the main phase of uplift in the Palmyrides (Barazangi *et al.* 1993), and widespread subsidence in the Euphrates depression and throughout much of eastern Syria. Initial inversion of the Mesozoic Sinjar trough probably also began about this time, but uplift mainly occurred later than in the Palmyrides (Metwalli *et al.* 1974; Lovelock 1984). Convergence between the Arabian plate and the Anatolian and Eurasian plates has continued throughout Neogene and Quaternary time, but has had various manifestations in different parts of the northern Arabian plate, as discussed below.

Database

Over 2600 km of seismic reflection data along the Euphrates Valley were examined in the form of paper records (Fig. 3). The data were collected by various contractors between 1978 and 1988. Vibroseis was generally employed as the source, although dynamite was used near the river on portions of some lines. In general, the data in the northwestern part of the study area were collected by Compagnie Generale de Geophisique (CGG) between 1978 and 1980, using three vibrators and eight 12 s sweeps per shot point. Shot point and receiver group intervals were 100 m, and the data were stacked at nominal 24-fold. Most of the data in the southeastern part of the study area were collected between 1983 and 1988 by a variety of contractors, typically with four vibrators and two 12 s sweeps per shot point. Shot point and group intervals were generally 50 or 25 m, resulting in stacks varying from 48 to 72 nominal fold. The data were subjected to a processing sequence standard for the industry at the time of acquisition. Most of the stacks have been migrated using 2D finite difference algorithms.

Formation tops from approximately 36 wells in the immediate area (Fig. 3) were used to constrain the seismic

Age		Formation	Maximum Thickness (m)
Quaternary		Bakhtiary	1000
Tertiary	Pliocene	Upper Fars	
Tertiary	Miocene	Lower Fars	700
		Jeribe	125
		Dibbane	250
		Euphrates	200
	Oligocene	Chilou	500
	Eocene	Jaddala	600
	Paleocene	Kermav (Aliji)	600
Cretaceous	Upper: Maastricht.	Shiranish	1600
	Upper: Campanian, Santonian	Soukhne/Massive	700
	Upper: Coniacian	Derro	150
	Upper: Turonian, Cenomanian	Judea	1200
	Lower	Rutba/Ghouna	500
Jurassic		Haramoun (Kamchoka)	1800
Triassic	Upper	Sarjelu	700
		Allan/Muss	150
		Adaya	150
		Butma	300
	Middle	Kurrachine Anhydrite	400
		Kurrachine Dolomite	800
	Lower	Amanous Shale	250
Permian		Amanous	750
Carboniferous		Markada	1200
Silurian		Tanf	750
Ordovician		Affendi	1000
		Swab	1000?
		Khanasser	1500?
Cambrian		Sosink	750+
		Burj	150+
		Zabuk	?

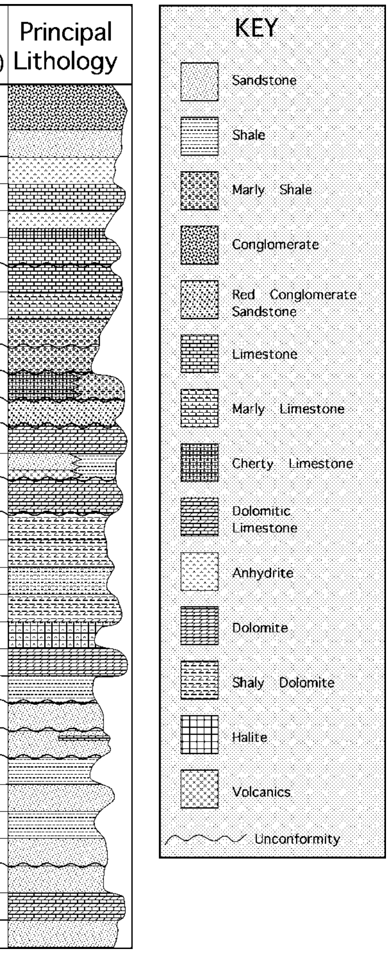

Fig. 2. Generalized lithostratigraphic column of Syria. Based on compilations of Syrian Petroleum Company composite logs. Formation names and ages are slightly different to those used in Iraq.

interpretation. Sonic logs for 12 wells provided velocity information for time-depth conversion and calculation of synthetic seismograms in the following manner: a reflection coefficient series generated from each sonic log was convolved with a Klauder wavelet made of frequencies identical to the seismic source. The same frequency filter and gain used in the seismic processing were applied to the resulting synthetic seismogram. Other available data included 1:200 000 scale geological maps (Ponikarov 1964) augmented by a high-resolution digital elevation model and Landsat MSS imagery to map surface structures and constrain the seismic interpretation.

Data analysis and interpretation

A variety of nomenclature has been used to describe the geology of the Euphrates area in Syria. In this study, we consider the Euphrates graben system to be a network of relatively deep, Late Cretaceous grabens and half-grabens largely confined to southeastern Syria (although we note that aspects of this graben system continue far to the northwest). The Euphrates depression is the Late Maastrichtian-Cenozoic, primarily Palaeogene, sag basin overlying the Euphrates graben system. Lovelock (1984) described the Al-Furat fault as a major transcurrent fault extending from Turkey to Iraq, and serving as the northeastern boundary of the Euphrates graben but extending far to the northwest. Since we recognize a complex network of branching faults with similar overall trend rather than a single fault zone bounding the Euphrates graben system, the entire network is herein referred to as the Euphrates fault system.

For the purposes of this study, it is convenient to divide the Euphrates fault system in Syria into three segments. Mapping of the main structural elements delineates the extent of the Euphrates fault system and deformation within each of these segments (Fig. 4). The southeastern segment comprises the area generally considered to be the Euphrates graben and depression, consisting of thick Campanian–Maastrichtian and Cenozoic sediments. The central segment is a complex zone of interaction between the Euphrates trend, the northeastern terminus of the Palmyride mountain belt, and possibly the Sinjar and Abd El Aziz uplifts in northeastern Syria. The northwestern segment, part of which is sometimes referred to as the north Euphrates basin, shares some characteristics with the southeastern segment, but lacks the thick sediments seen there. Well correlation charts and seismic examples are used to illustrate structural variations among these segments (Fig. 3).

Figure 5 illustrates variations in formation thicknesses along the axis of the Euphrates fault system. Although numerous unconformities are apparent, several features are particularly noteworthy. First, the Omar-103 well, near the deepest part of the Euphrates depression, includes anomalously thick Upper Triassic sediments (primarily shale, limestone, and dolomite). Considerable variations in thicknesses of Upper Triassic formations are also apparent in numerous other nearby wells. This suggests uneven subsidence in the area of the Euphrates depression during Triassic time, possibly an earlier episode of

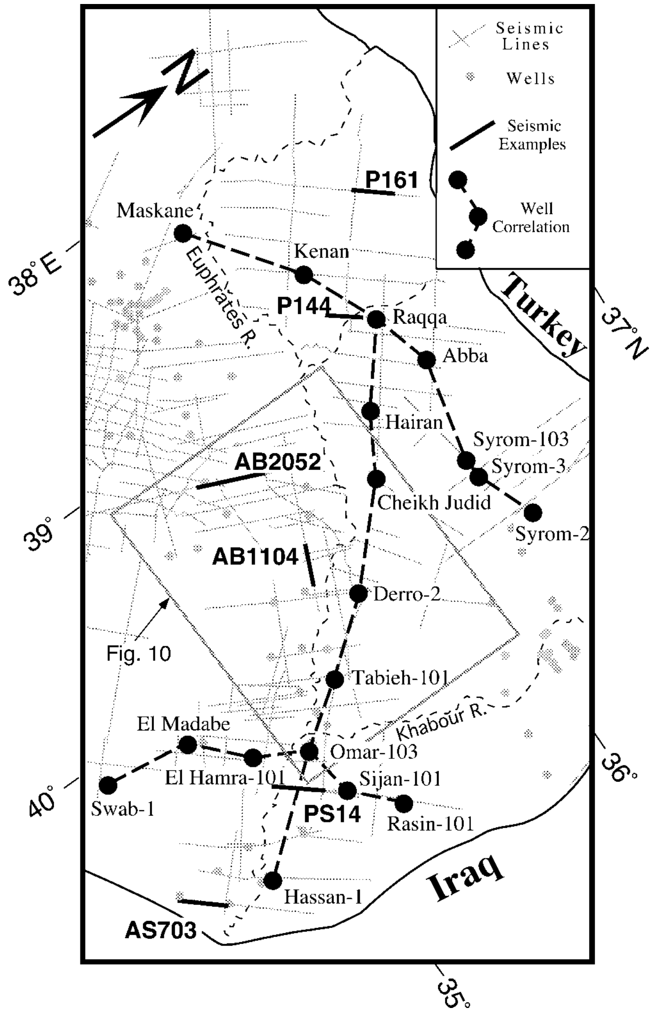

Fig. 3. Map showing seismic reflection and well database available in study area. Also shown are the locations of well correlation charts and examples of seismic lines shown in subsequent figures. See Fig. 1 for location.

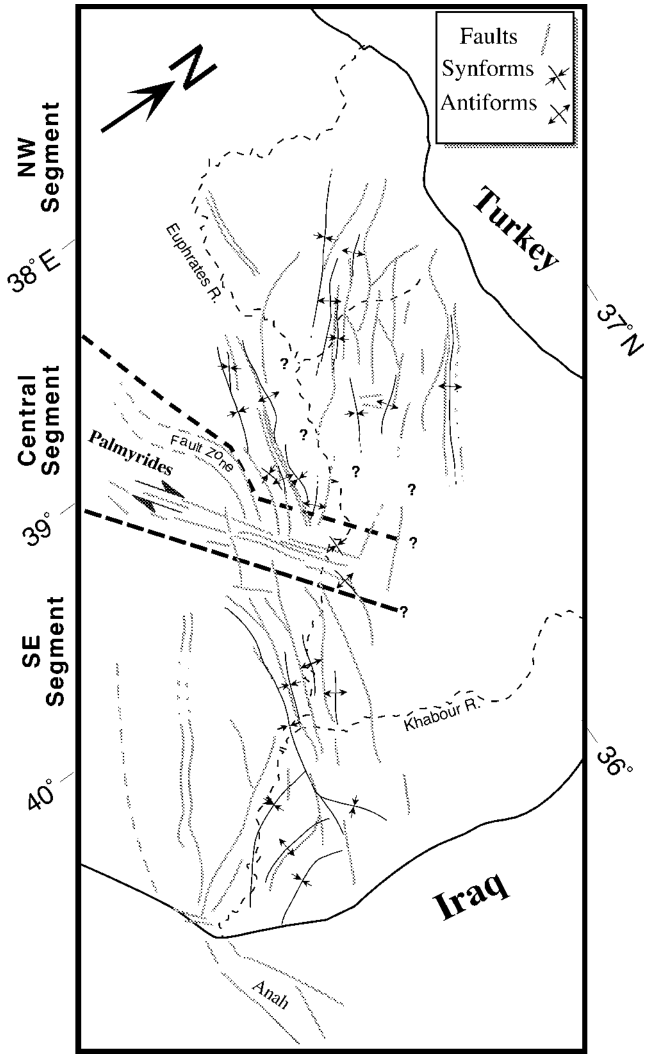

Fig. 4 Structural framework of the Euphrates fault system interpreted from seismic reflection and well data. The southeastern and northwestern segments are distinguished from the central segment, which is dominated by interaction with the Palmyride mountain belt. Many faults have experienced a combination of normal, strike-slip, and reverse movement, as discussed in text, hence offsets are not shown. Gray dashed lines denote inferred faults. Heavy dashed lines separate the three sections of the Euphrates fault system. Question marks denote areas of limited or no data. See Fig. 3 for database.

extension prior to the main phase of graben formation during Senonian (Coniacian–Maastrichtian) time. However, Triassic sediments may have been deposited more uniformly, and preferentially eroded from the graben flanks prior to the Senonian. Relatively thin pre-Senonian Cretaceous carbonates in the Omar and other nearby wells indicate that the southeastern Euphrates area did not participate in Cretaceous subsidence to the same extent as the Palmyride and Sinjar troughs (e.g., Best *et al.* 1993).

The opening of the Euphrates graben system is signalled by scattered occurrences of the Coniacian Derro redbed in southeastern Syria (de Ruiter *et al.* 1995), followed by dramatic variations in thickness of the marly shale and cherty and argillaceous limestones of the Santonian–Maastrichtian Soukhne and Shiranish formations. The Omar-103 well (Figs 5 & 6) records 1 km of Senonian accumulation (thicknesses approaching 2 km occur locally). Increased thickness of the Shiranish Formation in Raqqa-1 and other wells in the northwestern segment (Fig. 5) provides evidence that subsidence extended beyond the Euphrates depression proper. However, thin Senonian deposits indicate that the intervening Derro-Cheikh Judid area, near the junction with the Palmyrides, was structurally high and had less participation in subsidence. Thick Palaeocene and Eocene marly limestone deposits in the southeast thin gradually to the northwest. Interestingly, however, during the Oligocene the depocentre appears to have shifted to central Syria, with some of the thickest Oligocene deposits in Syria recorded in the Cheikh Judid and Derro-2 wells. Lower Miocene evaporites and carbonate rocks in eastern Syria generally thin toward the northwest. These rocks are overlain by Upper Miocene clastic sedimentary rocks throughout eastern Syria, particularly thick in the Euphrates depression and the area surrounding the Sinjar/Abd El Aziz uplift.

Southeastern Euphrates segment

In southeastern Syria, the Euphrates graben system comprises a branching network of steep-sided grabens and half grabens

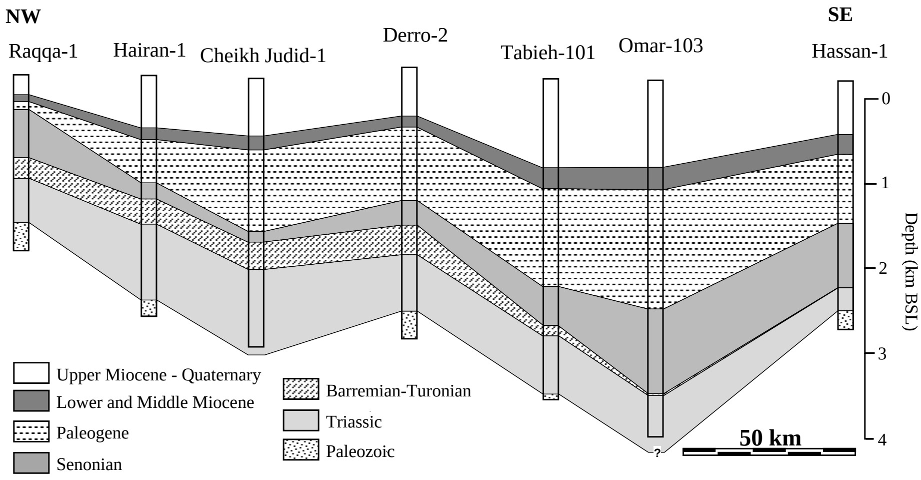

Fig. 5. Well-based cross-section along axis of Euphrates trend showing thickness variations of Senonian section and other features discussed in text. Location shown in Fig. 3.

trending generally northwest to west-northwest (Fig. 4). Abrupt changes in thickness of the uppermost Cretaceous Shiranish formation date the principal phase of graben formation to Campanian–Maastrichtian time (Fig. 6). Up to 2600 m of relatively undeformed Cenozoic sediments overlie the graben deposits.

One of these grabens is imaged by seismic line AS-703 (Fig. 7). The As-Sayyal 101 well, which penetrates Silurian rocks, ties the section northeast of the portion of the line shown here, and the Akash-101 well ties the line as shown in Fig. 7. The southwestern margin of the graben is clearly delineated by a steeply-dipping normal fault, with thickening of the uppermost Cretaceous Shiranish formation from less than 500 m to approximately 1400 m. The corresponding, albeit lesser, increase in thickness between the interpreted base Cretaceous (near the base Shiranish) and top Silurian horizons seems to indicate the presence of an earlier phase of extension. Abrupt changes in thickness of Triassic rocks in nearby wells and the existence of a major unconformity between the Carboniferous and Upper Triassic (Sawaf *et al*. 1993) suggest that a minor phase of extension may have occurred during the Triassic, coeval with extension in the Palmyrides and elsewhere.

The northeastern boundary of this graben is complicated by interaction with an uplift that appears to be cored by a

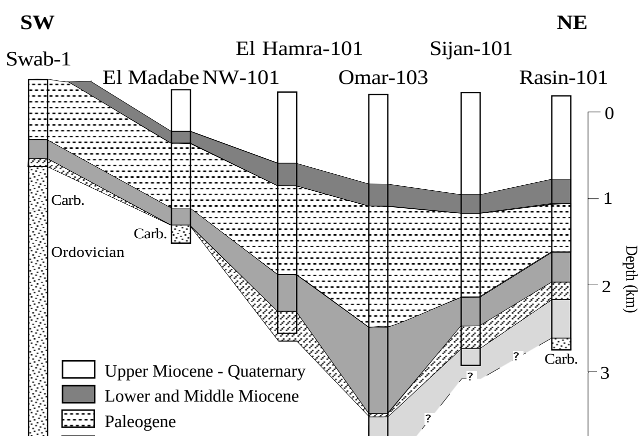

Fig. 6. Well-based cross-section across Euphrates graben/depression in southeastern Syria. Location shown in Fig. 3.

near-vertical fault (Fig. 7). This flower structure probably indicates strike-slip faulting (Harding 1985) at the northeastern margin of the graben, and may represent the Al-Furat fault of Lovelock (1984). However, faulting continues considerably farther northeast, and the complex network of both strike-slip and normal faults observed is not consistent with the existence of a single continuous fault zone (Fig. 4). Faulting occurs rather as en echelon or diverging/converging fault patterns with associated changes in deposition related to contemporaneous sedimentation. Since both the graben and flower structure appear to have experienced roughly contemporaneous movement in Late Cretaceous, this may be an example of strain partitioning along a transtensive graben system. However, movement along the flower structure apparently continued into Palaeocene time, and minor rollover also evidences slight uplift as late as Plio-Pleistocene (Fig. 7). A branch of this fault coincides with a minor dextral fault mapped at the surface. Note that the Shiranish formation also appears to be thicker on this faulted high than on the small horst block immediately to the southwest, indicating that it was a site of Late Cretaceous extension or transtension. The area is now characterized by a topographic low, indicating Quaternary subsidence or quiescence. No evidence of lineaments indicative of present-day uplift is visible on topographic or MSS data. Slight rollover on Miocene and Pliocene reflections is visible on several structures in the lower Euphrates depression, indicating a late episode of minor compression or transpression reactivating earlier structures. This deformation is also present farther northeast, as several near-vertical, probable strike-slip faults and another half-graben are also observed toward the northeastern end of line AS-703 (not shown).

Constrained by ties with the Sijan-101 and El Hamra-101 wells located near the deepest part of the central Euphrates graben (Fig. 3), seismic line PS-14 (Fig. 8) shows a somewhat different seismic signature of the Euphrates graben system than seen farther southeast. Discordant dips between the top and base of the Shiranish formation provide the principal evidence for deformation, with an angular unconformity apparent along the upthrown sides of several faults. Thickening of the Shiranish formation to a maximum of about 1800 m occurs along several subparallel faults, rather than on a single, sharply defined fault. In this locality, the overall graben morphology is grossly symmetrical and dominated by normal faults striking west-northwest (Figs 4 & 8). The Cenozoic section is essentially undeformed.

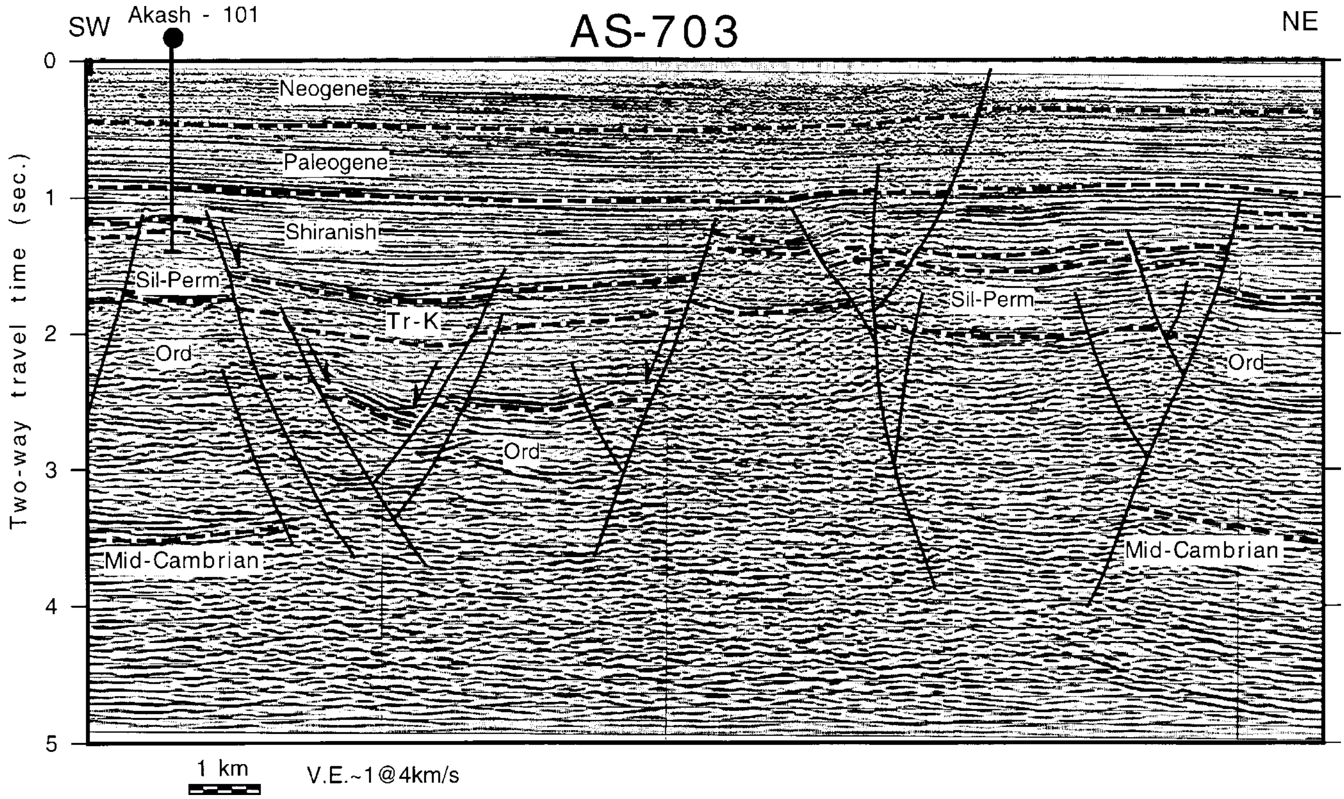

Fig. 7. Portion of interpreted seismic line across part of Euphrates graben system in southeastern Syria. As-Sayyal 101 well ties this section 5 km to the NE. Datum for all seismic sections is 300 m. Migrated using a finite difference algorithm. Location shown in Fig. 3.

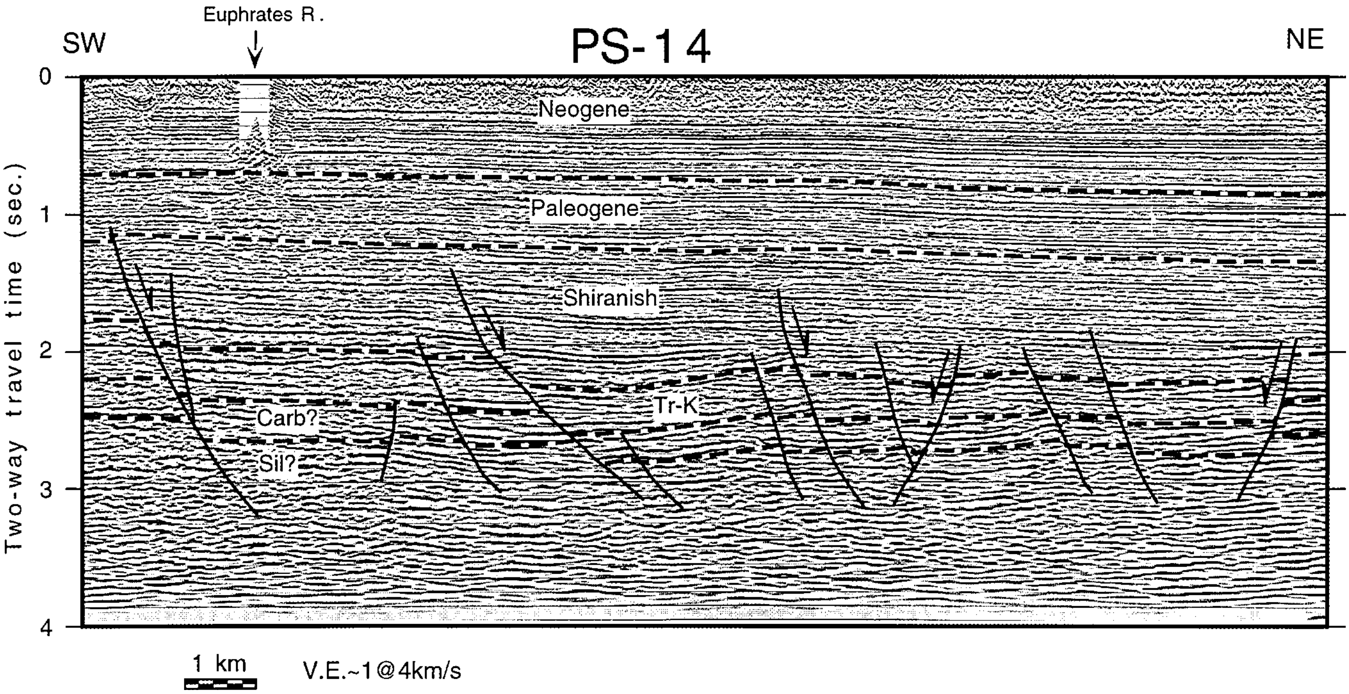

Fig. 8. Example of interpreted seismic line across central Euphrates graben/depression illustrating deep, relatively symmetric graben system cored by Late Cretaceous normal faults, with minimal Cenozoic reactivation. Migrated using a finite difference algorithm. Location shown in Fig. 3.

In both examples, faults generally do not extend upwards through the entire Shiranish section. Rather, reflections from the uppermost Shiranish are continuous and parallel to Palaeocene reflections. This observation generally holds throughout the Euphrates graben system suggesting that active faulting ceased during the latest Maastrichtian.

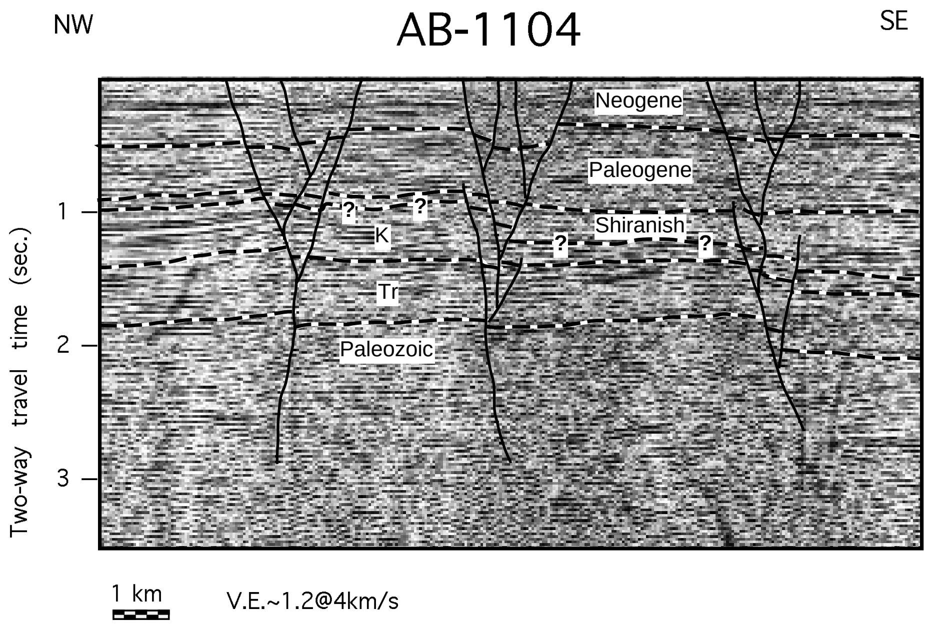

Fig. 9. Seismic line showing flower structures interpreted as strike-slip faults bounding the Palmyride Bishri block. Migrated using a finite difference algorithm. Location shown in Fig. 3.

Euphrates–Palmyrides junction

Structures of the Euphrates graben continue to the northwest to the junction with the Palmyrides, where the northeastern province of the Palmyrides is represented by the Bishri crustal block. In contrast to thin-skinned thrusting and folding exhibited in the southwestern Palmyrides, thick-skinned transpressional deformation of the Bishri block has produced a broad, antiformal uplift (Best 1991). Despite relatively poor seismic data in this area (probably due to both complex subsurface structures and poor surface conditions), combining seismic and auxiliary data results in the following general observations. A series of near-vertical northeast-trending faults are apparent on several seismic lines (Fig. 9), and can be mapped using seismic data some 80 km in distance and tied to the surface exposure of the South Al-Bishri fault (Fig. 4), a right-lateral transpressive fault that forms the southern boundary of the Bishri block (Alsdorf *et al.* 1995). These faults are also apparent as lineaments on digital topography data (Fig. 10) and Landsat imagery. Topographic expression as well as minor earthquake activity along the South Al-Bishri fault (Chaimov *et al.* 1990), indicate that these faults are still active. A magnitude $M_s = 4.9$ earthquake that occurred on 20 November 1994 was located near one of these lineaments, at a depth of 15 km, northeast of the mapped extent of the South Al-Bishri fault (Fig. 10). Evidence concerning the sense of motion of these faults is not conclusive. The focal mechanism for a 1970 earthquake ($m_b = 4.8$) was determined to be dextral (Chaimov *et al.* 1990), but an initial solution for the 1994 event suggests sinistral motion (Dziewonski *et al.* 1995). For events this small, teleseismic determination of locations and focal mechanisms may not be definitive. Moreover, field evidence

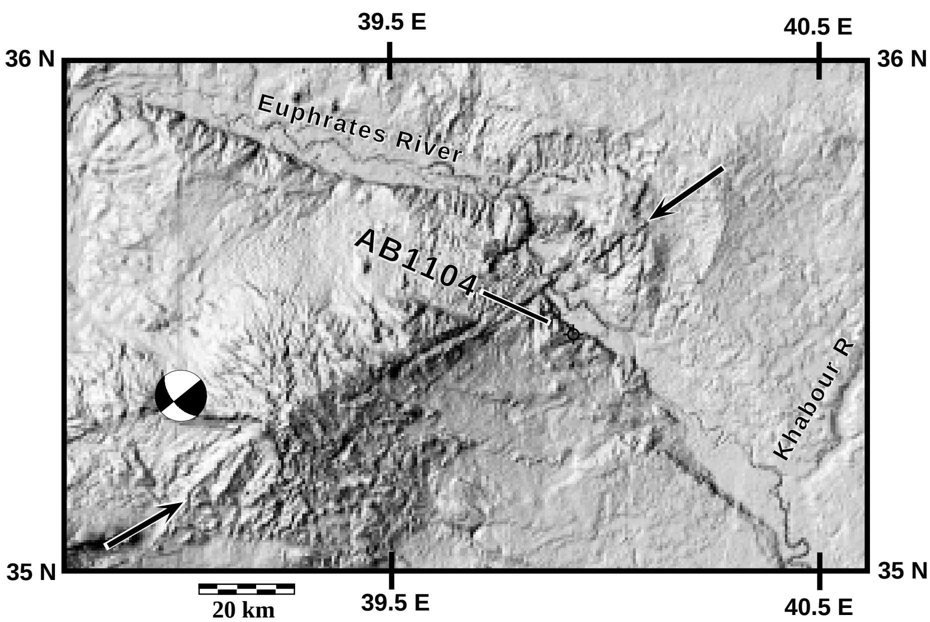

Fig. 10. Map showing topography of Palmyride/Euphrates junction from a digital elevation model; artificial illumination from northwest (for location see Fig. 3). Lineaments highlighted by arrows coincide with flower structures on seismic line AB1104 (Fig. 9), and appear to extend to South Al-Bishri fault in southwestern corner of figure (see Fig. 1). Reported location of $M_s = 4.9$ earthquake of 20 November 1994 with focal mechanism also shown; shaded quadrants are compressional (Dziewonski *et al.* 1995).

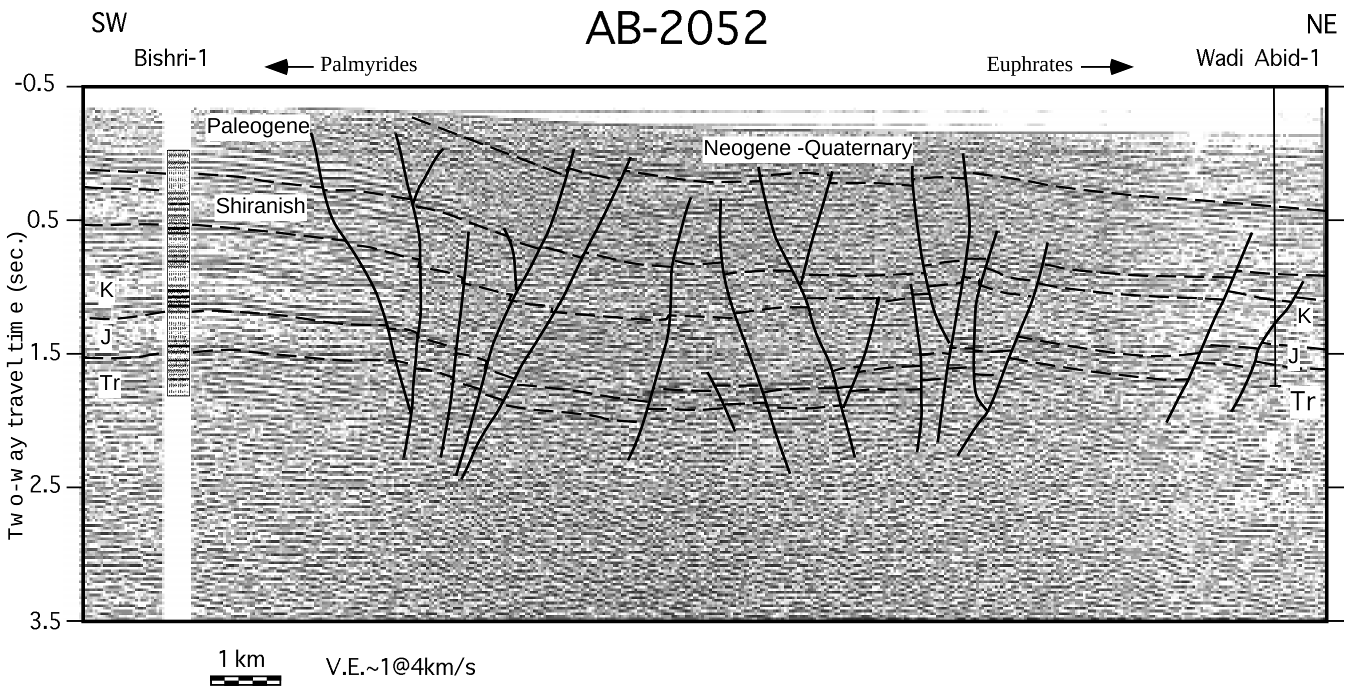

Fig. 11. Portion of seismic line showing complex fault system at northern edge of Bishri block. Interpretation constrained by well data including synthetic seismogram in Bishri-1 well. Note thickening of Mesozoic section from Wadi Abid to Bishri wells. Neogene uplift of Bishri block thus appears to have reactivated bounding fault zone of Mesozoic Palmyride trough. Migrated using a finite difference algorithm. Location shown in Fig. 3.

(Searle 1994) and kinematic models (Chaimov *et al.* 1993; Searle 1994) are consistent with dextral motion along the South Al-Bishri fault. Al-Saad *et al.* (1992) also reported evidence for dextral motion on the nearby Jhar fault. In addition, one of the faults identified here appears to offset the Euphrates river valley by several km in a dextral sense (Fig. 10). The fact that the Shiranish formation thins significantly across this fault zone implies that either it has experienced substantial Neogene dextral motion, or that it was active during the Late Cretaceous, perhaps as a dextral transfer fault. We interpret these features as a right-lateral strike-slip fault system marking the boundary between the Bishri block and the Euphrates fault system (see also Alsdorf *et al.* 1995).

Northwest of these faults a very different structure is apparent (Fig. 11). The flat-lying sediments of the Euphrates area are disrupted and uplifted by some 1200 m at a flexural feature here interpreted as the northeastern boundary of the Bishri block. In map view, this bounding flexure curves from the westerly strike shown here to strike southwest (Fig. 4). Based partly on earthquake focal mechanism data, Chaimov *et al.* (1990) suggested a right-lateral sense of motion along the northwestern boundary of the Bishri block. The existence of Quaternary sediments indicative of subsidence above the fault zone are consistent with a right-lateral sense of motion along the curving northern boundary of the Bishri within an overall transpressive regime.

A digitized sonic log from the Bishri-1 well was used to create a synthetic seismogram tying line AB-2052; a relatively good match was obtained (Fig. 11). Note that well control requires the Mesozoic section to be much thicker in the Bishri block than in the Euphrates area, although the Bishri block is structurally higher. This indicates that the structure on Fig. 11 represents true inversion of the Mesozoic Palmyride trough.

Northwestern Euphrates segment

Northwest of the Palmyride–Euphrates intersection, northwest-trending structures are again apparent on the seismic data (Fig. 4). Variations in formation thicknesses are noted at several levels across the Euphrates area, and are again most prominent in the Shiranish formation (Fig. 12). On the seismic data, these structures are manifested by thickening of the Shiranish formation on the downthrown side of normal faults. Many of these faults show little or no offset of Cenozoic reflections, dating their main period of movement to Campanian–Maastrichtian time. This northwest-trending fault system is very diffuse, comprising an area perhaps as wide as 80 km, but nowhere do these grabens and half-grabens attain the thicknesses of those in the southeastern Euphrates segment.

Farther northwest, reverse motion is apparent at the top of Cretaceous and higher stratigraphic levels, requiring either larger, older normal displacements at lower levels or a thicker Shiranish section in the hanging wall to explain deeper reflection patterns (Fig. 13). Well control from the Raqqa-1 and Kenan-1 wells (see Figs 3 & 12) requires significant thickening of the Shiranish formation across one or more of these faults. This observation establishes clear evidence for Cenozoic inversion of Late Cretaceous normal faults. Many of the faults are near-vertical and branched (e.g., Fig. 13), suggesting a component of strike-slip motion possibly indicative of transpressional reactivation of transtensional structures. Correlating these faults along strike toward the northwest, we note a transition in some of these structures from Cretaceous faults with normal

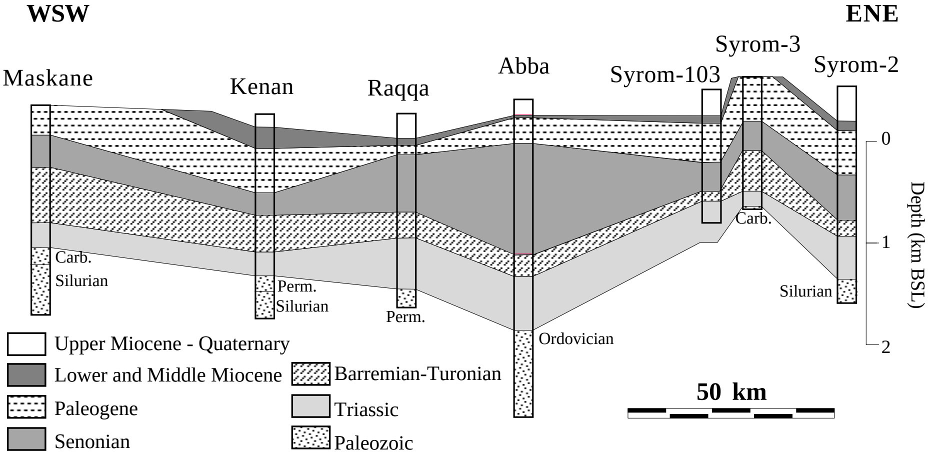

Fig. 12. Well-based cross-section across Euphrates fault system in north-central Syria. Location shown in Fig. 3.

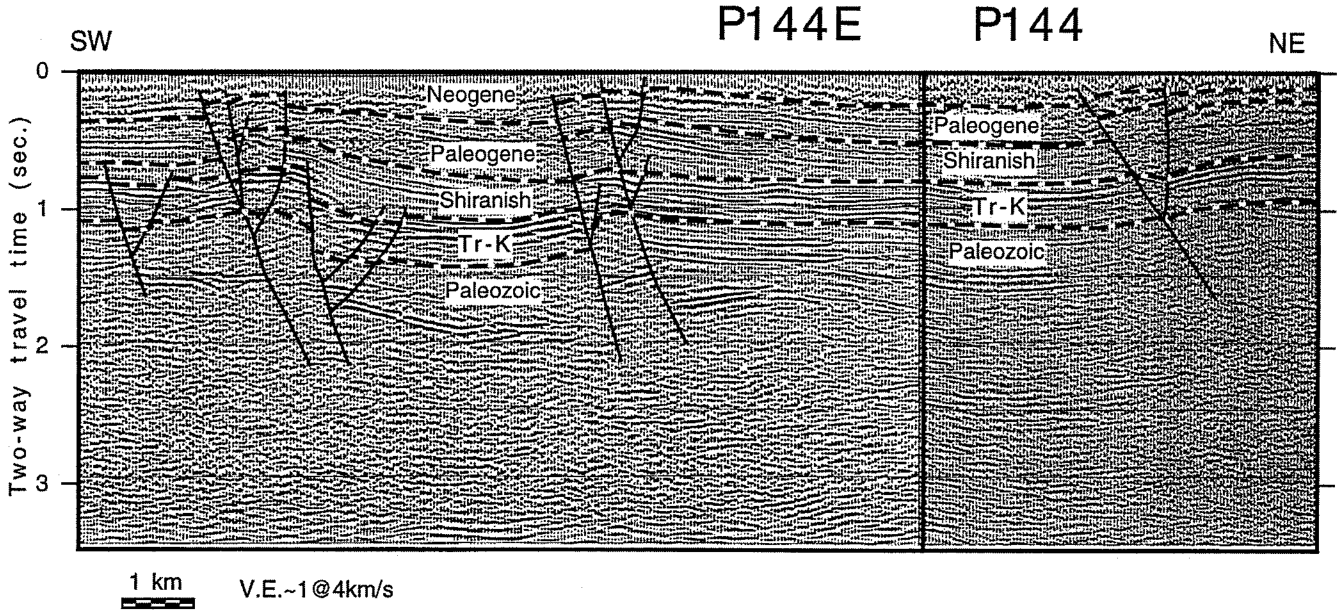

Fig. 13. Portion of seismic line showing thickening of Shiranish formation on upthrown fault blocks, indicating Neogene compressional or transpressional reactivation of Late Cretaceous extensional or transtensional faults. Migrated using a finite difference algorithm. Location shown in Fig. 3.

displacement to faults showing slight Cenozoic inversion (Fig. 13) to significant Cenozoic uplifts (Fig. 14). Line P161, constrained by the Kenan-1 well (see Figs 3 & 12) and Cretaceous exposures along the line, show a large uplifted structure with a thickened Shiranish section on the upthrown side of a fault zone. Upper Miocene outcrops unconformably overlie Cretaceous rocks at the crest of the structure, indicating that principal uplift was accomplished before Late Miocene. We interpret this pattern of deformation in terms of Late Cretaceous transtension followed by late Mid-Miocene or early Late Miocene transpression associated with continental collision along the northern margin of the Arabian plate about 100 km north of this region. In Fig. 14, the Cenozoic uplift coincides with a Late Cretaceous fault that, in turn, clearly overlies a major late Palaeozoic (Hercynian?) structure, as evidenced by the sharp angular unconformity interpreted to lie at the base of Triassic rocks. Additional investigation of the Palaeozoic history of this area is needed to determine the significance of Palaeozoic structures and their relationship to subsequent deformation in northern Syria.

Discussion

Mesozoic evolution

During Mesozoic time, much of Gondwanaland was dominated by several episodes of extension (e.g., Lambiase 1989). Cretaceous time in particular saw intraplate rifting over much of northern Africa, from the Sirte basin of Libya to the ancestral East African rift in Kenya (e.g., Bosworth 1992; Bosworth & Morley 1994). This study further documents that the Arabian platform, then still a part of the African plate, also participated in this major phase of intracontinental extension.

By early Mesozoic time the northern Arabian platform had evolved into an amalgam of stable blocks (the Rutbah, Rawda or Khleisia, Aleppo, and Mardin) separated by weak crustal zones in the Palmyride, Euphrates, and Sinjar/Abd El Aziz zones. From Late Permian or Early Triassic to Late Cretaceous time, extension associated with opening of the Levantine ocean was accompanied by subsidence along a northeast-

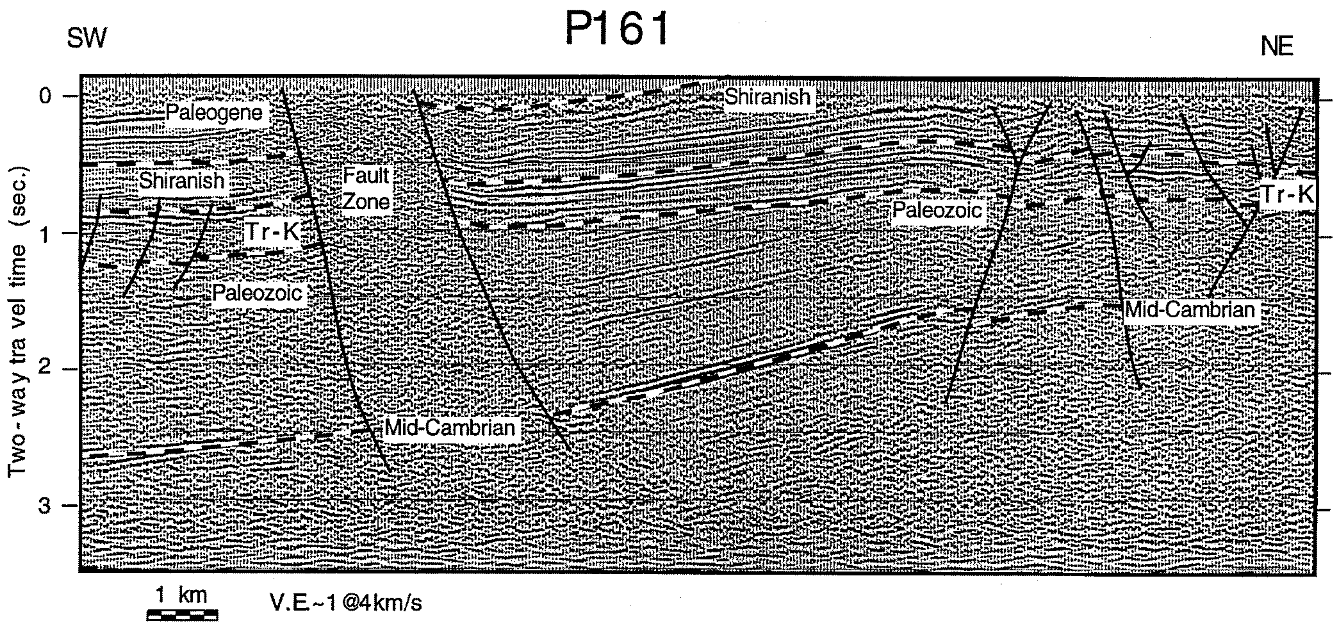

Fig. 14. Portion of seismic line showing significant Cenozoic uplift, again reactivating Late Cretaceous normal motion as evidenced by thickening of Shiranish formation. In this example, a major angular unconformity at base Triassic suggests multiple reactivation of an older, late Palaeozoic structure. Seismically transparent area labelled 'Fault Zone' probably represents zone of complex deformation not resolved here. Migrated using a finite difference algorithm. Location shown in Fig. 3.

trending aulacogen through the Palmyride and Sinjar areas (Ponikarov 1967; Best *et al.* 1993) (Fig. 15a). This trough largely mimicked late Palaeozoic trends, but was separated into two main depocentres by a saddle-like high just northeast of the present-day Euphrates River. Deposition of over 1600 m of Triassic and over 2000 m of Cretaceous rocks are recorded in both the Palmyride and Sinjar areas, but a total of less than 1300 m were deposited in the intervening saddle (e.g., Derro-2 well, Fig. 5). During this time, deposition in Syria was principally restricted to the Sinjar and Palmyride troughs and Levantine margin, but isopachs indicate up to 600 m of Upper Triassic and Lower Cretaceous deposits in the deepest part of the proto-Euphrates graben (Sawaf *et al.* 1988), consistent with the seismic interpretation shown above. This suggests initial extension of the Euphrates graben system during Late Triassic time; however, some of this discrepancy may be due to Cretaceous erosion experienced on the Rutbah and Rawda structural highs. Initiation of minor subsidence in the east-west trending Anah graben of western Iraq is ascribed to Liassic time by Ibrahim (1979), and incipient rifting of the Azraq/Sirhan graben in Saudi Arabia and Jordan began in Early Cretaceous time (Abu-Jaber *et al.* 1989). According to these authors, both areas experienced considerably accelerated subsidence during the Late Cretaceous.

Our studies show that during the Late Cretaceous, the locus of deposition began to shift from the Levantine margin to central Syria. By Coniacian to Campanian time, active rifting in the Euphrates (this study), Azraq/Sirhan (Abu-Jaber *et al.* 1989), and possibly Anah grabens (described as 'Late Cretaceous' by Ibrahim, 1979), and continued deposition in the Bishri and Sinjar areas (Sawaf *et al.* 1988) accounted for the bulk of sedimentary deposits (Fig. 15b). Our results also show widespread but relatively modest extension and strike-slip deformation in the northwestern segment of the Euphrates fault system in north-central Syria during Campanian–Maastrichtian time. This period of active subsidence continued well into the Maastrichtian. The generalized extensional environment demonstrated by the sedimentation in these weak zones came to an end in latest Cretaceous time (Fig. 15c). Ophiolite obduction along the margins of the northern Arabian plate accompanied a major plate reorganization (Dercourt *et al.* 1986). Chaimov *et al.* (1992) inferred that this event was reflected in Syria by initial minor uplift in the southwestern Palmyrides during the Maastrichtian. Salel & Séguret (1994) argued that thrusting of the Palmyrides initiated prior to Eocene time, and also favored the onset of compression during the Maastrichtian. The interpretation presented here indicates that active rifting of the Euphrates graben in southeastern Syria ceased at about this time, giving way to a thick sequence of relatively undeformed beds consistent with post-rift deposition (e.g., Fig. 8). There is some evidence, however, that strike slip faulting occurred along the Euphrates fault system into the early Palaeogene (e. g., Fig. 7). These considerations are consistent with a model in which the northwestern part of the Arabian plate became subject to collision, abruptly curtailing extension in western and central Syria and Jordan, and initiating the onset of Palmyride inversion (Fig. 15c). Although ophiolite emplacement occurred around many of the margins of the Arabian plate during Late Cretaceous time, plate reconstructions generally depict exotic continental crust sundering the Levantine (Mesogean) and Neotethys oceans near the northwestern corner of the Arabian plate (Dercourt *et al.* 1986), referred to as the Taurus block by Beydoun (1991). Here we propose that the northwestern Arabian plate may have collided with such a landmass, substantial enough to impede its northward motion, as early as latest Cretaceous. This convergence episode transformed the northern Arabian plate from a generally extensional to a generally compressional environment.

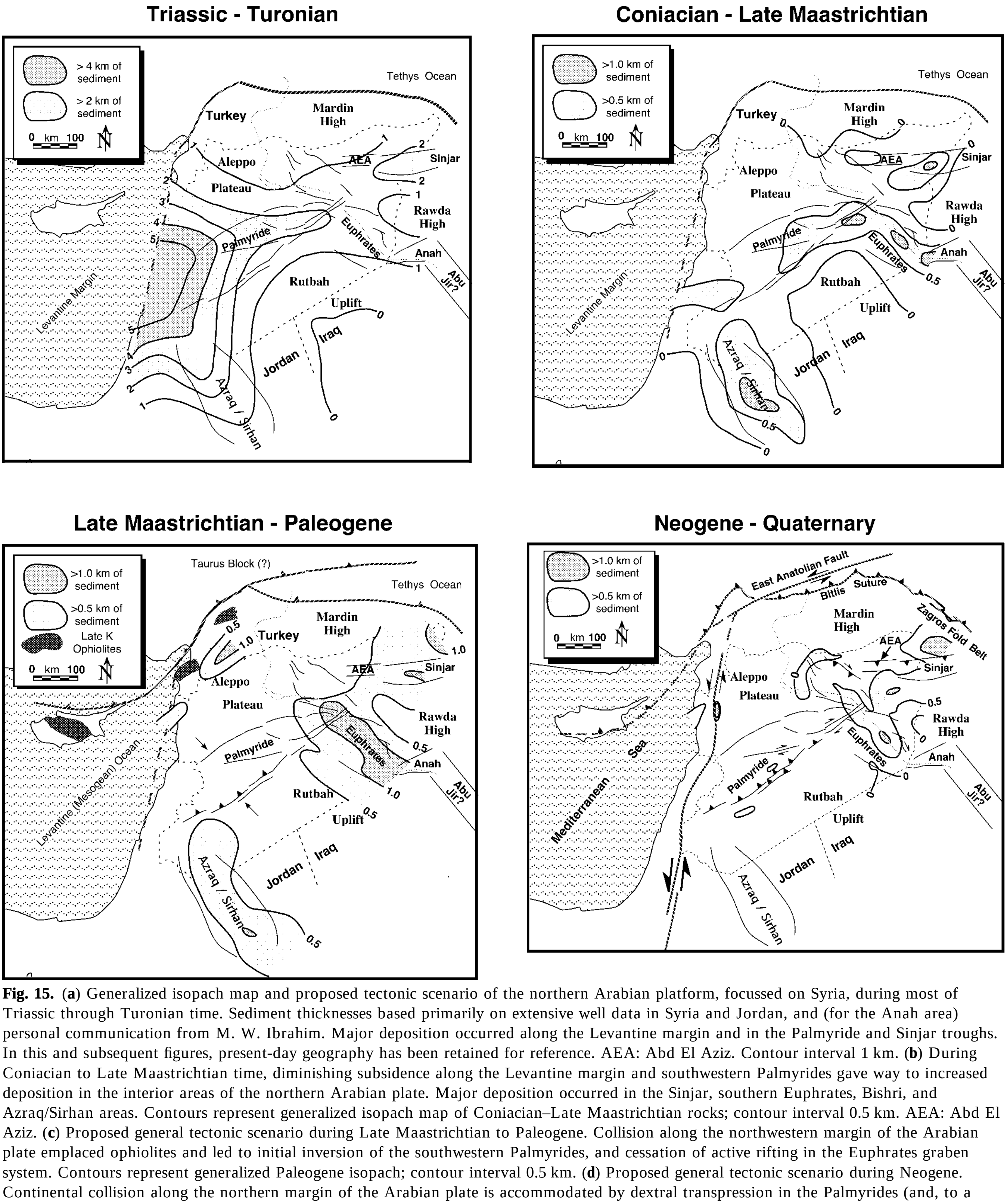

Fig. 15. (**a**) Generalized isopach map and proposed tectonic scenario of the northern Arabian platform, focussed on Syria, during most of Triassic through Turonian time. Sediment thicknesses based primarily on extensive well data in Syria and Jordan, and (for the Anah area) personal communication from M. W. Ibrahim. Major deposition occurred along the Levantine margin and in the Palmyride and Sinjar troughs. In this and subsequent figures, present-day geography has been retained for reference. AEA: Abd El Aziz. Contour interval 1 km. (**b**) During Coniacian to Late Maastrichtian time, diminishing subsidence along the Levantine margin and southwestern Palmyrides gave way to increased deposition in the interior areas of the northern Arabian plate. Major deposition occurred in the Sinjar, southern Euphrates, Bishri, and Azraq/Sirhan areas. Contours represent generalized isopach map of Coniacian–Late Maastrichtian rocks; contour interval 0.5 km. AEA: Abd El Aziz. (**c**) Proposed general tectonic scenario during Late Maastrichtian to Paleogene. Collision along the northwestern margin of the Arabian plate emplaced ophiolites and led to initial inversion of the southwestern Palmyrides, and cessation of active rifting in the Euphrates graben system. Contours represent generalized Paleogene isopach; contour interval 0.5 km. (**d**) Proposed general tectonic scenario during Neogene. Continental collision along the northern margin of the Arabian plate is accommodated by dextral transpression in the Palmyrides (and, to a lesser extent, in the Euphrates), compression in the Sinjar/Abd El Aziz area, and minor compression in the Anah area. Contours represent generalized isopach map of Neogene–Quaternary sediments; widespread deposition in eastern Syria probably represents northwestern terminus of the Mesopotamian foredeep. Contour interval 0.5 km.

Cenozoic evolution

As convergence continued during Palaeogene time, deposition in Syria was mainly confined to the Euphrates depression and Sinjar trough. In contrast to Cretaceous graben formation, however, Palaeogene subsidence in the Euphrates depression involved development of a sag basin and generally lacked significant faulting. Over 600 m of the Upper Miocene Lower Fars formation are recorded in the Omar-103 and several other wells. However, these thick deposits extend throughout eastern Syria, denoting that they are probably only indirectly related to the Euphrates depression. Rather, they may represent the northwestern terminus of the Mesopotamian foredeep associated with the Neogene Zagros continental collision farther to the east.

At some point during Cenozoic time, the earlier phase of transtension along the Euphrates system became reactivated as transpressional deformation. Evidence for the timing of this reactivation may be found in an unconformity in the northwestern Euphrates segment at the base of the Upper Miocene (see Fig. 5), possibly due to Mid- to Late Miocene uplift and erosion. Early–Mid-Miocene time marked the onset of both the main phase of motion along the Dead Sea fault system and major uplift in the Palmyrides (Chaimov *et al.* 1992). In nearby southern Turkey, full-scale continental collision along the Bitlis suture (Sengör *et al.* 1980; Yilmaz 1993) and initiation of motion along the East Anatolian fault (Burke & Sengör 1986) are ascribed to Late Miocene time. Late Miocene time also appears to have marked the beginning of primary uplift of the Sinjar. These events are consistent with north-directed compression in northern Syria resulting in shortening in the Sinjar and Palmyrides, and right-lateral transpression along the Euphrates (Fig. 15d). The fact that transpressional structures are less pronounced in the southeastern Euphrates may be explained by accommodation of strain in the Sinjar and Abd El Aziz uplifts. The kinematics of this model also require minor compressional reactivation of the Anah graben (see Fig. 15d). In fact Dunnington (1958) describes an east-trending anticline in the Anah 'graben', ascribed by Lovelock (1984) to Miocene inversion. Minor uplift in the southeastern Euphrates also affects Pliocene reflections and thus continued through at least Pliocene time, but is probably no longer active since the area is now a topographic low.

The Palmyrides are currently in a state of right-lateral transpression (Chaimov *et al.* 1993), with right-lateral motion principally accommodated along the Jhar (Khoury *et al.* 1975; Al-Saad *et al.* 1992) and South Al-Bishri faults. Minor seismicity (Chaimov *et al.* 1990) and the apparent offset of the Euphrates River valley by the continuation of the South Al-Bishri fault (see Fig. 10) indicate that they are still active. Right-lateral motion along these faults is consistent with a northwest direction of principal stress (Chaimov *et al.* 1993). However, we have previously argued for shortening in the Sinjar/Abd El Aziz and Anah zones and right-lateral transpression along the Euphrates, consistent with a north or north-northeast-directed compressive stress. This apparent discrepancy can be resolved by noting that the curving northern boundary of the Arabian plate may result in a variation in the direction of maximum horizontal stress, with the effects of the northwest-striking Zagros collision superimposed, in eastern Syria, on an overall northwesterly-directed stress (Fig. 15d). The differing orientations of the Palmyrides and Euphrates with respect to the principal stress direction is probably primarily responsible for the fact that the Palmyrides have experienced much more significant Cenozoic inversion than the Euphrates system.

With the continuation of the South Al-Bishri fault to the Euphrates River, it appears that the Bishri block may be undergoing counter-clockwise rotation. This reorientation may be interpreted as an eastward extrusion of the Bishri block in response to the convergence occurring in the southwestern Palmyrides, and it occurs near a kink in the Euphrates River valley between two rather linear segments (see Fig. 1). However, unlike the situation involving the Anatolian block (e.g., Burke & Sengör 1986), no free surface exists to the east of the Bishri block or Aleppo plateau, rendering a kinematic interpretation problematic. Further documentation of the amount of dextral offset and the extent of the South Al-Bishri and associated faults is necessary to resolve this question. We have found no clear evidence that Palmyride structures continue in the subsurface to the Sinjar, as some have speculated (e.g., Ponikarov 1967; Lovelock 1984). However, the structures in the complex area between the Euphrates River and the Sinjar/Abd El Aziz structures have yet to be fully investigated. More thorough study of northeastern Syria is required to fully integrate structures in northeastern Syria into a comprehensive model of regional kinematics.

Reactivation and tectonic heritage

In its purest version, the original formulation of plate tectonic theory postulated a small number of rigid plates with deformation wholly restricted to the plate boundaries (Morgan 1968). It is now generally recognized, however, that a plate's deformational history may profoundly affect its response to subsequent plate boundary events. That is, the existence of older sutures, shear zones, and failed rifts is common in plate amalgamation and tectonic reactivation. The Arabian plate may be one area where this phenomenon is especially manifest. The structures described in this study can be considered in terms of the response of long-lived stable blocks and intervening mobile zones reflecting a tectonic heritage dating back at least to Mesozoic time, and perhaps to the Palaeozoic or even Proterozoic.

The orientations of many of these weak zones may have been established during the Late Proterozoic/Early Cambrian assembly of the Arabian plate from a series of island arcs and/or continental microplates (e.g., Stoesser & Camp, 1985). In particular, the northwest-trending Najd fault system (Fig. 1) is exposed over an area of more than 1200 by 300 km on the Arabian shield (e.g., Agar 1987; Husseini 1989; Beydoun 1991). This fault system is thought to represent a complex zone of strike-slip faulting active late in the Proterozoic Pan-African orogeny (Agar 1987; Brown *et al.* 1989). Much subsequent tectonism, including the Euphrates/Abu Jir trend in Syria and Iraq, the Azraq/Sirhan grabens in Jordan and Saudi Arabia, and the Red Sea rift, is oriented subparallel to the Najd faults (Fig. 1), hinting that Najd faulting may extend beneath the Phanerozoic cover of the northern Arabian plate. Enigmatic Neogene and Quaternary basaltic volcanism has occurred throughout much of the northern Arabian plate (Ponikarov 1966), often along northwesterly-striking vents that suggest reactivation of Najd-type fractures. Beydoun (1993) suggested that the Zagros trend also developed on a Najd-oriented fracture zone. Many of the Mesozoic and Cenozoic rift basins of northern and eastern Africa also parallel this trend, and reactivation of Late Proterozoic shear zones has been suggested by some workers in the East African rift system (Strecker *et al.* 1990; Smith & Mosley 1993). The emplacement of the Najd fabric may thus have played a fundamental role in the response of the Arabian plate to subsequent tectonic events.

The northeast-trending Palmyrides may also reflect a Proterozoic inheritance. From modelling a *c.* 20 mGal difference in Bouguer gravity values, Best *et al.* (1990) argued that the crustal blocks of the Aleppo Plateau and Rutbah Uplift are fundamentally different in either thickness or mean density, and inferred that the intervening Palmyrides may thus represent a Late Proterozoic terrane boundary (i.e., a suture or shear zone) analogous to those exposed on the Arabian shield farther south. Similarly, Bouguer gravity values between the Rutbah Uplift and Rawda High in eastern Syria and western Iraq differ by an even greater amount: approximately 40 mGal. Hence, it seems plausible that the same explanation could be applied there. Modelling of the gravity field in eastern Syria by Brew *et al.* (1997) confirms the viability of this interpretation, suggesting that the area of the present Euphrates depression in southeast Syria may also represent a Proterozoic terrane boundary, following the speculation of Best *et al.* (1993). The fact that the Euphrates fault system parallels the Late Proterozoic Najd faults mapped in the Arabian Shield to the southwest (Fig. 1) lends further credence to the notion that the Euphrates fault system possesses a Proterozoic heritage.

The relationship between the Rawda High, the Mardin High in southern Turkey, and the intervening Sinjar Uplift and Abd El Aziz structural zone (Fig. 1) is less clear. The tectonic history of the Sinjar shares many elements with the Palmyrides, both areas encompassing Mesozoic depocentres uplifted during Cenozoic inversion (Sawaf *et al.* 1993). However, this area has not yet received extensive study in the open literature, and its earlier history remains largely unknown. The pre-Mesozoic relationship between the Mardin High and Aleppo Plateau across the northwestern Euphrates fault system is also obscure. The postulated Proterozoic 'Euphrates suture' may have extended through this area, making the present-day Palmyride/Euphrates intersection a Proterozoic triple-junction. Alternatively, the Aleppo and Mardin zones may have been a single stable block before being disrupted by Cretaceous and subsequent deformation centred to the southeast. The latter explanation would appear to be consistent with the greater magnitude of deformation experienced in the southeastern segment of the Euphrates fault system. Clearly, further study is needed on the pre-Mesozoic history of this region.

Conclusions

The Mesozoic and Cenozoic geological evolution of the Euphrates fault system is documented along its 350 km length in Syria. Throughout much of Mesozoic time, the Euphrates trend constituted a saddle-like ridge between the Palmyride and Sinjar/Abd El Aziz troughs. However, an extensive system of normal and strike-slip faults along the Euphrates trend reflects the development of a transtensive regime by Late Cretaceous time. This regime is manifested by a network of deep grabens and half-grabens along the Euphrates in southeastern Syria, with similar but less pronounced features in the northwestern segment of the Euphrates system. Development of an overlying Palaeogene sag basin in southeastern Syria was followed by Miocene subsidence in eastern Syria. Miocene–Pliocene transpressional reactivation of the Euphrates faults was particularly noteworthy in the northwestern segment in north-central Syria, and probably commenced earlier than in southeastern Syria.

Integrating these observations with other regional tectonic elements results in aspects of a new kinematic model for the northern Arabian plate, components of which remain to be tested by more extensive mapping in eastern Syria. In this proposed model, a series of plate boundary events interact with pre-existing structures, some of which probably reflect the Late Proterozoic assembly of the Arabian plate. A Mesozoic extensional regime was later altered by Late Cretaceous collision along the northwestern margin of the Arabian plate, resulting in initial minor uplift of the Palmyride mountains and cessation of active rifting along the Euphrates fault system. Widespread north-south shortening in Miocene time along the Bitlis and Zagros sutures resulted in inversion and uplift of the Palmyride and Sinjar troughs, right-lateral transpression in north-central Syria, and subsidence in eastern Syria in association with development of the Mesopotamian foredeep. Continuing Plio-Pleistocene convergence caused additional (minor) transpression along the length of the Euphrates fault system accompanied by right-lateral strike-slip faulting and counterclockwise rotation in the northeastern Palmyrides, and continuing uplift of the Sinjar region.

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References

ABU-JABER, N.S., KIMBERLEY, M.M. & CAVAROC, V.V. 1989. Mesozoic-Palaeogene basin development within the eastern Mediterranean borderland. *Journal of Petroleum Geology*, **12,** 419–436.

AGAR, R.A. 1987. The Najd fault system revisited; a two-way strike-slip orogen in the Saudi Arabian Shield. *Journal of Structural Geology*, **9,** 41–48.

AL-SAAD, D., SAWAF, T., GEBRAN, A., BARAZANGI, M., BEST, J. & CHAIMOV, T. 1992. Crustal structure of central Syria: The intracontinental Palmyride mountain belt. *Tectonophysics*, **207,** 345–358.

ALSDORF, D., BARAZANGI, M., LITAK, R., SEBER, D., SAWAF, T. & AL-SAAD, D. 1995. The intraplate Euphrates depression–Palmyrides mountain belt junction and relationship to Arabian plate boundary tectonics. *Annali di Geofisica*, **38,** 385–397.

BARAZANGI, M. 1989. Continental collision zones: Seismotectonics and crustal structure. *In*: JAMES, D.E. (ed.) *The Encyclopedia of Solid Earth Geophysics*. Van Nostrand Reinhold Company, New York, 58–75.

——, SEBER, D., CHAIMOV, T., BEST, J., LITAK, R., AL-SAAD, D. & SAWAF, T. 1993. Tectonic evolution of the northern Arabian plate in western Syria. *In*: MANTOVANI, E., MORELLI, A. & BOSCHI, E. (eds) *Recent Evolution and Seismicity of the Mediterranean Region*. NATO ASI Series, Kluwer Academic Publishers, The Netherlands, 117–140.

BERBERIAN, F. & BERBERIAN, M. 1981. Tectono-plutonic episodes in Iran. *In*: GUPTA, H. & DELANY, F. (eds) *Zagros, Hindu Kush, Himalaya geodynamic evolution*. American Geophysical Union, Geodynamics Series **3,** 5–32.

—— & KING, G.C.P. 1981. Towards a paleogeography and tectonic evolution of Iran. *Canadian Journal of Earth Sciences*, **18,** 210–265.

BEST, J.A. 1991. *Crustal evolution of the northern Arabian platform beneath the Syrian Arab Republic*. PhD. Dissertation, Cornell University, Ithaca, NY.

——, BARAZANGI, M., AL-SAAD, D., SAWAF, T. & GEBRAN, A. 1990. Bouguer gravity trends and crustal structure of the Palmyride Mountain belt and surrounding northern Arabian platform in Syria. *Geology*, **18,** 1235–1239.

——, ——, ——, —— & —— 1993. Continental margin evolution of the northern Arabian platform in Syria. *American Association of Petroleum Geologists Bulletin*, **77,** 173–193.

BEYDOUN, Z.R. 1991. *Arabian plate hydrocarbon geology and potential—a plate tectonic approach.* American Association of Petroleum Geologists Studies in Geology **33**.

—— 1993. Evolution of the northeastern Arabian plate margin and shelf: Hydrocarbon habitat and conceptual future potential. *Revue de l'Institut Français du Pétrole,* **48,** 311–345.

BOSWORTH, W. 1992. Mesozoic and early Tertiary rift tectonics in East Africa. *Tectonophysics,* **209,** 115–137.

—— & MORLEY, C.K. 1994. Structural and stratigraphic evolution of the Anza rift, Kenya. *Tectonophysics,* **236,** 93–115.

BREW, G.E., LITAK, R.K., SEBER, D., BARAZANGI, M., AL-IMAM, A. & SAWAF, T. 1997. Basement depth and sedimentary velocity structure in the northern Arabian platform, eastern Syria. *Geophysical Journal International,* **128,** 617—631.

BROWN, G.F., SCHMIDT, D.L. & HUFFMAN, A.C. JR. 1989. Shield area of western Saudi Arabia. *In*: *Geology of the Arabian peninsula.* US Geological Survey Professional Paper **560-A.**

BURKE, K. & SENGÖR, C. 1986. Tectonic escape in the evolution of the continental crust. *In*: BARAZANGI, M. & BROWN, L. (eds) *Reflection Seismology: The Continental Crust.* American Geophysical Union, Geodynamics Series **14,** 41–53.

CHAIMOV, T., BARAZANGI, M., AL-SAAD, D., SAWAF, T. & GEBRAN, A. 1990. Crustal shortening in the Palmyride fold belt, Syria, and implications for movement along the Dead Sea fault system. *Tectonics,* **9,** 1369–1386.

——, ——, ——, —— & —— 1992. Mesozoic and Cenozoic deformation inferred from seismic stratigraphy in the southwestern intracontinental Palmyride fold-thrust belt, Syria. *Geological Society of America Bulletin,* **104,** 704–715.

——, ——, —— & —— 1993. Seismic fabric and 3-D upper crustal structure of the southwestern intracontinental Palmyride fold belt, Syria. *American Association of Petroleum Geologists Bulletin,* **77,** 2032–2047.

COCHRAN, J.R. 1983. Model for the development of the Red Sea. *American Association of Petroleum Geologists Bulletin,* **67,** 41–69.

COLEMAN-SAAD, S. 1978. Fold development in Zagros simply folded belt, southwestern Iran. *American Association of Petroleum Geologists Bulletin,* **62,** 984–1003.

DE RUITER, R.S.C., LOVELOCK, P.E.R. & NABULSI, N. 1995. The Euphrates Graben of eastern Syria: A new petroleum province in the northern Middle East. *In*: AL-HUSSEINI, M.I. (ed.), *GEO '94: The Middle East Petroleum Geosciences,* **1**, Gulf PetroLink, Manama, Bahrain, 357–368.

DERCOURT, J. & 18 OTHERS 1986. Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. *Tectonophysics,* **123,** 241–315.

DUNNINGTON, H.V. 1958. Generation, migration, accumulation, and dissipation of oil in northern Iraq. *In*: WEEKS, L.G. (ed.) *Habitat of Oil.* American Association of Petroleum Geologists, Tulsa, Oklahoma, USA, 1194–1251.

DZIEWONSKI, A.M., EKSTROM, G. & SALGANIK, M.P. 1995. Centroid-moment tensor solutions for October-December 1994. *Physics of the Earth and Planetary Interiors,* **91,** 187–201.

FREUND, R., GARFUNKEL, Z., ZAK, I., GOLDBERG, M., WEISSBROD, T. & DERIN, B. 1970. The shear along the Dead Sea rift. *Philosophical Transactions of the Royal Society of London,* **A267,** 107–130.

GARFUNKEL, Z. 1981. Internal structure of the Dead Sea leaky transform (rift) in relation to plate kinematics. *Tectonophysics,* **80,** 81–108.

HARDING, T.P. 1985. Seismic characteristics and identification of negative flower structures, positive flower structures, and positive structural inversion. *American Association of Petroleum Geologists Bulletin,* **69,** 582–600.

HEMPTON, M.R. 1985. Structure and deformation history of the Bitlis suture near Lake Hazar, southeastern Turkey. *Geological Society of America Bulletin,* **96,** 233–243.

HUSSEINI, M.I. 1989. Tectonic and deposition model of late Precambrian-Cambrian Arabian and adjoining plates. *American Association of Petroleum Geologists Bulletin,* **73,** 1117–1131.

IBRAHIM, M.W. 1979. Shifting depositional axes of Iraq: An outline of geosynclinal history. *Journal of Petroleum Geology,* **2,** 181–197.

KARIG, D.E. & KOZLU, H. 1990. Late Paleogene-Neogene evolution of the triple junction region near Maras, south-central Turkey. *Journal of the Geological Society, London,* **147,** 1023–1034.

KHOURY, M., LATREILLE, M. & PARIS, M. 1975. *Preliminary structural analysis of Palmyrides (Syria).* The General Establishment of Geology and Mineral Resources: Ministry of Petroleum, Electricity, and Mineral Resources of Syria.

LAMBIASE, J.J. 1989. The framework of African rifting during the Phanerozoic. *Journal of African Earth Sciences,* **8,** 183–190.

LOVELOCK, P. 1984. A review of the tectonics of the northern Middle East region. *Geological Magazine,* **121,** 577–587.

MCBRIDE, J.H., BARAZANGI, M., BEST, J., AL-SAAD, D., SAWAF, T., AL-OTRI, M. & GEBRAN, A. 1990. Seismic reflection structure of intracratonic Palmyride fold-thrust belt and surrounding Arabian platform, Syria. *American Association of Petroleum Geologists Bulletin,* **74,** 238–259.

METWALLI, M.H., PHILIP, G. & MOUSSLY, M.M. 1974. Petroleum-bearing formations in northeastern Syria and northern Iraq. *American Association of Petroleum Geologists Bulletin,* **58,** 1781–1796.

MORGAN, W.J. 1968. Rises, trenches, great faults, and crustal blocks. *Journal of Geophysical Research,* **73,** 1959–1982.

PONIKAROV, V.P. (ed.) 1964. *The geological map of Syria, scale 1:200 000.* Ministry of Industry, Damascus, Syrian Arab Republic.

—— (ED.) 1966. *The geological map of Syria, scale 1:1 000 000.* Ministry of Industry, Damascus, Syrian Arab Republic.

—— (ED.) 1967. *The geology of Syria: explanatory notes on the geological map of Syria, scale 1:500 000, part I: Stratigraphy, igneous rocks, and tectonics.* Ministry of Industry, Damascus, Syrian Arab Republic.

QUENNELL, A.M. 1984. The Western Arabian rift system. *In*: DIXON, J.E. & ROBERTSON, A.H.F. (eds) *The Geological Evolution of the Eastern Mediterranean.* Geological Society, London, Special Publications, **17,** 775–778.

SALEL, J.F. & SÉGURET, M. 1994. Late Cretaceous to Palaeogene thin-skinned tectonics of the Palmyrides belt (Syria). *Tectonophysics,* **234,** 265–290.

SAWAF, T., AL-SAAD, D., GEBRAN, A., BARAZANGI, M., BEST, J.A. & CHAIMOV, T. 1993. Structure and stratigraphy of eastern Syria across the Euphrates depression. *Tectonophysics,* **220,** 267–281.

——, ZAZA, T. & SYRRIAH, O. 1988. *The distribution and litho-stratigraphic base for the sedimentary formations in the Syrian Arab Republic.* Unpublished report, Syrian Petroleum Company, Damascus, Syria.

SEARLE, M.P. 1994. Structure of the intraplate eastern Palmyride Fold Belt, Syria. *Geological Society of America Bulletin,* **106,** 1332–1350.

SEBER, D., BARAZANGI, M., CHAIMOV, T.A., AL-SAAD, D., SAWAF, T. & KHADDOUR, M. 1993. Upper crustal velocity structure and basement morphology beneath the intracontinental Palmyride fold-thrust belt and north Arabian platform in Syria. *Geophysical Journal International,* **113,** 752–766.

SENGÖR, A.M.C. & KIDD, W.S.F. 1979. Post collisional tectonics of the Turkish-Iranian plateau and a comparison with Tibet. *Tectonophysics,* **55,** 361–376.

—— & YILMAZ, Y. 1981. Tethyan evolution of Turkey: A plate tectonic approach. *Tectonophysics,* **75,** 181–241.

——, BURKE, K. & DEWEY, J. 1980. Tectonics of the North Anatolian transform fault. *In*: ISIKARA, A.M. & VOGEL, A. (eds) *Multidisciplinary approach to earthquake prediction.* Friedr. Vieweg and Sohn, Braunschweig/Weisbaden, 3–22.

——, GORUR, N. & SAROGLU, F. 1985. Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study. *In*: BIDDLE, K.T. & CHRISTIE-BLICK, N. (eds) *Strike-Slip Deformation, Basin Formation, and Sedimentation.* Society of Economic Paleontologists and Mineralogists Special Publications, **37,** 227–265.

SMITH, M. & MOSLEY, P.N. 1993. Crustal heterogeneity and basement influence on the development of the Kenya Rift, East Africa. *Tectonics,* **12,** 591–606.

STOESSER, D.B. & CAMP, V. 1985. Pan-African microplate accretion of the Arabian shield. *Geological Society of America Bulletin,* **96,** 817–826.

STRECKER, M.R., BLISNIUK, P.M. & EISBACHER, G.H. 1990. Rotation of extension direction in the central Kenya Rift. *Geology,* **18,** 299–302.

YILMAZ, Y. 1993. New evidence and model on the evolution of the southeast Anatolian orogen. *Geological Society of America Bulletin,* **105,** 251–271.

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