GeoArabia, Vol. 6, No. 4, 2001
Gulf PetroLink, Bahrain

Tectonic and Geologic Evolution of Syria

Graham Brew and Muawia Barazangi, Cornell University
Ahmad Khaled Al-Maleh, Damascus University
and Tarif Sawaf, Syrian Petroleum Company

ABSTRACT

Using extensive surface and subsurface data, we have synthesized the Phanerozoic tectonic and geologic evolution of Syria that has important implications for eastern Mediterranean tectonic studies and the strategies for hydrocarbon exploration. Syrian tectonic deformation is focused in four major zones that have been repeatedly reactivated throughout the Phanerozoic in response to movement on nearby plate boundaries. They are the Palmyride Mountains, the Euphrates Fault System, the Abd el Aziz-Sinjar uplifts, and the Dead Sea Fault System. The Palmyrides include the SW Palmyride fold and thrust belt and two inverted sub-basins that are now the Bilas and Bishri blocks. The Euphrates Fault System and Abd el Aziz-Sinjar grabens in eastern Syria are large extensional features with a more recent history of Neogene compression and partial inversion. The Dead Sea transform plate boundary cuts through western Syria and has associated pull-apart basins.

The geological history of Syria has been reconstructed by combining the interpreted geologic history of these zones with tectonic and lithostratigraphic analyses from the remainder of the country. Specific deformation episodes were penecontemporaneous with regional-scale plate-tectonic events. Following a relatively quiescent early Paleozoic shelf environment, the NE-trending Palmyride / Sinjar Trough formed across central Syria in response to regional compression followed by Permian-Triassic opening of the Neo-Tethys Ocean and the eastern Mediterranean. This continued with carbonate deposition in the Mesozoic. Late Cretaceous tectonism was dominated by extension in the Euphrates Fault System and Abd el Aziz-Sinjar Graben in eastern Syria associated with the closing of the Neo-Tethys. Repeated collisions along the northern Arabian margin from the Late Cretaceous to the Late Miocene caused platform-wide compression. This led to the structural inversion and horizontal shortening of the Palmyride Trough and Abd el Aziz-Sinjar Graben.

INTRODUCTION

Since the late 1980s, the goal of the 'Cornell Syria Project' has been to analyze and map the tectonic history of the structurally deformed areas of Syria. Understanding this rich history can yield a fuller appreciation of the plate-tectonic processes in the eastern Mediterranean region. It can also provide a better understanding of the likely occurrence and distribution of natural resources. Although not comparable with the vast hydrocarbon reserves of the Arabian Gulf, the resources of Syria are nonetheless economically important, and there is potential for further significant discoveries.

Much previous work has concentrated on relatively distinct structural provinces within Syria. The goal of this paper was to synthesize the tectonic evolution of the entire country by integrating our previous interpretations with new regional structural maps, and incorporating significant additional lithostratigraphic knowledge. After outlining the tectonic setting of the area, we provide a brief summary of previous work. Our regional mapping is then discussed, including a database description and presentation of new lithostratigraphic interpretations, structural maps, and a new tectonic map of Syria. The result is a Phanerozoic geologic and tectonic model for Syria in a plate-tectonic framework. We conclude by discussing the hydrocarbon habitats in Syria, and their relationship to the tectonic evolution of the region.

GEOLOGICAL REVIEW

Tectonic Setting

Syria is close to the leading edge of a continent / continent collision where the Arabian Plate is converging on Eurasia at 18 ± 2 mm / year in a roughly north-northwesterly direction (McClusky et al., 2000). This collision is manifest in the active transform and convergent plate boundaries that are currently proximal to Syria (Figure 1), and have been so for most of the Phanerozoic. The events on these boundaries (and their ancient counterparts) have largely controlled the Paleozoic, and particularly Mesozoic-Cenozoic, tectonics of Syria.

The most prominent plate margin at the present-day is the Zagros fold and thrust belt (Figure 1) that trends northwesterly through western Iran and eastern Iraq. It accommodates the convergence of Arabia with Eurasia by widespread thrusting, folding, and significant crustal shortening. Along the

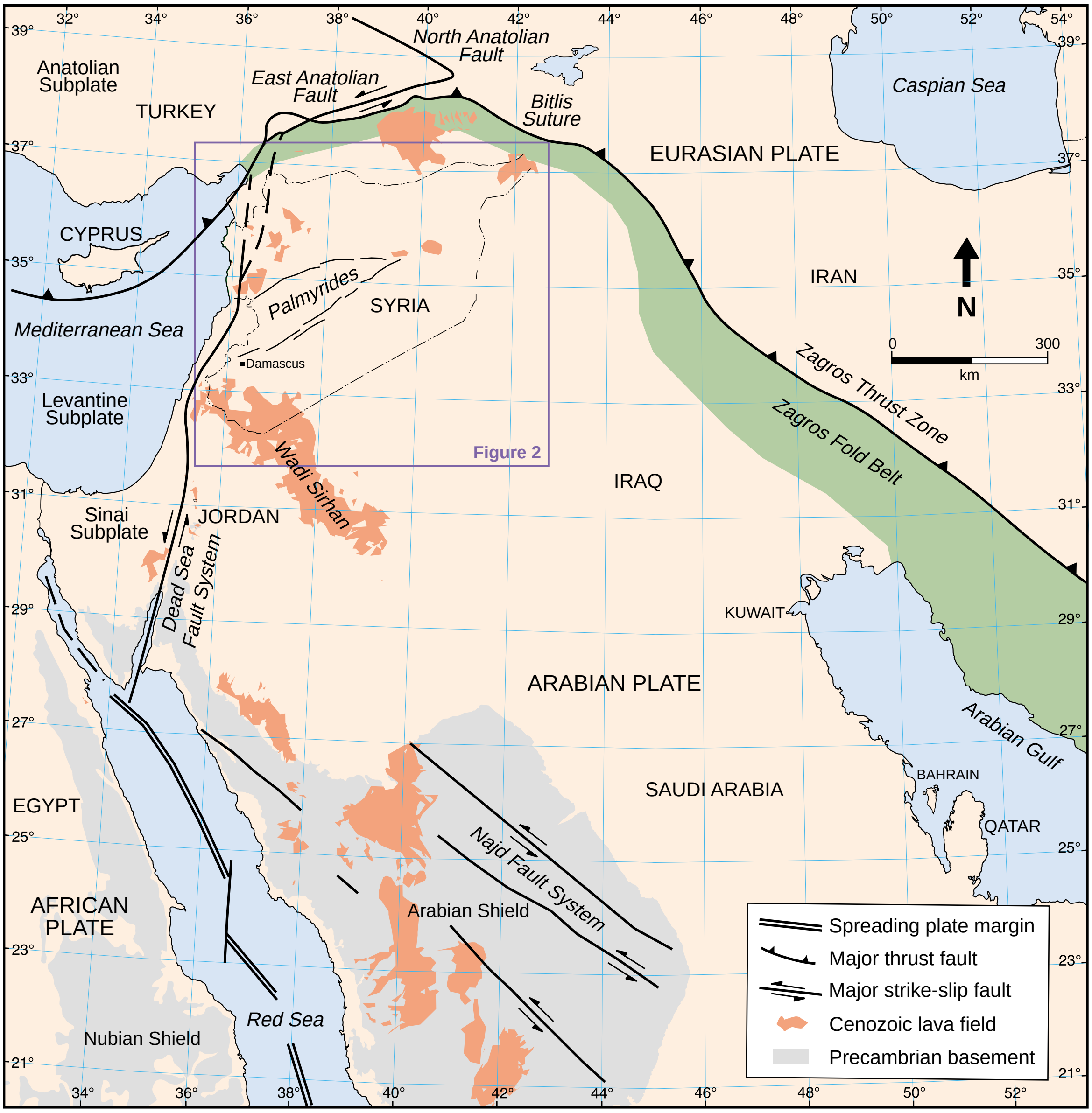


Figure 1: Regional tectonic map of the northern part of the Arabian Plate and adjacent areas showing the proximity of Syria to several active plate boundaries.

northern Arabian margin, the Zagros belt becomes the Eocene-Miocene Bitlis Suture joining the Eurasian and Arabian plates (Hempton, 1985). To the northwest of the Arabian Plate, the dextral Miocene-Pliocene North Anatolian Fault, and the sinistral East Anatolian Fault accommodate movement on the Anatolian subplate that is escaping westward owing to the Arabian-Eurasian convergence (McClusky et al., 2000).

Converging with the East Anatolian Fault from the south is the Cenozoic Dead Sea Fault System (Figure 1). This sinistral transform fault accommodates the differential northward motion of the Arabian and African plates (Levantine and Sinai subplates) created by the opening of the Red Sea. The extensional Red Sea and Gulf of Aden plate boundaries form the southwestern and southern boundaries of the Arabian Plate.

Previous Geologic Studies of Syria

At a gross scale, Syria can be divided spatially (Figure 2) into four major 'tectonic zones' and intervening structural highs (Barazangi et al., 1993). These zones—the Palmyride area, the Abd el Aziz-Sinjar area, the Euphrates Fault System, and the Dead Sea Fault System—have accommodated most of tectonic deformation in Syria throughout the Phanerozoic, whereas the intervening stable areas remained structurally high and relatively undeformed. The style of structural reactivation is dependent on the orientation of the tectonic zones to the prevailing stress pattern.

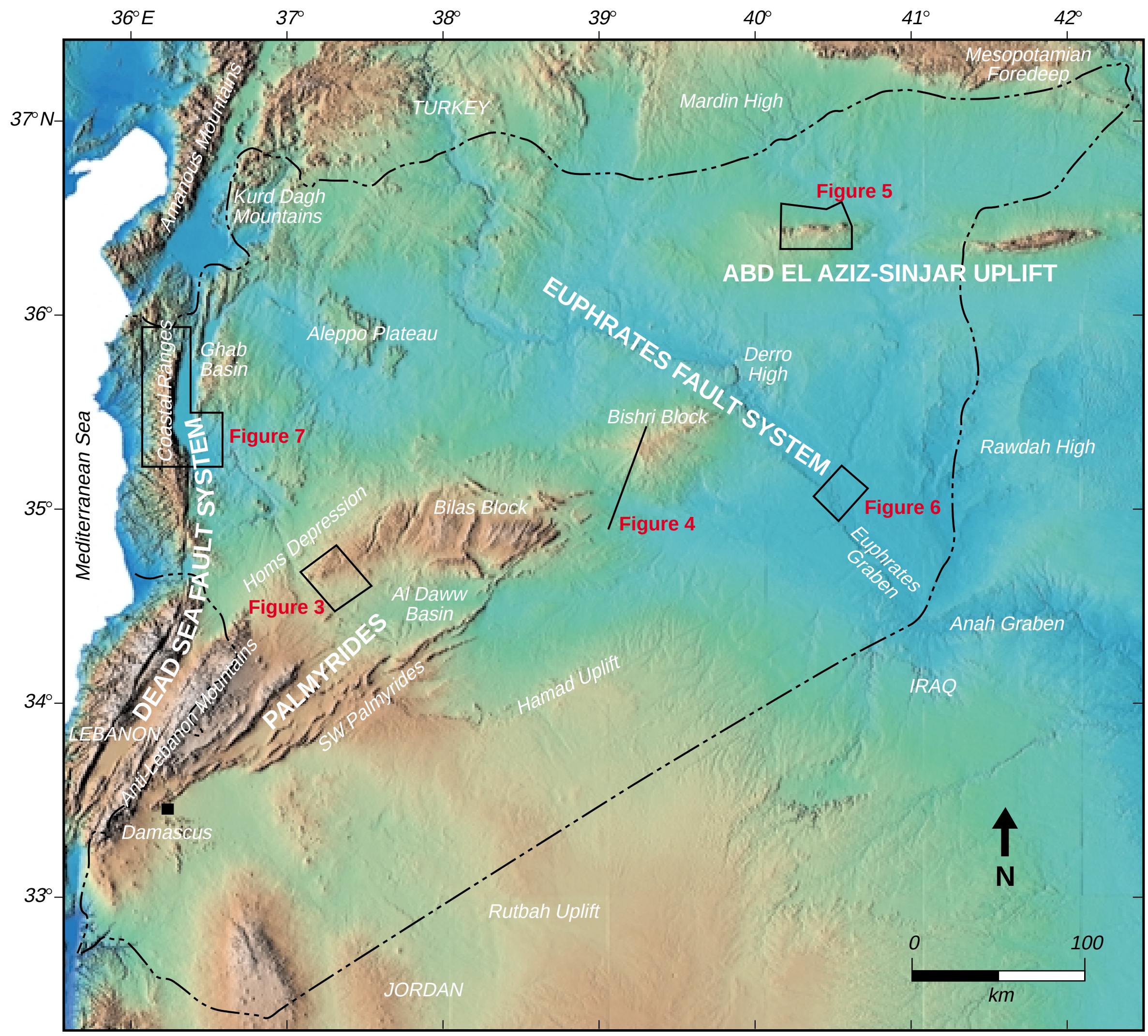


Figure 2: Topography of Syria, tectonic zones, and location of various text figures. Shaded relief image of topography illuminated from the west.

Palmyride Area

The area loosely referred to as the 'Palmyrides', can be further divided into the 'SW Palmyrides', and the Bilas and Bishri blocks of the 'NE Palmyrides' (Figure 2). During most of the Phanerozoic the Palmyride zone was a sedimentary depocenter (the 'Palmyride/Sinjar Trough'). Seismic reflection data (Chaimov et al., 1992, 1993) and drilling records show the SW Palmyrides to have been controlled by NW-dipping late Paleozoic and Mesozoic listric normal faults that were structurally inverted in the Neogene. Unfortunately, poor seismic reflectivity of the older section precludes precise documentation of Paleozoic tectonics.

A significant part of the thickening in the Palmyride Trough can be related to broad subsidence rather than extensional faulting (Chaimov et al., 1992), particularly during the Triassic. In the Jurassic and Late Cretaceous, however, normal faulting dominated according to Best (1991), Chaimov et al. (1993), and Litak et al. (1997). Since the Late Cretaceous, the Palmyrides have been subjected to episodic compression leading to folding and the currently observed topographic uplift.

The SW Palmyrides are dominated by a series of short, SE-verging folds controlled by reverse faults. The short-wavelength anticlines have steeply dipping (in some case overturned) forelimbs, and more shallowly dipping backlimbs, and are progressively steeper toward the southwest. Chaimov et al. (1993) argued that these folds were the result of fault-propagation folding above inverted normal faults, linked by sinistral transfer faults. This is supported by well data and outcrop evidence where Triassic strata are thrust over Santonian rocks (Mouty and Al-Maleh, 1983). Reverse faults with significantly decreasing fault dip in the shallow section could reconcile the tight fold axes with the relatively low-angle faults seen at the surface.

Chaimov et al. (1992) mapped a locally developed Triassic detachment level that accommodated some fault-bend fold formation, especially in the northern part of the SW Palmyrides (Figure 3). However, on a regional scale, Chaimov et al. (1993) documented similarly deformed Upper Cretaceous and lower Paleozoic strata, thus arguing against a regional-scale Mesozoic detachment in the SW Palmyrides.

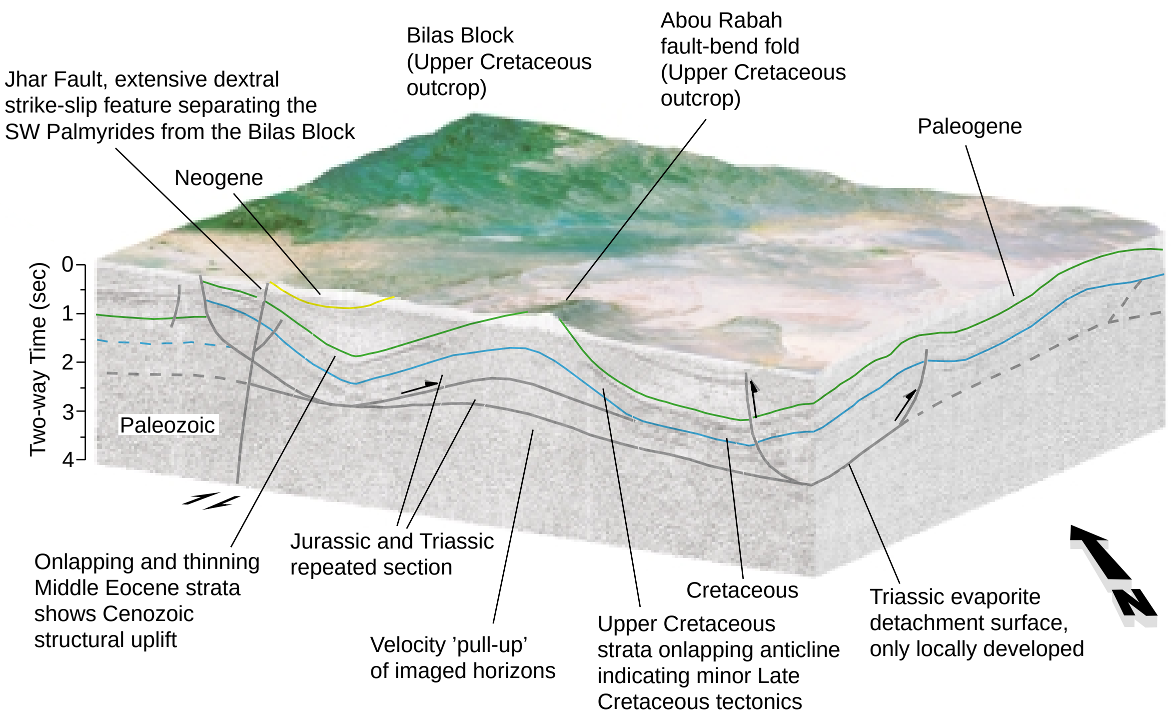


Figure 3: Perspective block model of the Abou Rabah anticlinal structure in the northern part of the SW Palmyrides (see Figure 2 for location). Surface is Thematic Mapper imagery draped over topography. Faces shown are seismic lines CH-36 (dip line) and CH-45. Image is 31x32 km with approximately no vertical exaggeration.

In contrast, in the central and northern Palmyrides, Searle (1994) mapped complex folding often in the form of box folds above an Upper Triassic detachment, but only minor reverse faulting. Hence, we interpret strong along-strike structural variations in the Palmyrides, with thrust faulting becoming less influential toward the northeast. This would agree with the cross-sections of Chaimov et al. (1990) that showed total shortening decreasing from around 20 km in the SW Palmyrides to almost zero in the far northeast.

The extensive low-relief Al-Daww Basin (Figure 2) lies between the SW Palmyrides and the Bilas Block. Dated as a Miocene to Recent depocenter, this intermontane basin contains more than 2,000 m of Cenozoic strata (Chaimov et al., 1992). To the north of the Basin, the Jhar Fault separates the SW Palmyrides from the NE Palmyrides. The Fault has been traced for nearly 200 km in a ENE-direction and shows an average of 1,000 m of uplift on its northern side and significant, but undetermined, amounts of dextral strike-slip (Al-Saad et al., 1992). Well data indicate this was an active extensional fault at least since the Jurassic. The structural inversion along the Jhar Fault controls the southern edge uplift of the Bilas Block (Figure 2). Deformation within the Block is dominated by strike-slip duplexing where large, relatively undeformed anticlines are bound by steep faults that show very little shortening (Chaimov et al., 1990). Along the northern margin of the Palmyrides is the Homs Depression (Figure 2). This large basin shows little or no sign of the structural inversion so prominent in the adjacent Palmyrides, which perhaps suggests a significant fault-controlled detachment of the depression from the uplifted Bilas Block.

To the north and east of the Bilas Block, the prominent right-lateral Bishri Fault separates the Bilas and Bishri blocks. Similar to the Jhar Fault, the transpressional Bishri Fault accommodates uplift of one block relative to the other. NE-striking Mesozoic normal faults were more active in the Bishri Block than in other parts of the Palmyrides, particularly in Jurassic and Late Cretaceous times (Figure 4). Cenozoic structural inversion of these faults is controlling the present-day NE-plunging anticlinal morphology of the blocks (McBride et al., 1990; Best, 1991).

Abd el Aziz-Sinjar Area

During the late Paleozoic to Late Cretaceous, the Sinjar (Figure 2) and surrounding areas were the northeastern part of the Palmyride/Sinjar Trough. As in the Palmyrides, accommodation space for late Paleozoic and Mesozoic clastic sediments several kilometers thick was created largely through broad subsidence, although some contemporaneous NE-striking normal faults have been identified (Brew et al., 1999).

Other than this broad trough formation, no significant extension occurred around the Abd el Aziz and Sinjar structures until the formation of a network of E-striking faults in the latest Cretaceous. These predominantly S-dipping normal faults and the resulting half grabens formed in the latest Campanian and Maastrichtian and accommodated up to 1,600 m of synrift calcareous, marly sedimentation (Figure 5). The cessation of the extension, as indicated by the termination of faulting, came abruptly at the end of the Cretaceous.

The currently observed topographic highs (the Abd el Aziz and Sinjar uplifts, Figure 2) are the result of Cenozoic structural inversion that has been most active in the Late Pliocene to Holocene (Kent and Hickman, 1997; Brew et al., 1999). Specifically, the Late Cretaceous E-striking normal faults are being reactivated in a reverse sense creating fault-propagation folds (Figure 5). Based on limited data, similar and contemporaneous deformation apparently affected the Mesopotamian Foredeep in the extreme northeast of Syria (Figure 2).

Euphrates Fault System

The Euphrates Graben (Figure 2) is a fault-bounded failed rift studied extensively by Litak et al. (1998) and de Ruiter et al. (1994). Litak et al. (1997) showed that the Euphrates Fault System is a related but less-deformed zone of extension that extends from the Iraqi border in the southeast to the Turkish border in the northwest and includes the Euphrates Graben. The lack of widespread inversion limits the topographic expression of the Euphrates Fault System (Figure 2).

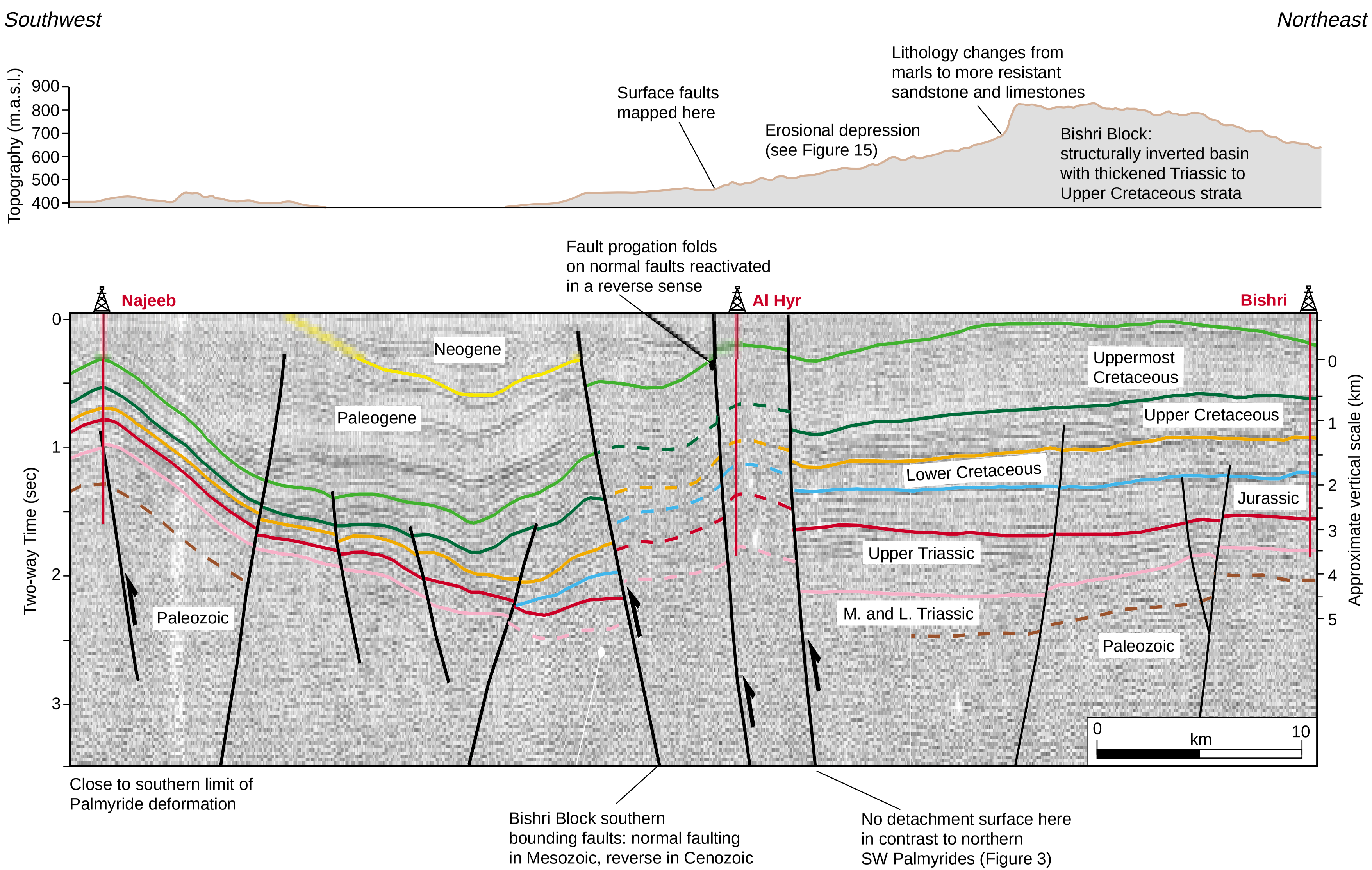


Figure 4: Interpretation of migrated seismic profile ALAN-90-10 from SW edge of Bishri Block in the NE Palmyrides (see Figure 2 for location). Dashed interpretation is speculative because of poor data.

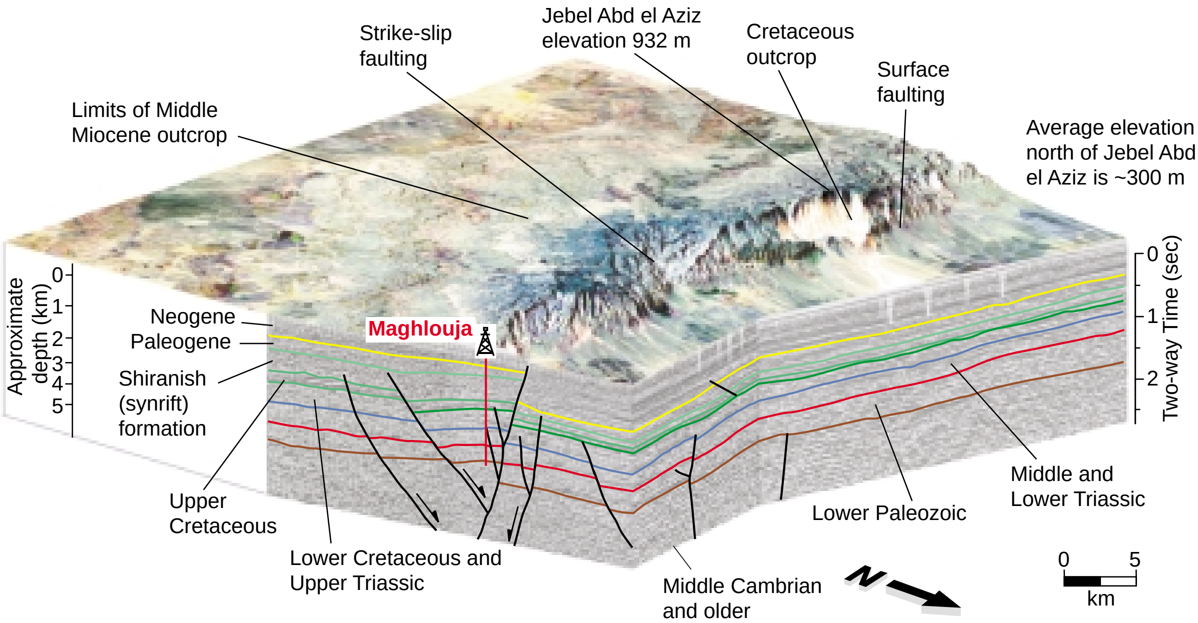


Figure 5: Perspective block model of the Abd el Aziz uplift in NE Syria (see Figure 2 for location). Surface is Thematic Mapper imagery draped over topography. Faces shown are seismic lines UN-350 (dip) and SY-48N. Image 29x41 km: topographic exaggeration about x 5; subsurface exaggeration about x 2.

A Turonian-Coniacian age unconformity—probably marking prerift uplift—is extensively developed in the Euphrates Graben, and the underlying limestone is eroded and dolomitized. Overlying redbeds grade into progressively deeper water carbonate facies (Litak et al., 1998). Senonian rifting that resulted in about 6 km of extension and an undetermined amount of strike-slip movement was accommodated by a distributed system of steep normal faults. The synrift carbonate deposition culminated in the Campanian to early Maastrichtian with the deposition of up to 2,300 m of deep-water marly limestones within the graben (Figure 6). Rift-related extension stopped during the Maastrichtian.

The Paleogene was marked by widespread thermal subsidence as the lithosphere reestablished thermal equilibrium after rifting (Litak et al., 1998). The Euphrates Fault System experienced minor dextral transpression and reactivation during the Neogene. Compressional features are best developed in the northwest of the fault zone where reverse and strike-slip movement and some associated minor fault-propagation folding occurred on reactivated Late Cretaceous normal faults. To the south and west of the Euphrates Graben is the Rutbah Uplift. The term ‘Hamad Uplift’ has been used by Mouty and Al-Maleh (1983) to describe the NE-trending paleogeographic high on the northern margin of the Rutbah Uplift in Syria (Figure 2).

Dead Sea Fault System

The Dead Sea Fault System is a major sinistral transform plate boundary separating Africa (Levantine subplate) from Arabia, and accommodating their differential movement. Total offset on the southern portion of the fault is well established to be around 105 km (Quennell, 1984). Some authors have suggested two episodes of strike-slip motion on the Dead Sea Fault System in concert with a two-phase Red Sea opening—Miocene slip of 60 to 65 km, and post-Miocene slip of 40 to 45 km (Freund et al., 1970; Quennell, 1984). Other authors (e.g., Steckler and ten Brink, 1986) have advocated a more constant Red Sea extension.

Along the northern segment of the fault (from Lebanon northward) the age and rates of faulting are unclear due to a lack of piercing points, although total post-Miocene offset has been reported as less than 25 km (Trifonov et al., 1991). These observations and work in the Palmyrides have been combined

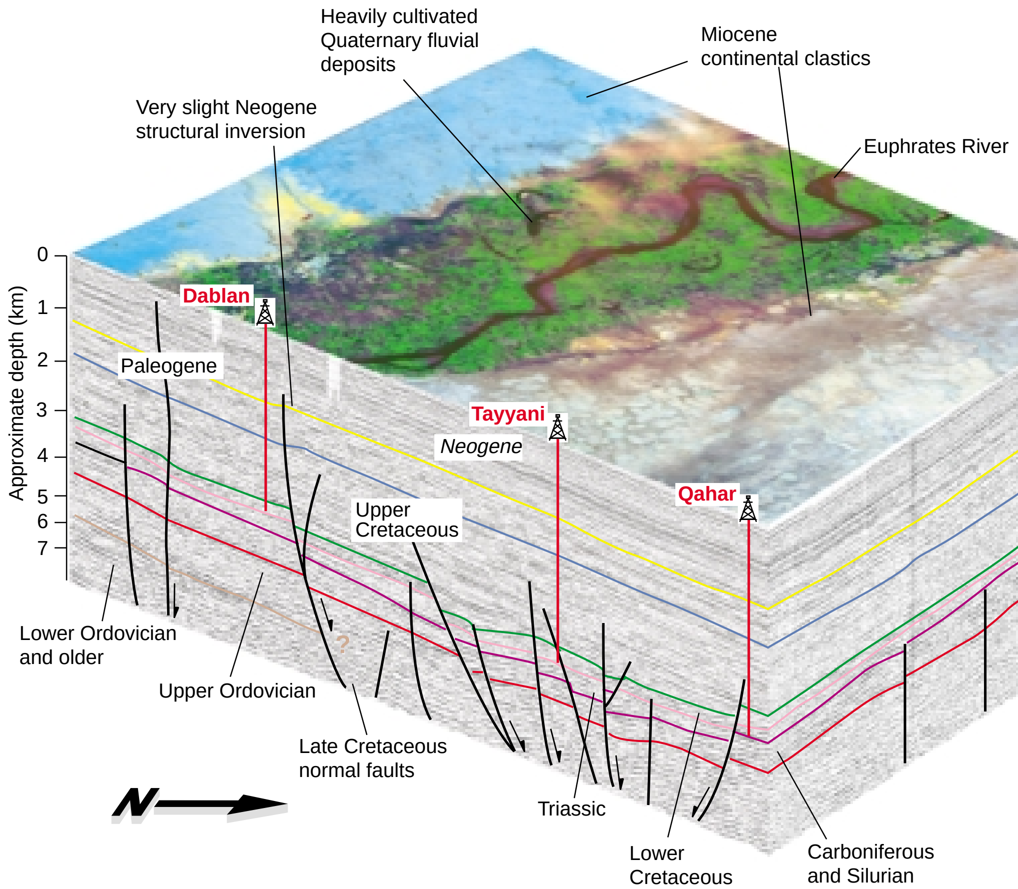


Figure 6: Perspective block model of the Euphrates Graben (see Figure 2 for location). Surface is Thematic Mapper imagery draped over topography. Faces shown are seismic lines PS-14 (dip) and PS-11. Image 31x20 km.

into a model in which the northern part of the Dead Sea Fault System has been active only during the second (post-Miocene) phase of faulting. In this model, 20 to 25 km of post-Miocene sinistral motion has been accommodated along the northern fault segment, and another 20 km in the shortening of the adjacent Palmyride fold and thrust belt (Chaimov et al., 1990), thus accommodating the full 40 to 45 km of post-Miocene slip.

The northern segment of the Dead Sea Fault System strikes parallel to the coast through western Syria, and is clearly defined both topographically and structurally (Figure 2). Along the fault in western Syria is the Ghab Basin (Figure 7), a deep Pliocene to Holocene pull-apart structure (Brew et al., 2001). The Ghab Basin opened in response to a left-step in the fault, although sinistral motion fails to be fully transferred across the basin, resulting in the ‘horse-tailing’ of the fault system observed northward into Turkey.

The Syrian Coastal Ranges, in places more than 1,500 m high, occupy most of the Syrian onshore area west of the Dead Sea Fault and Ghab Basin (Figure 2). An extensive karst terrain, a gently dipping (about 10º) western limb, and a chaotic, steep, eastern limb where Triassic strata are exposed, characterize the area. Stratigraphic relationships indicate that the uplift of the Coastal Ranges is part of the extensive Syrian Arc deformation (Late Cretaceous and Tertiary compressional folding along the eastern Mediterranean coast) that has been documented in the Levant (Walley, 2001). The Coastal Ranges have clearly been affected by the propagation of the Dead Sea Fault System and formation of the Ghab Basin, resulting in the steep eastern limb (Figure 7) and the possible rotation of the block (Brew et al., 2001).

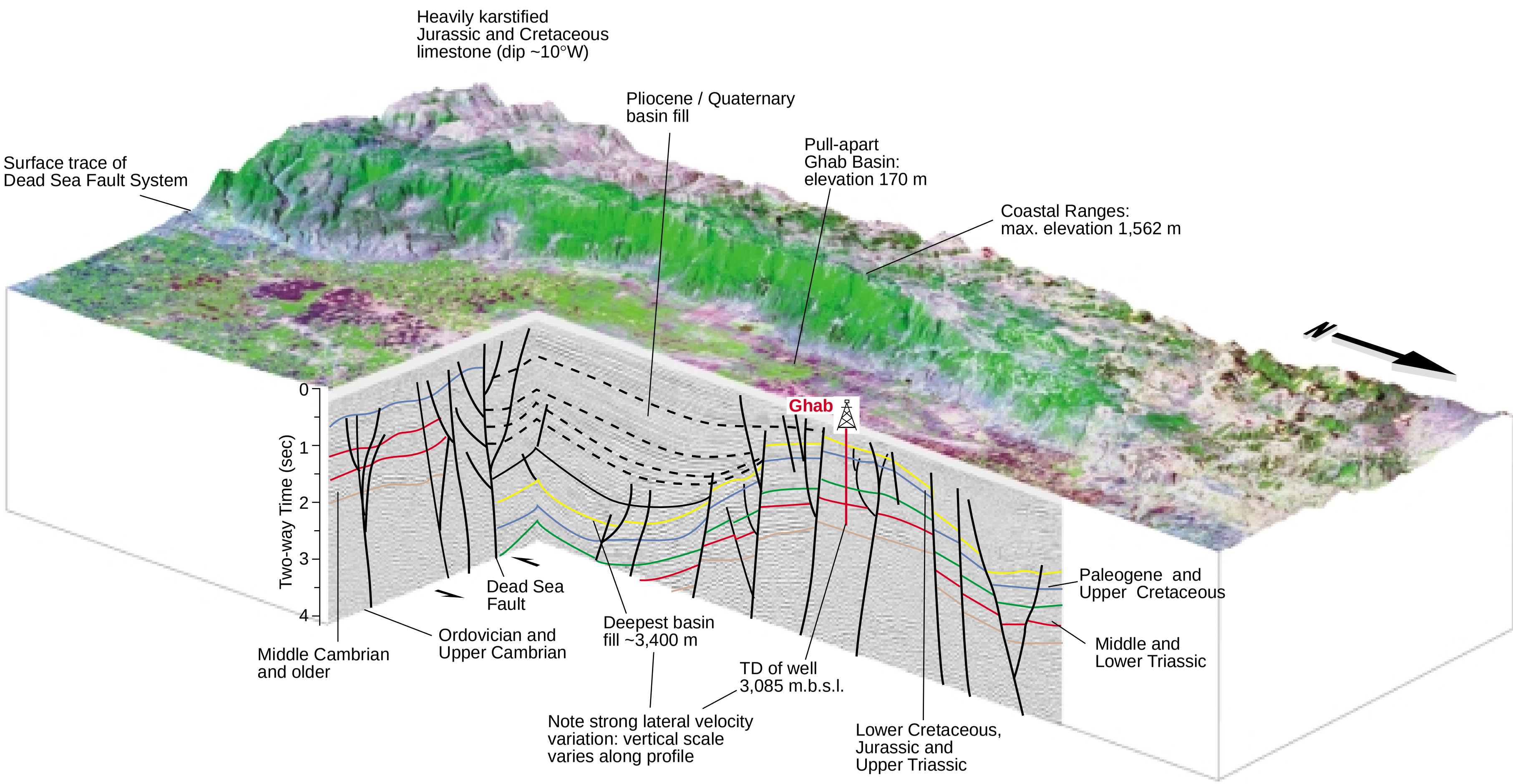


Figure 7: Perspective block model of the Coastal Ranges/Ghab Basin along the line of the Dead Sea Fault System (see Figure 2 for location). Surface is Thematic Mapper imagery draped over topography. Along-basin seismic profile is line GA-6 and cross-basin profile is GA-3. Image 90x41 km: topographic exaggeration about x 4.

STRUCTURAL AND STRATIGRAPHIC MAPPING

Database

The database available for this work is extensive by academic research standards, and this is the first time that all the data have been considered together. The primary data are 18,000 km of hardcopy migrated seismic reflection profiles of various vintages, and drilling records from over 400 wells—many with comprehensive suites of logs (Figure 8). Supplemental data include 1,000 km of seismic refraction, remote sensing and topographic imagery, gravity maps, and 1:200,000-scale geologic maps.

Concerning the interpretation of the seismic reflection profiles, the Cenozoic section is fairly unreflective with the exception of some Miocene evaporite layers (the Lower Fars and Dibbane formations). The carbonate Mesozoic section contains prominent seismic reflectors, and regional unconformities are easily distinguished. The clastic Paleozoic section is poorly reflective with the exception of several abrupt facies changes in Cambrian and Ordovician strata that form regionally observed reflectors. Paleozoic reflectors include the Burj limestone between the clastic Zabuk and Sosink formations, and the Swab shale between the Khannaser and Affendi sandstones (Figure 9). Data quality decreases markedly in areas of complex structure, most notably in the deeper areas of the Euphrates Graben and most of the SW Palmyrides. Recordings are also very poor in areas of Cretaceous limestone on the

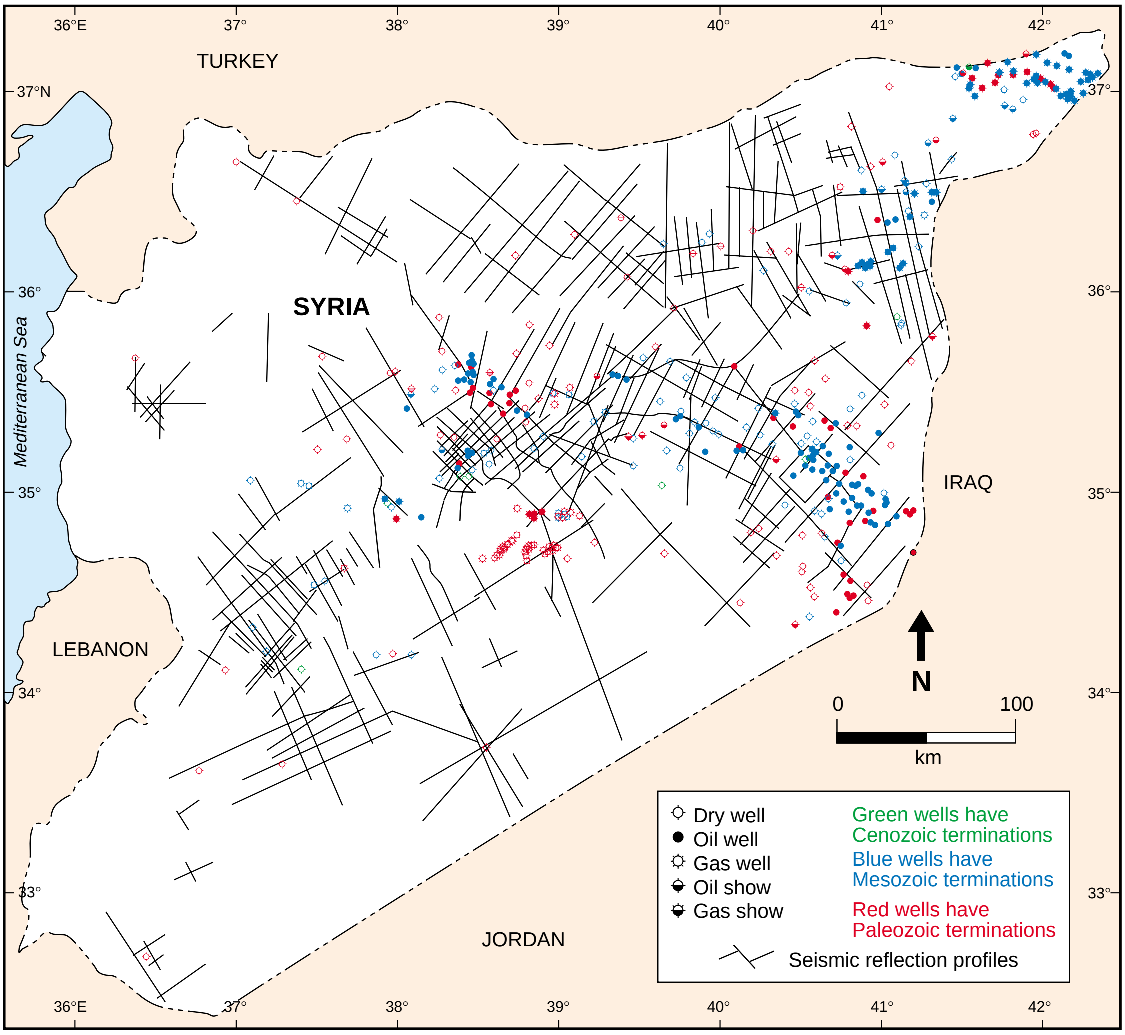


Figure 8: Locations of seismic reflection surveys and exploration and development wells. Well colors indicate depth of penetration; symbols show best available knowledge of the status of wells summarized from various literature sources.

Bilas Block, and basaltic outcrops (Wadi Sirhan traps) in southwestern Syria. Because the metamorphic basement does not form a clear event on reflection records, high-quality, multifold refraction data have been used to determine the depth to basement throughout Syria (Seber et al., 1993; Brew et al., 1997). Well-to-seismic ties are based on synthetic seismograms and associated time-depth curves.

The locations of our data, including all digitally held data, are stored within a Geographical Information System (GIS) for easy retrieval and analysis. Many data interpretations have been conducted within the GIS, thus harnessing the power of multiple-dataset visualization, manipulation, and combination (for more details see Brew et al., 2000). As the limitations of a printed journal do not allow a full appreciation of this digital approach, we have provided downloadable versions of many of our results and interpretations via the Internet (http://atlas.geo.cornell.edu/syria/welcome.html).

Lithostratigraphic Evolution

Recent contributions to the understanding of Syrian stratigraphy and paleogeographic evolution are relatively numerous (e.g., Ponikarov, 1966; Al-Maleh, 1976, 1982; Mouty and Al-Maleh, 1983, 1988, 1992, 1994; Sawaf et al., 1993; Mouty, 1998). These workers have concentrated on the extremely well-exposed Mesozoic carbonate section in the Palmyride fold and thrust belt, the Syrian Coastal Ranges, and the Kurd Dagh Mountains (Figure 2). Most recently, Sharland et al. (2001) have provided the first sequence stratigraphic synthesis of Arabian Plate stratigraphy.

Using extensive drilling records, surface observations, and preexisting studies, we present a new generalized lithostratigraphic chart showing the variations of Syrian strata in time and space (Figure 9). The dating of the drilling records was accomplished using the biostratigraphic techniques of the Syrian Petroleum Company. Clearly illustrated in Figure 9 is the shift from predominantly clastic Paleozoic deposition to Mesozoic and Cenozoic carbonates. Furthermore, numerous widespread unconformities showing long-lived hiatuses and erosion occur throughout the section, particularly during the Devonian and Late Jurassic. Many of the unconformities that we recognize in Syria are penecontemporaneous with the boundaries of Arabian Plate (AP) tectonstratigraphic megasequences of Sharland et al. (2001), denoted AP 1 to 11. These correlations are noted in the text and on Figure 9. Throughout this work we have used the timescale of Gradstein and Ogg (1996), consistent with Sharland et al. (2001).

Figure 10 is a series of isopach maps of the four major Mesozoic and Cenozoic sedimentary packages, as derived from well and seismic data. The long-lived Rutbah-Rawda Uplift and Aleppo Plateau (Figure 2) show the least complete stratigraphic sections whereas the section is most complete in the prominent Palmyride/Bishri/Sinjar depocenter. For much of the early Mesozoic, the Palmyride deposition was linked to the Sinjar area (Figures 10a and 10b), whereas for the Late Cretaceous, Sinjar strata show much closer affinity to rocks of similar age in the Euphrates Graben. This reflects the shift in subsidence from the Palmyride/Sinjar Trough to the Late Cretaceous fault-bounded extension in eastern Syria (Figure 10c). Furthermore, note the limited Jurassic/Lower Cretaceous section caused by widespread erosion and non-deposition related to regional Late Jurassic/Early Cretaceous uplift. Preserved Cenozoic patterns are dominated by subsidence along the Euphrates Fault System (Figure 10d).

The various formation names used in Syria are often site-specific (Figure 9), leading to a cluttered and confusing nomenclature. Furthermore, surface and subsurface geologists have historically used different nomenclatures, so compounding the already difficult task of correlating subsurface and surface formations. Paleozoic formations in particular are notoriously difficult to distinguish because of scattered drilling penetrations that compound the often poor differentiation in drill logs, thus rendering detailed chronology impossible (e.g. Ravn et al., 1994). In rocks of Mesozoic age, confusion involving the Kurrachine through Serjelu formations is well-known as they have distinctly different ages in Syria compared to the similarly named formations in Iraq—Middle Triassic to Upper Triassic in Syria, versus Upper Triassic to Middle Jurassic in Iraq (see Sharland et al., 2001). In our discussion of Triassic and Jurassic strata we have used traditional formation names (as maintained by the Syrian Petroleum Company and widely used in the literature) and their modern (e.g. Mulussa Group) equivalents. The detailed correlation of Syrian formations, and integration into the regional scheme of Sharland et al. (2001) is of pressing importance.

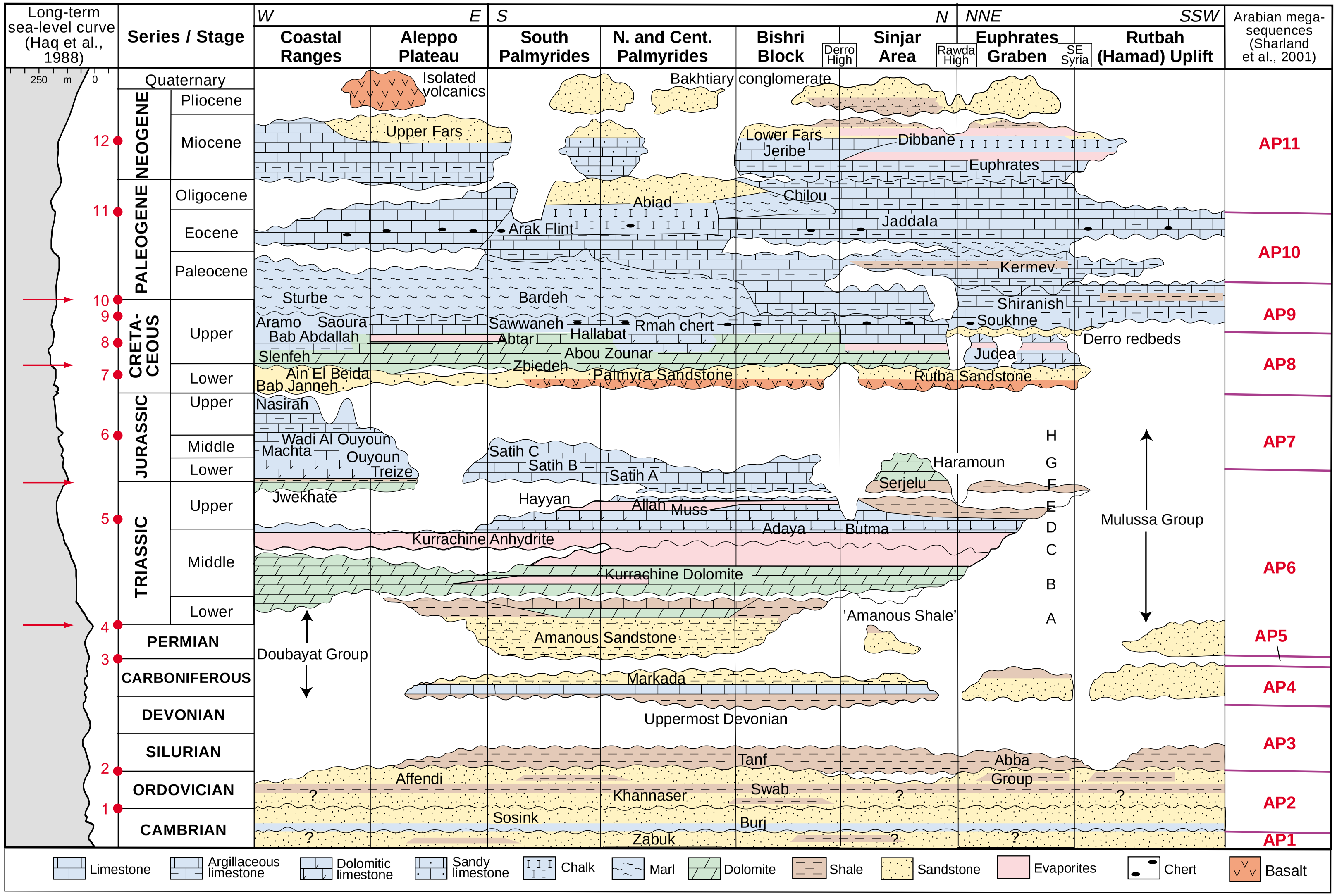


Figure 9: Generalized lithostratigraphy of Syria based on surface observations and drilling records. Time intervals not to scale; relative dates of Arabian Plate (AP) tectonostratigrahic megasequence boundaries (Sharland et al., 2001) shown for reference. Red arrows indicate four horizons mapped in Figure 12; red dots and numbers correspond to time points on Figure 16. Note alternative formation names in lower Mesozoic of Euphrates Basin (Mulussa A, B, C, etc.).

The main trends of Phanerozoic thickness changes in Syria (Figure 11) include a southward and eastward thickening of early Paleozoic strata (illustrated by the East Ratka-101 well), on the Gondwana passive margin. In the late Paleozoic and Mesozoic, deposition shifted to the west (Abou Zounar section) as the Levantine passive margin developed (Best et al., 1993). From the late Paleozoic onward, the influence of the long-lived structural highs of the Rutbah-Rawda Uplift (Tanf-1 well) and Aleppo Plateau (Khanasser-1 well) is apparent. Late Paleozoic and Mesozoic strata are concentrated in the Palmyride / Sinjar Trough, with significant along-strike variation apparent (Bishri-1 and Derro-2 wells). Rapid thickness changes in eastern Syria are associated with Late Cretaceous basin formation (Ishara-101 well, Euphrates Graben; Tichreen-301 well, Sinjar Graben), and the influence of Neogene Mesopotamian Foredeep formation (Swedieh-110 well). Finally, evidence of the uplift and erosion of the Cenozoic section is seen in the Palmyrides (Balaas-1 well and Abou Zounar section) and Sinjar Uplift (Tichreen-301 well).

Subsurface Structural Maps

We present new subsurface structural maps of four horizons chosen for their geophysical prominence and tectonic significance (Figures 12a to 12d; stratigraphic positions shown in Figure 9). Each map shows the present depth to the top of the subject horizon, together with the overlying subcropping formation, and the current structure.

Areas of highest data density in Syria are invariably those where hydrocarbon production is highest, or where the structure is most complex. Accordingly, these maps show most structure on the Euphrates Fault System, parts of the Palmyrides, and in northeastern Syria. However, as data quality and density decrease with depth, so does the accuracy of these maps. For example, 460 wells penetrate the top Cretaceous horizon whereas only 190 reach as deep as the Paleozoic (Figure 8). The degree of reliability in the subsurface mapping of the lower Mesozoic and Paleozoic of the Palmyride region is the lowest, as seismic data are generally not interpretable and well penetrations are few.

In eastern Syria in particularly, the structural mapping was at a much larger scale (typically 1:500,000) than presented in this paper. As a result, there are countless small structures beyond the presentation resolution; conversely, in areas of very low data density, some large faults undoubtedly remain unmapped. The chosen scale of presentation is a compromise.

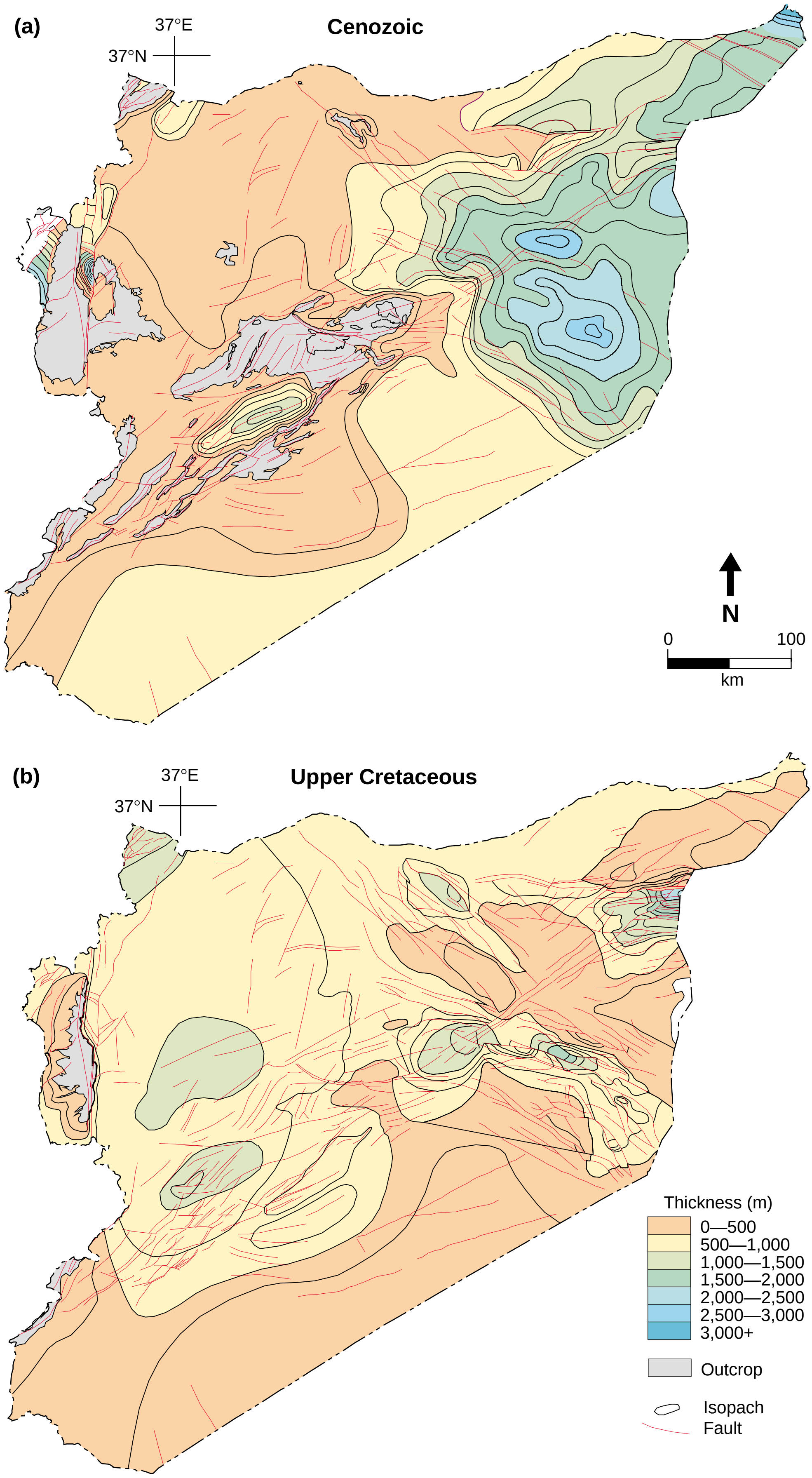
The maps are not structurally restored. They show present deformation rather than the structure and depths at the time of deposition of the target horizon. This is why, for example, the Top Triassic horizon demonstrates reverse faulting in the SW Palmyrides although at the time of deposition these were normal faults. The symbols on the faults are designed to show the approximate past history of fault movement. In addition, present-day depths are shown not those during deposition. For example, the top Paleozoic in the Palmyrides is shown as predominantly uplifted (Figure 12d), whereas it was a depositional topographic low.

Top Cretaceous

The Top Cretaceous horizon (Figure 12a) illustrates well the effects of Syrian Cenozoic compressional tectonics. Note the strongly inverted Palmyride Trough (especially the Bilas Block), and the Abd el Aziz-Sinjar Uplift. The large sag above the Euphrates Graben is a result of the Paleogene thermal subsidence. Recent basin formation in western Syria is also illustrated. In general, faulting in eastern Syria halted before the end of the Cretaceous. Hence, unless there has been Cenozoic reactivation and fault-propagation of these features, the faulting is not observed at the Top Cretaceous level. The well-developed Al-Daww Basin in the central Palmyrides affected all stratigraphic levels.

Top Lower Cretaceous

The Lower Cretaceous sandstone is a good seismic reflector and forms many hydrocarbon reservoirs in Syria (Figure 12b). Hence it is of particular economic interest. As shown by the subcrop distribution, this sandstone was deposited across most of Syria except on the exposed Rutbah-Rawda Uplift from


(a)
37°E
37°N
Cenozoic
N
0
100
km
(b)
37°E
37°N
Upper Cretaceous
Thickness (m)
0—500
500—1,000
1,000—1,500
1,500—2,000
2,000—2,500
2,500—3,000
3,000+
Outcrop
Isopach
Fault

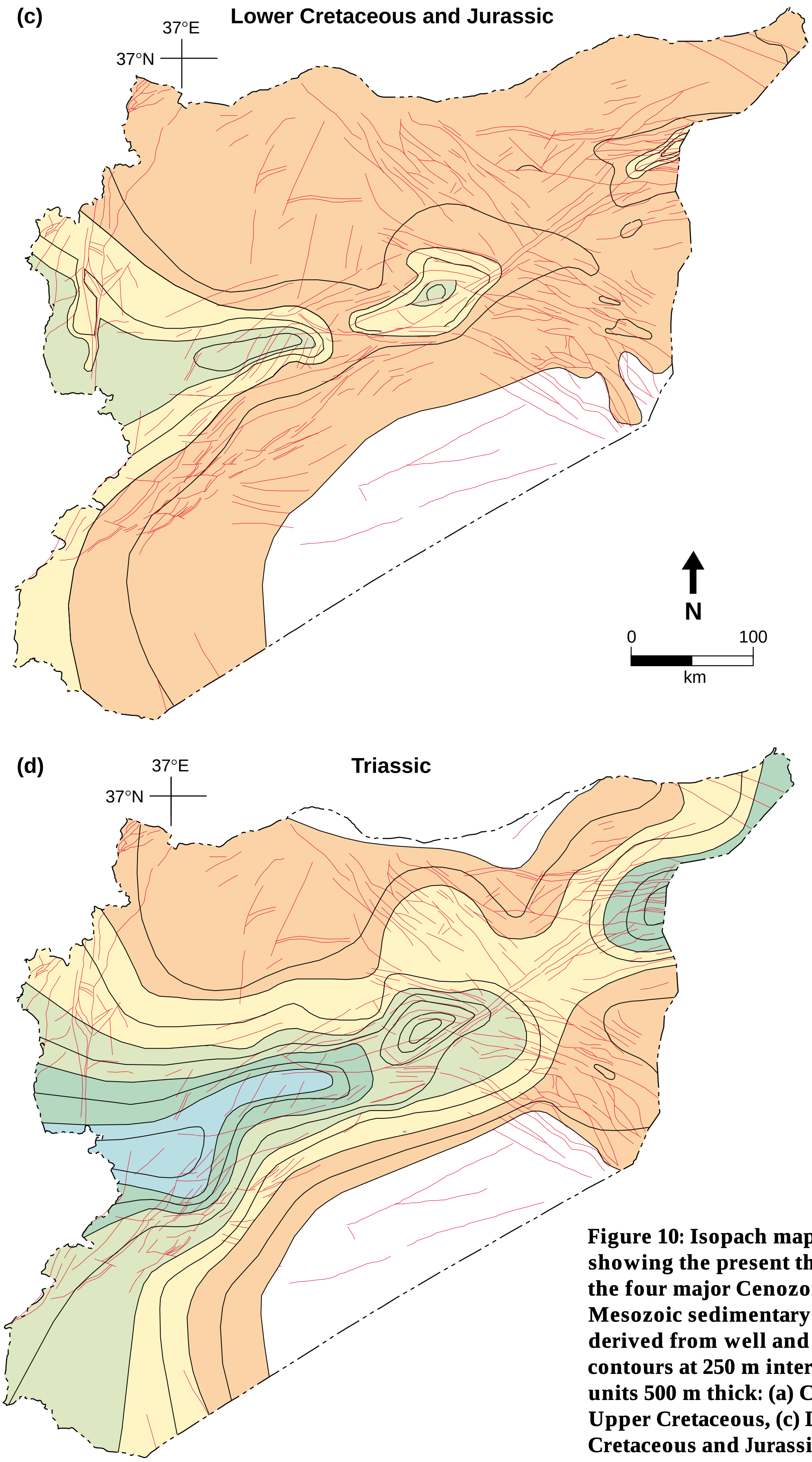


Figure 10: Isopach maps of Syria showing the present thickness of the four major Cenozoic and Mesozoic sedimentary packages, as derived from well and seismic data; contours at 250 m intervals; colored units 500 m thick: (a) Cenozoic, (b) Upper Cretaceous, (c) Lower Cretaceous and Jurassic, (d) Triassic.

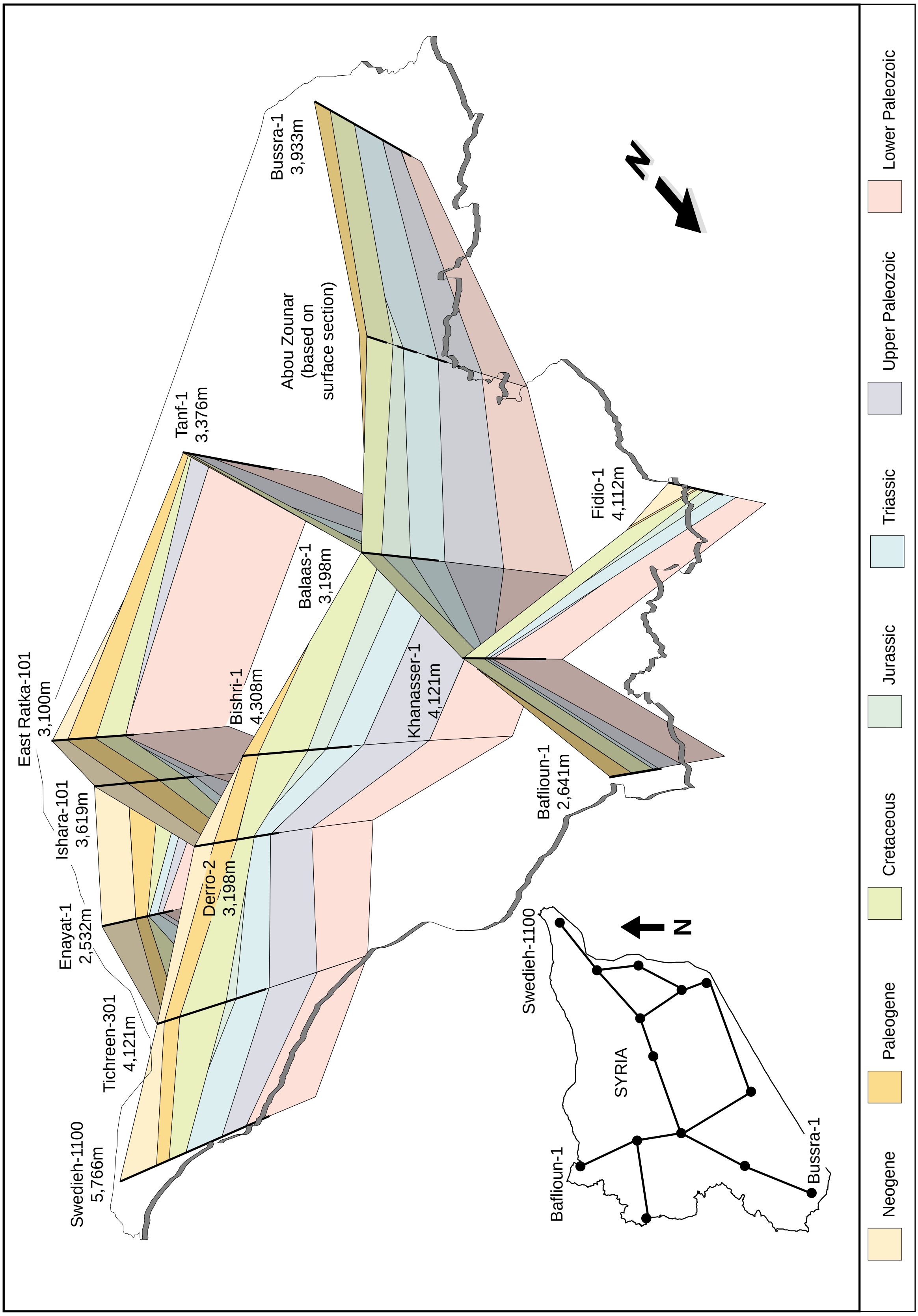


Figure 11: 3-D fence diagram generalizing present sedimentary thickness variations throughout Syria. Note that the diagram is viewed from the NW.

which these sands were largely derived (de Ruiter et al., 1994). Later, they were eroded from exposed parts of eastern Syria.

The map shows the full extent of the Euphrates Fault System and Abd el Aziz-Sinjar deformation. Note the distribution of normal faulting in the Euphrates Graben with no major rift-bounding faults. In northeastern Syria, the superposition of the three prominent fault directions is illustrated. This map and those on underlying horizons (Figures 12c and 12d), generally show very similar structures. This is because much of the structure in Syria developed on deeply penetrating, high-angle faults. The net sense of offset of any particular horizon changes down section and this is observed on many of the mapped faults. However, the locations of the faults remain essentially fixed at this scale of presentation. Although some faults only cut the lower portion of the sedimentary column, they are often either too small or too poorly imaged to be mapped. The biggest difference between Figures 12a to 12d is the depth to top of the chosen horizon. Obviously, this is a function of the thickness of the strata above it. As we have seen (Figure 11), this can change considerably throughout Syria.

Top Triassic

The Triassic subcrop distribution (Figure 12c) shows the extensive Mulussa F deposition (uppermost Triassic, Serjelu Formation) that covered much of the country. It marks the beginning of a regional transgression that continued through the Early Jurassic. Note that some of the Formation was removed by Late Jurassic / Early Cretaceous erosion especially in eastern Syria; thus the original deposition was even more extensive. The underlying Mulussa Group shows progressively limited extent up-section, again affected by widespread Late Jurassic / Neocomian erosion after regional deposition (Sharland et al., 2001).

Top Paleozoic

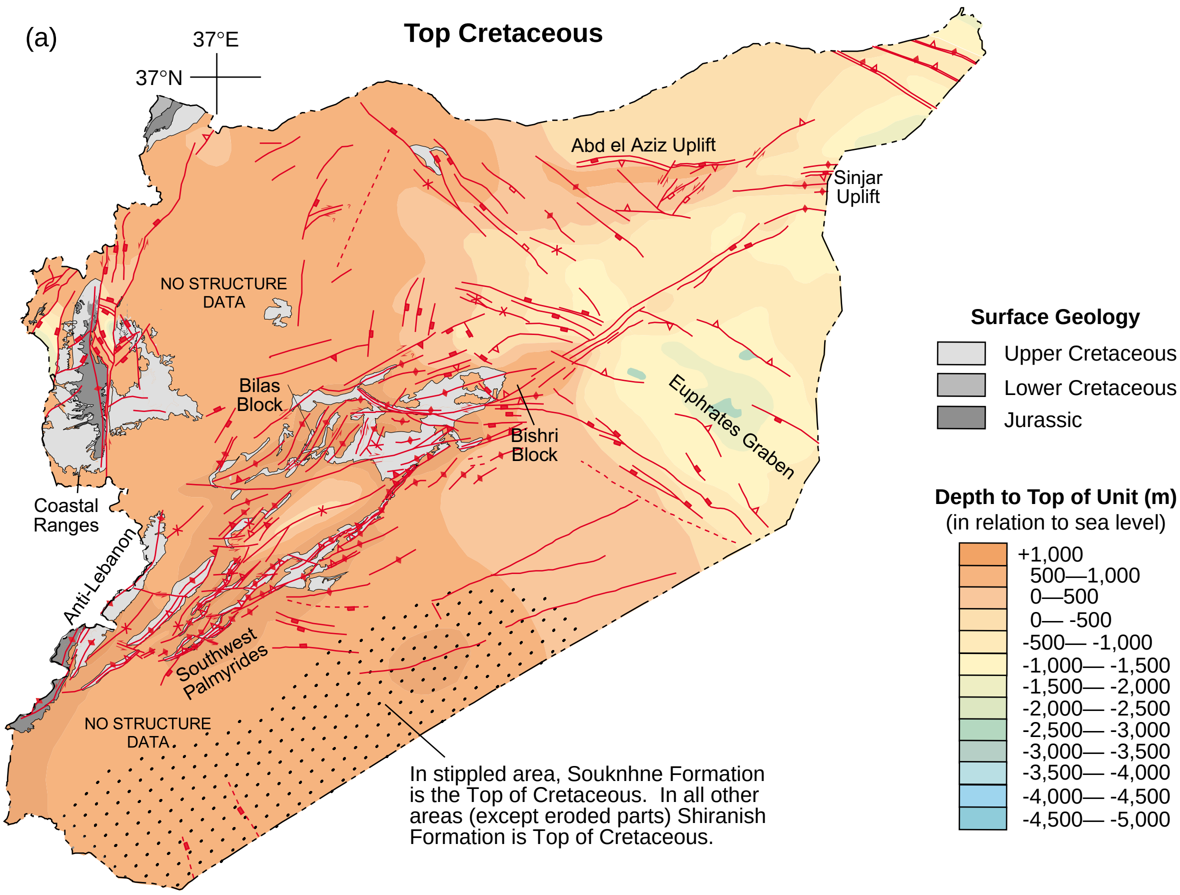
Figure 12d has the poorest accuracy of the four maps presented due to a severe decrease in the quality of seismic reflection data from Paleozoic depths, and fewer well penetrations. As with the overlying horizons, the greatest depths are found in the Sinjar Trough and the Euphrates Graben, and in isolated basins of western Syria. Note the broader downwarping at this level in the Sinjar area that indicates the broad extent of the Triassic Sinjar Trough.

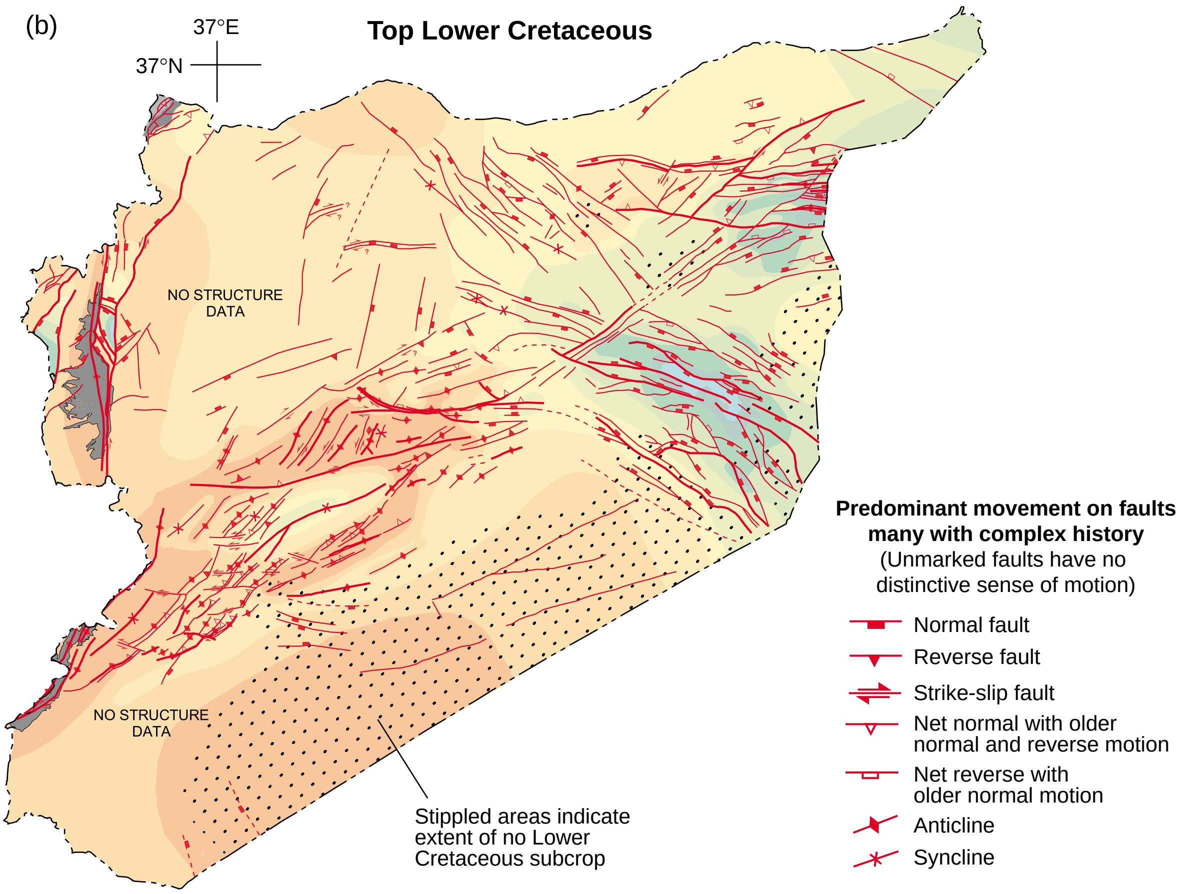
The subcrop pattern is dominated by the widespread Permian Amanous Formation. The map also shows the continuation of the Permian Palmyride Trough into the Sinjar area. Note that in the inverted areas of the Palmyrides and Sinjar uplifts, reverse faults are still shown at this level based on well and seismic data showing uplift across these structures. However, associated fault-propagation folds are greatly subdued or absent (Chaimov et al., 1993). Furthermore, in the southwest of the Palmyride fold and thrust belt, the Top Paleozoic is below the local Triassic-age detachment, and therefore is not significantly faulted or folded. However, in the Bilas and Bishri blocks, the thick-skinned deformation has affected all structural levels. Again, the quality of the mapping is relatively poor for these structures.

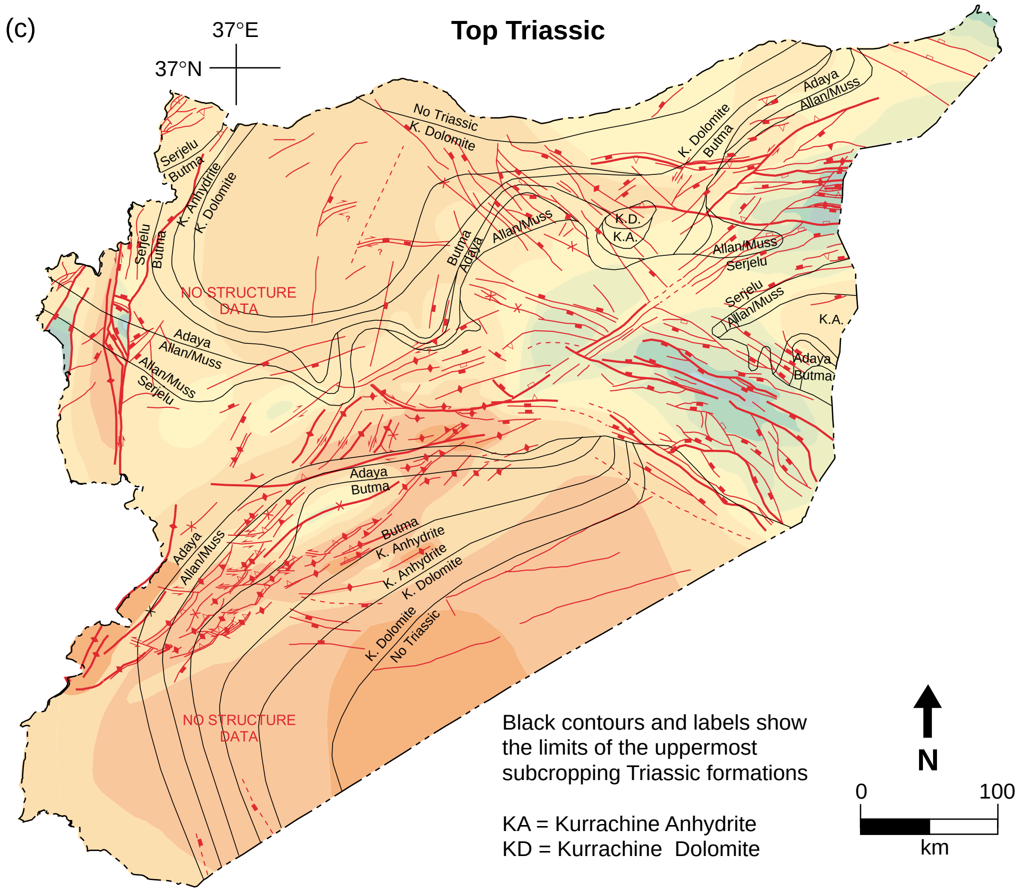
Deeper Crustal Structure

The crystalline Precambrian basement in Syria is generally deep (>6 km) and has not been penetrated by drilling. Furthermore, the basement does not form a good seismic reflector. Hence, we have mapped the basement (Figure 13) using seismic refraction data (Seber et al., 1993; Brew et al., 1997). The depth to the Moho beneath Syria has been estimated from receiver function analysis (E. Sandvol, personal communication, 2000). The limits of Moho depths shown on Figure 13 have been calculated from average crustal velocities in the range of 6.2 to 6.8 km / sec. Using the Bouguer gravity anomaly field for Syria (BEICIP, 1975), plus the additional information for basement and Moho depths, we developed new gravity models along two profiles across the Palmyrides (Figure 14).

The first profile crosses the Aleppo Plateau, SW Palmyrides, and the Rutbah Uplift, and shows a clearly dichotomous gravity anomaly on either side of the Palmyrides (Figure 14a). External controls on Moho and basement depths projected along strike into the section, are shown as boxed annotations.


(a)
37°E
37°N
Top Cretaceous
Abd el Aziz Uplift
Sinjar
Uplift
NO STRUCTURE
DATA
Bilas
Block
Bishri
Block
Euphrates Graben
Coastal
Ranges
Anti-Lebanon
Southwest
Palmyrides
NO STRUCTURE
DATA
In stippled area, Souknhne Formation is the Top of Cretaceous. In all other areas (except eroded parts) Shiranish Formation is Top of Cretaceous.
Surface Geology
Upper Cretaceous
Lower Cretaceous
Jurassic
Depth to Top of Unit (m)
(in relation to sea level)
+1,000
500—1,000
0—500
0— -500
-500— -1,000
-1,000— -1,500
-1,500— -2,000
-2,000— -2,500
-2,500— -3,000
-3,000— -3,500
-3,500— -4,000
-4,000— -4,500
-4,500— -5,000


(b)
37°E
37°N
Top Lower Cretaceous
NO STRUCTURE
DATA
NO STRUCTURE
DATA
Stippled areas indicate extent of no Lower Cretaceous subcrop
Predominant movement on faults many with complex history
(Unmarked faults have no distinctive sense of motion)
Normal fault
Reverse fault
Strike-slip fault
Net normal with older normal and reverse motion
Net reverse with older normal motion
Anticline
Syncline



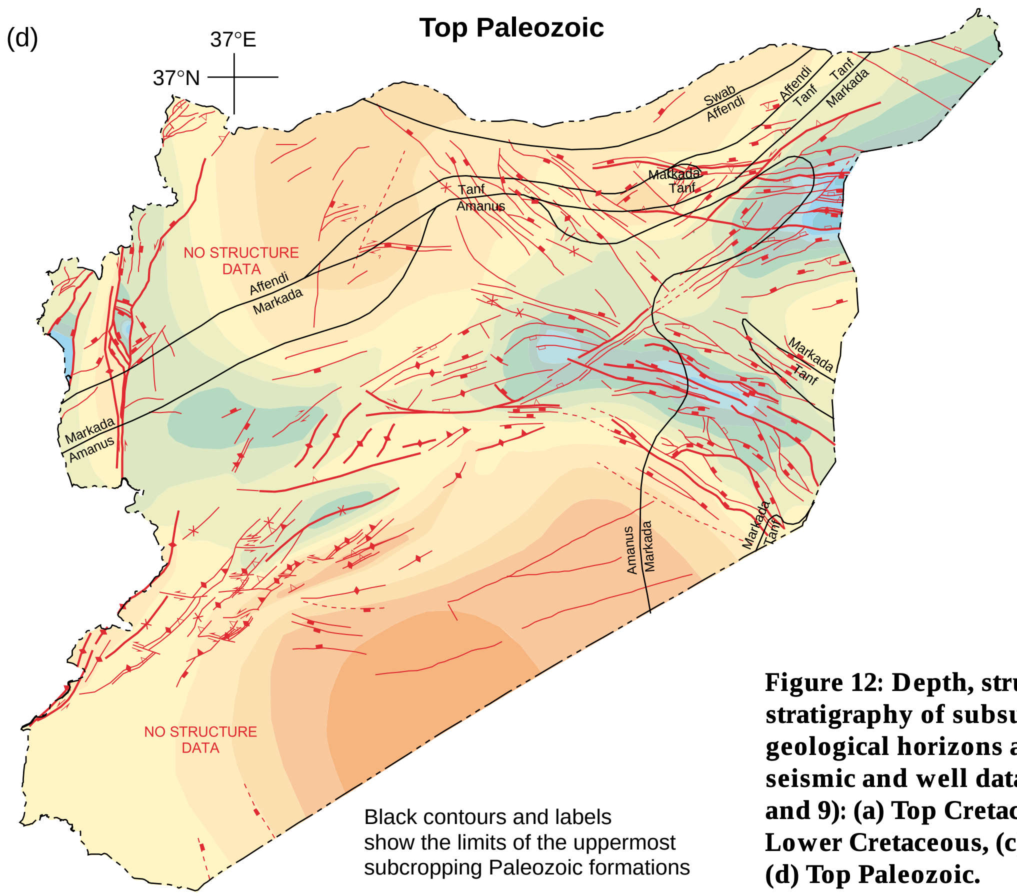


Figure 12: Depth, structure, and stratigraphy of subsurface geological horizons as derived from seismic and well data (see Figures 8 and 9): (a) Top Cretaceous, (b) Top Lower Cretaceous, (c) Top Triassic, (d) Top Paleozoic.

Using these constraints, we constructed a suitable density model beneath the profile with less than about 3 mgal difference between 'observed' and 'calculated' gravity responses. Firstly, we investigated crustal-scale effects without concern for the 'second-order' anomalies. The result (black line in Figure 14a) shows a large difference in crustal thickness and density on either side of the Palmyrides, with a discontinuity around the present surface position of the Jhar Fault. A small 'crustal root', of 2 to 3 km, is required beneath the SW Palmyrides to satisfy the receiver-function Moho depth. Speculative modeling of the second-order anomalies along this transect (dashed pink model and anomaly in Figure 14a) shows that arbitrary, high-density intrusions beneath the Palmyrides can be used to match the observed anomalies very closely. These intrusions could perhaps be an extension of the Rmah trend clearly imaged by the gravity data (Figure 13), and described by Best et al. (1990).

The second gravity profile also crosses the Aleppo and Rutbah highs, but traverses the Bilas Block of the Palmyrides (Figure 14b). Large density and thickness differences on either side of an interface at or near the Jhar Fault are again required. There is no requirement for a well-developed crustal root, but a small flexing of the southern block on the southern margin of the Palmyrides improves the fit of the model.

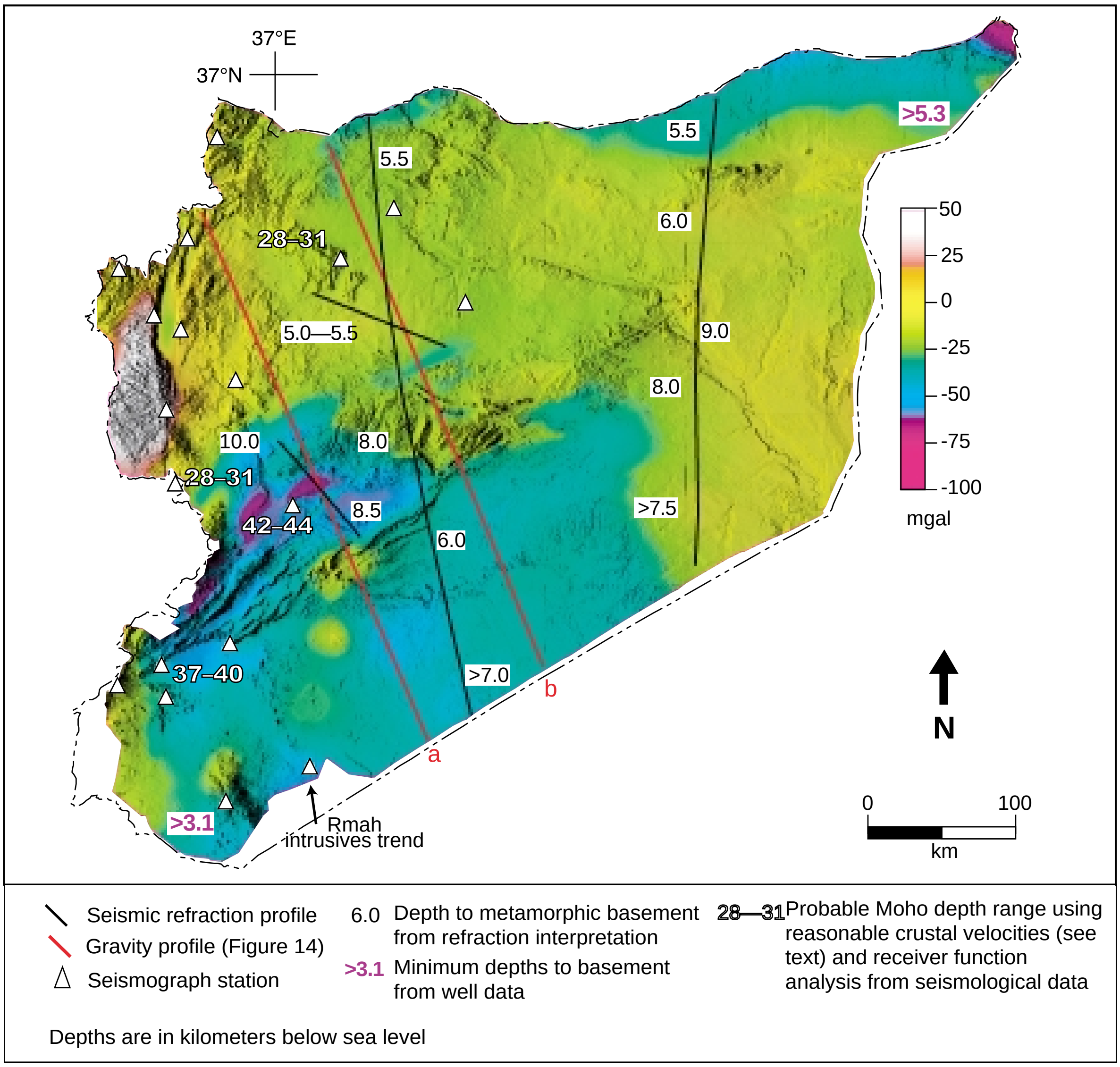


Figure 13: Bouguer anomaly map of Syria (BEICP, 1975) together with topographic imagery. Note (1) abrupt along-strike variation in gravity anomalies in the Palmyrides coincident with topographic change, and (2) contrast between Bouguer anomalies north and south of the Palmyrides.

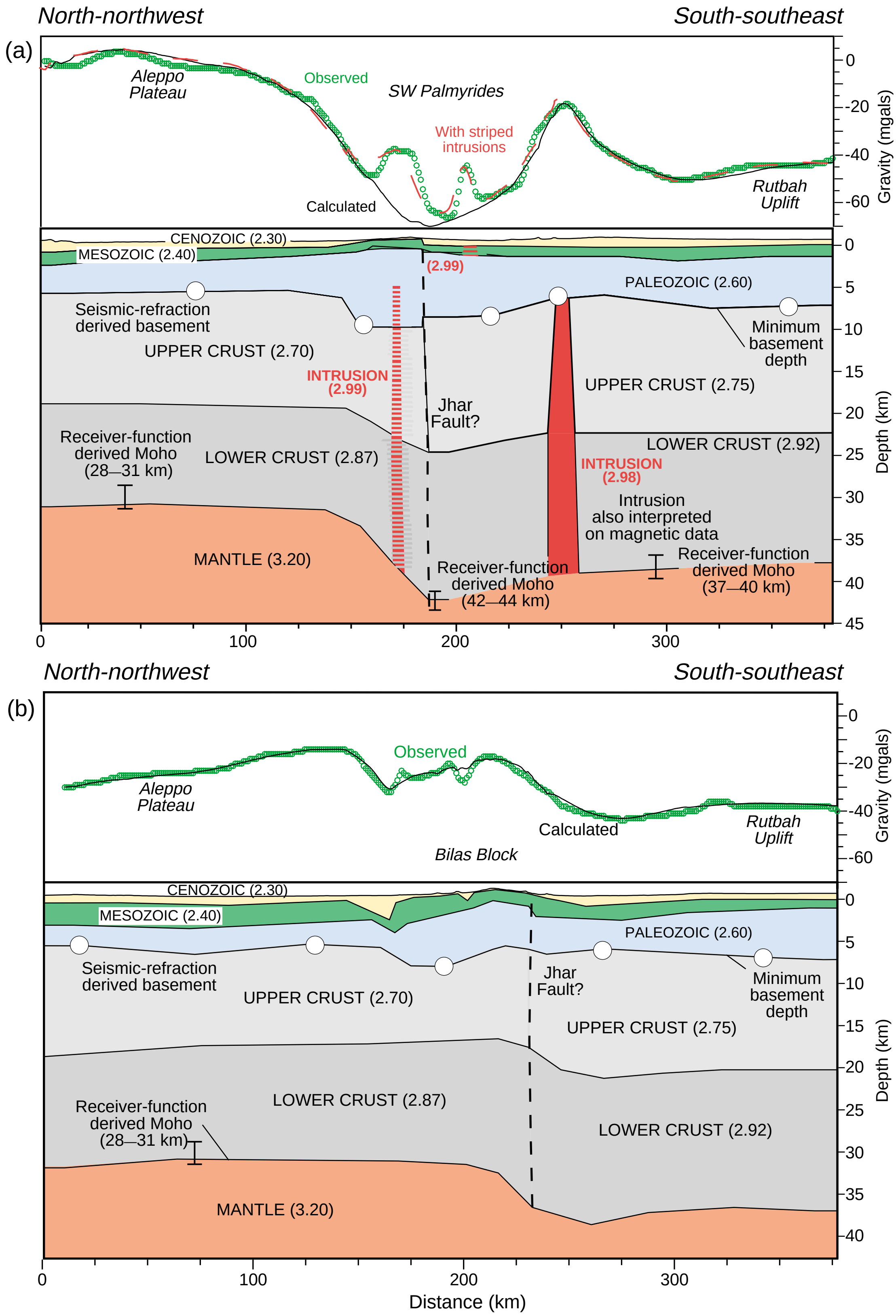


Figure 14: Gravity models on profiles through central Syria (see Figure 13 for locations). Densities in g/cm^3 in parentheses; boxed comments are constraints other than through gravity modeling; white dots show locations of seismic refraction constraints. (a) Aleppo Plateau, SW Palmyrides, and Rutbah Uplift; anomaly shown with and without two otherwise unconstrained intrusive bodies (striped) that account for second-order gravity anomalies. (b) Bilas Block: note that model does not require a significant crustal root beneath the Block.

These results support the hypothesis that Syria, like the rest of the Arabian Plate, formed through a Proterozoic amalgamation of microplates and island arcs—the Pan-African system (Stoeser and Camp, 1985). This left a series of suture / shear zones underlying the continent that have acted as zones of weakness throughout the Phanerozoic. The difference in basement depth, and crustal thickness and density on either side of the Palmyrides could indicate that northern and southern Syria are different crustal blocks, sutured along the Palmyride trend. Furthermore, the Jhar Fault, one of the major structural features of the Palmyride area, could be marking the position of the suture as first suggested by Best et al. (1990). Assuming this scenario, crust of 'Rutbah-Rawda Uplift' affinity underlies the predominantly thin-skinned deformation of the SW Palmyrides, whereas 'Aleppo Plateau' crust underlies the Bilas and Bishri blocks that exhibit predominantly thick-skinned tectonics. This might demonstrate that the Proterozoic architecture of the Arabian Plate is controlling the style, as well as the location, of Phanerozoic deformation. Walley (1998) argued that this suture zone is traceable westward through Lebanon. He correlated the deformation style of the northern and southern Lebanese Mountains with the NE Palmyrides and SW Palmyrides. Walley (1998) mapped many tens of kilometers of north-south separation between the present locations of his 'Lebanese' and 'Syrian' sutures, presumably suggesting this much translation on the northern part of the Dead Sea Fault System.

The presence of a crustal root appears to follow the leading edge of the southern block. The root observed in Figure 14a and the flexure that is observed in Figure 14b could both be interpreted as bending at the leading edge of the southern block. This could be a loading effect created by the Palmyrides themselves preferentially affecting the Rutbah Block, suggesting it may be flexurally 'weaker'. Alternatively, the increased root formation in the west could be explained by the proximity of profile 14a to the Anti-Lebanon, a crustal load much larger than the Palmyrides.

INTEGRATED TECTONIC MAP

The new tectonic map of Syria (Figure 15: as poster in pocket between p. 596–597) shows general tectonic elements, outcrop distribution, shaded relief imagery, and seismicity. The faults and folds shown in black were mapped at the surface by Dubertret (1955), Ponikarov (1966), and Searle (1994), or are from our surface observations and limited remote-sensing imagery interpretation. The subsurface structure, in red, is modified from the Top Lower Cretaceous structure map (Figure 12b). This level was chosen to represent the subsurface as most faulting cuts this horizon, yet it is still relatively close to the surface. As shown in Figure 12, the sense of motion on these faults may change according to the particular structural level that is considered.

Figure 15, although relatively accurate at the scale of presentation (1:1,000,000) is undoubtedly incomplete in some areas. The sense of motion on many of the mapped structures is also ambiguous. In particular, we have mapped many of the reverse faults that core the anticlines of the SW Palmyrides as being reactivated normal faults. Although this is true for many of the faults, some may be thrust faults detached in the Triassic. Strike-slip activity is also extremely difficult to map accurately in the subsurface and it is only noted where known with some certainty. Assuredly, many more faults have strike-slip components than are identified on this map. The map shows again how most deformation in Syria is focused within the four major structural zones of the Palmyrides, the Abd el Aziz-Sinjar area (NE Syria), the Euphrates Fault System, and the Dead Sea Fault System.

Earthquake locations are taken from the International Seismological Center's database (1964–94), and from the local Syrian seismograph network (1995–96). Also shown are Harvard CMT focal mechanisms (1977–96), supplemented by work at Cornell (Seber et al., 2000). These focal mechanisms are only loosely constrained because of the relatively small size of the events involved. Moreover, the apparent lack of events along the northern Dead Sea Fault System relative to the southern part of the fault system is a consequence of sparse station distribution in Syria. Nevertheless, there is an obvious concentration of events along the Dead Sea Fault System, some events within the other Syrian tectonic zones, and very few events in the stable areas of Syria. Also, note the clear alignment of many events across Syria on the line of the Palmyrides and farther northeast on the trend of the hypothetical suture / shear zone discussed above.

GEOLOGICAL EVOLUTION OF SYRIA

Our regional tectonic and geologic evolutionary model presents the interpreted evolution of Syria and Syrian tectonic zones in a regional and global context (Figure 16: as poster in pocket between p. 596–597). There are many paleoplate reconstructions for the evolution of the Tethys and eastern Mediterranean, and the issue is still under debate (e.g. Robertson and Dixon, 1984; Dercourt et al., 1986; Ricou, 1995; Stampfli et al., 2001). The reconstruction shown here (Figure 16) is generalized from Stampfli et al. (2001), and is an aid to discussion, rather than an endorsement of validity. Nevertheless, their model is broadly in agreement with our findings. In the discussions below, we refer to present-day polarities. For example, what we refer to as an early Paleozoic E-facing passive margin, was predominantly N-facing at that time (Figure 16, frame 1a), but was subsequently rotated approximately 90º. All the frames in Figure 16 are oriented with north roughly toward the top of the page.

Proterozoic (>545 Ma) to End Cambrian (495 Ma)

It has long been accepted that the southern Arabian Plate formed through Proterozoic accretion of island arcs and microplates against northeast Africa, most probably between about 950 Ma and 640 Ma (Beydoun, 1991) as part of the Pan-African orogeny. Suture zone relics from this accretion, and the Najd-style faults that formed when these sutures were reactivated are well exposed in the Arabian Shield (Stoeser and Camp, 1985). Based on geophysical evidence (see discussion above and Best et al., 1990; Seber et al., 1993; Brew et al., 1997) we suggest that the northern part of the Arabian Plate is a result of a similar concatenation although with a different orientation. Specifically, we find that the current Palmyride fold and thrust belt may overlie the approximate location of a Proterozoic suture / shear zone. Reactivation of this crustal weakness appears to have profoundly affected the tectonic evolution of Syria throughout the Phanerozoic, from the formation of the Palmyride / Sinjar Trough to the later Palmyride fold and thrust belt.

From about 620 Ma to 530 Ma, continental rifting and intracontinental extension followed the accretion, together with strike-slip movement on the Najd fault system, and Infracambrian and Early Cambrian synrift deposition (Husseini, 1989) (megasequence AP1 of Sharland et al., 2001). Owing to their great depth, no direct dating of the oldest sediments in Syria is available. However, from seismic refraction interpretation we infer Infracambrian to Lower Cambrian strata between 1 and more than 2.5 km thick across Syria (Seber et al., 1993; Brew et al., 1997). Significant thicknesses of Infracambrian sandstone and conglomerate are present in SE Turkey (Derik and Camlipinar formations) and in Jordan (Saramuj Formation). Husseini (1989) suggested that these synrift and postrift strata resulted from the 'Jordan Valley Rift' that formed between Sinai and Turkey during the Infracambrian (Figure 16).

The drilled Cambrian rocks of Syria are arkosic sandstones, probably derived from a granitic basement in the south, together with some siltstone and shale (Figure 16, frame 1a). The exception to the clastic Cambrian section is the Early to Middle Cambrian Burj limestone formation that is present throughout Syria (Figure 9), below the maximum flooding surface (MFS) Cm20 of Sharland et al. (2001). The regional extent of this monotonously carbonate formation on both sides of the 'Palmyrides suture' is more evidence for the cessation of cratonization and regional intracontinental extension of northern Arabia before the Middle Cambrian (about 515 Ma) as discussed above (Best et al., 1993).

An erosional unconformity at the top of the Cambrian (Figure 9), is just one of many unconformities that punctuate the Paleozoic section. This was a time of relatively shallow water over much of Arabia; consequently, relatively minor eustatic variations easily caused hiatuses and erosion.

Ordovician (495 Ma) to Early Silurian (428 Ma)

Ordovician strata were deposited across a wide epicontinental shelf that was especially well developed on the northern and eastern margins of the Arabian Plate. The Syrian Ordovician section increases in thickness from 1.6 km beneath the Aleppo Plateau to more than 3.5 km in the southeast beneath the Rutbah-Rawda Uplift (Figure 11), and in eastern Jordan. Wells in the west of Syria penetrated an almost wholly sandy Ordovician section, whereas those in the southeast intersected significant amounts of siltstone and shale (Figure 9; Figure 16, frame 1b). These facies and thickness trends in the Syrian Ordovician indicate open-marine conditions to the east, and also in Iraq and Turkey (Sharland et al., 2001). The source areas for the Ordovician, and other Paleozoic clastics, were the extensive Arabian and Indian Precambrian shields exposed to the south and west (Figure 16, frame 1a), and an ever-increasing amount of reworked sediments.

The top Ordovician unconformity is the base of megasequence AP3 of Sharland et al. (2001), who attribute the unconformity to hinterland uplift in western Saudi Arabia. The Rawda-Rutbah High (Figure 16, frame 2b) in the extreme east of Syria and the western part of Iraq was exposed during this Late Ordovician to Early Silurian regression. The Upper Ordovician Affendi Formation is missing in the extreme southeast of Syria, and thinned dramatically over the Rawda High (Best et al., 1993). Beydoun (1991) showed that this exposed / structurally high area extended from Turkey to Saudi Arabia during the Late Ordovician and Early Silurian, and probably had a tectonic origin.

Polar glaciation of much of Gondwana, including western Arabia, occurred in the Late Ordovician. Deglaciation in the Early Silurian, as Gondwana drifted towards the tropics, caused sea levels to rise sharply flooding much of Arabia and depositing what is now an extremely important regional hydrocarbon source rock (Beydoun, 1991). In Syria, these Early Silurian graptolitic shales (the Tanf Formation, Figure 9), were deposited during this transgression (Figure 16, frame 2b). Although now thickest within the Palmyride / Sinjar Trough (Best et al., 1993), they were probably originally 500 to 1,000 m thick across the entire region.

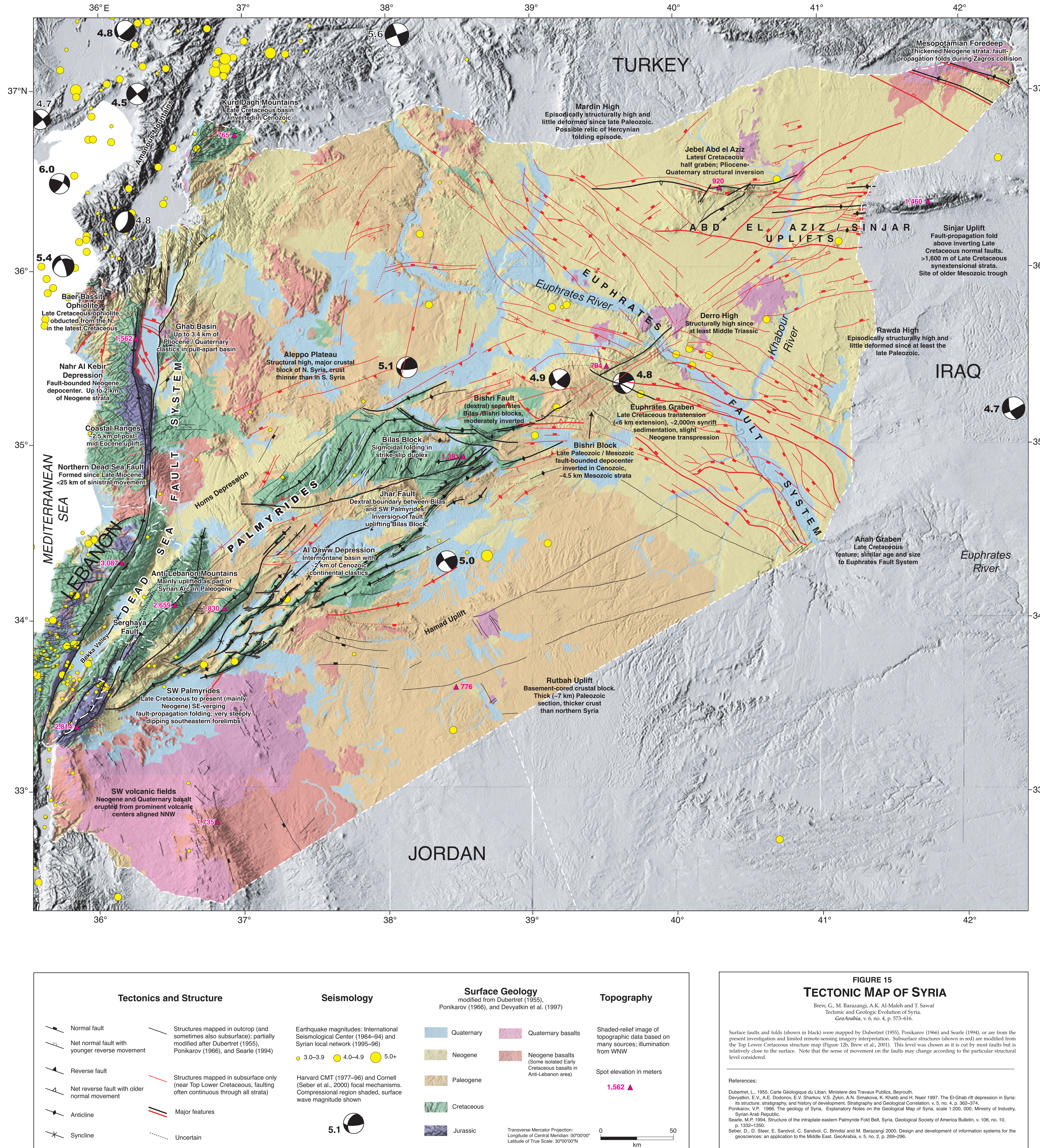
Late Silurian (428 Ma) to Devonian (354 Ma)

The Lower Silurian section in Syria is directly overlain by Carboniferous clastics, demonstrating an unconformity of major temporal and spatial extent. Strong tectonism and volcanism occurred contemporaneously at many localities in northern Gondwana. Some authors cite two events. The first—loosely referred to as ‘Caledonian’—is of Late Silurian age and the other is of Middle to Late Devonian / Early Carboniferous age, (Husseini, 1992), referred to as ‘Hercynian sensu lato’ by Sharland et al. (2001). The absence of preserved strata in Syria prevents such a distinction there. Suggestions of the cause of this tectonism include regional compression caused by the obduction of the Proto-Tethys on what is now Iran (Husseini, 1992); uplift on the flanks of the Paleo-Tethys rifting (Stampfli et al., 2001); or a more localized thermal uplifting event (Kohn et al., 1992) (Figure 16, frame 2a).

Whatever the tectonic cause, strata of Late Silurian and Devonian age are almost totally absent from Arabia, and the underlying Early Silurian shales are substantially eroded. The present subcrop pattern of Silurian strata in Syria shows an elongate depocenter roughly along the trend of the current Palmyrides (Best et al., 1993), and a thinned to absent Silurian succession to the north and south. This could be interpreted as evidence for an Early Silurian initiation of the major Palmyride / Sinjar Trough. However, based on a slight angular unconformity observed at the top of the Silurian (Best et al., 1993), we suggest that this subcrop pattern is a result of Late Silurian and Devonian preferential erosion on the Rutbah-Rawda and Aleppo structural highs southeast and northwest of the Palmyrides, respectively.

During both the Late Ordovician and Late Silurian / Devonian, the Rutbah and Rawda uplifts were apparently most prominently exposed east of the current structural and topographic high (compare Figure 2 with Figure 16, frame 2b). These highs were then centered near the present location of the Euphrates Graben. Previous publications (e.g. Litak et al., 1997) have examined the possibility that the Euphrates Fault System may have formed above a Proterozoic suture / shear zone similar to that proposed beneath the Palmyrides. However, given little evidence of subsidence or faulting along the Euphrates trend before Late Cretaceous time, this is now considered unlikely. The Rutbah and Rawda highs (Figure 2) were evidently connected through most of geologic time until Late Cretaceous dissection by the Euphrates Fault System. Other than a few episodes of minor subsidence after emergence in the Devonian, the basement-cored Rutbah-Rawda Uplift remained structurally high for the rest of the Phanerozoic. The difference in basement depth across the Euphrates Fault System (Brew et al., 1997) (Figure 13) could be explained by a continuation of the ‘Palmyride suture’ to the east, combined with the deep-seated Euphrates faulting.

TECTONIC MAP OF SYRIA



PRINTED AUGUST 2001

FIGURE 15

TECTONIC MAP OF SYRIA

Brew, G., M. Barazangi, A.K. Al-Maleh and T. Sawaf
Tectonic and Geologic Evolution of Syria.
GeoArabia, v. 6, no. 4, p. 573–616.

Surface faults and folds (shown in black) were mapped by Dubertret (1955), Ponikarov (1966) and Searle (1994), or are from the present investigation and limited remote-sensing imagery interpretation. Subsurface structures (shown in red) are modified from the Top Lower Cretaceous structure map (Figure 12b, Brew et al., 2001). This level was chosen as it is cut by most faults but is relatively close to the surface. Note that the sense of movement on the faults may change according to the particular structural level considered.

References:

Dubertret, L., 1955. Carte Géologique du Liban. Ministere des Travaux Publics, Beyrouth.

Devyatkin, E.V., A.E. Dodonov, E.V. Sharkov, V.S. Zykin, A.N. Simakova, K. Khatib and H. Nseir 1997. The El-Ghab rift depression in Syria: its structure, stratigraphy, and history of development. Stratigraphy and Geological Correlation, v. 5, no. 4, p. 362–374.

Ponikarov, V.P. 1966. The geology of Syria. Explanatory Notes on the Geological Map of Syria, scale 1:200, 000. Ministry of Industry, Syrian Arab Republic.

Searle, M.P. 1994. Structure of the intraplate eastern Palmyride Fold Belt, Syria. Geological Society of America Bulletin, v. 106, no. 10, p. 1332–1350.

Seber, D., D. Steer, E. Sandvol, C. Sandvol, C. Brindisi and M. Barazangi 2000. Design and development of information systems for the geosciences: an application to the Middle East. GeoArabia, v. 5, no. 2, p. 269–296.

Published by Gulf PetroLink,
P.O. Box 20393, Manama, Bahrain
e-mail: geoarabi@batelco.com.bh
http://www.gulfpetrolink.com

FIGURE 16

TECTONIC AND GEOLOGIC EVOLUTION OF SYRIA

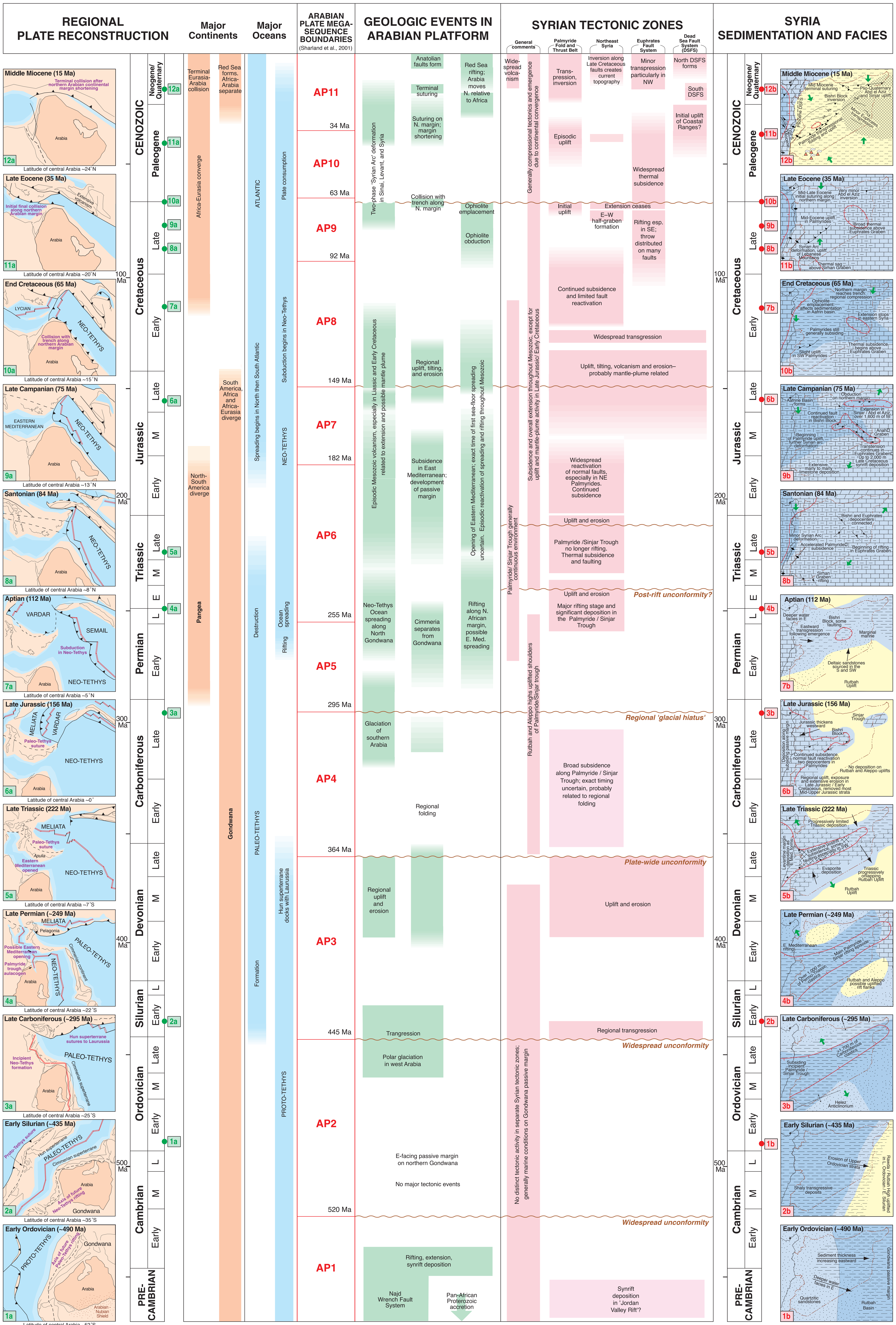
Brew, G., M. Barazangi, A.K. Al-Maleh and T. Sawaf
Tectonic and Geologic Evolution of Syria.
GeoArabia, v. 6, no. 4, 2001, p. 573-616.

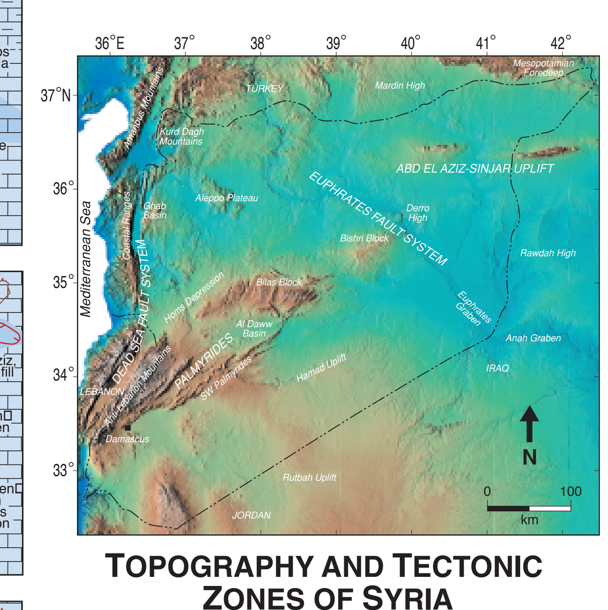
Syrian tectonic evolution as part of the northern Arabian Plate: plate reconstructions are shown in frames 'a' (left); timelines of significant regional and local tectonic events are central; and Syrian tectonic evolution and sedimentation are shown in frames 'b' (right). Plate reconstructions are simplified after Stampfli et al. (2001) and are not to scale relative to each other; present-day Arabia is highlighted. Gradational coloring of timelines indicates degree of certainty. Relative dates of Arabian Plate (AP) tectonostratigrahic megasequence boundaries (Sharland et al., 2001) have been added for reference. Tectonic/sedimentation frames show elements generalized and in the correct contemporaneous position.

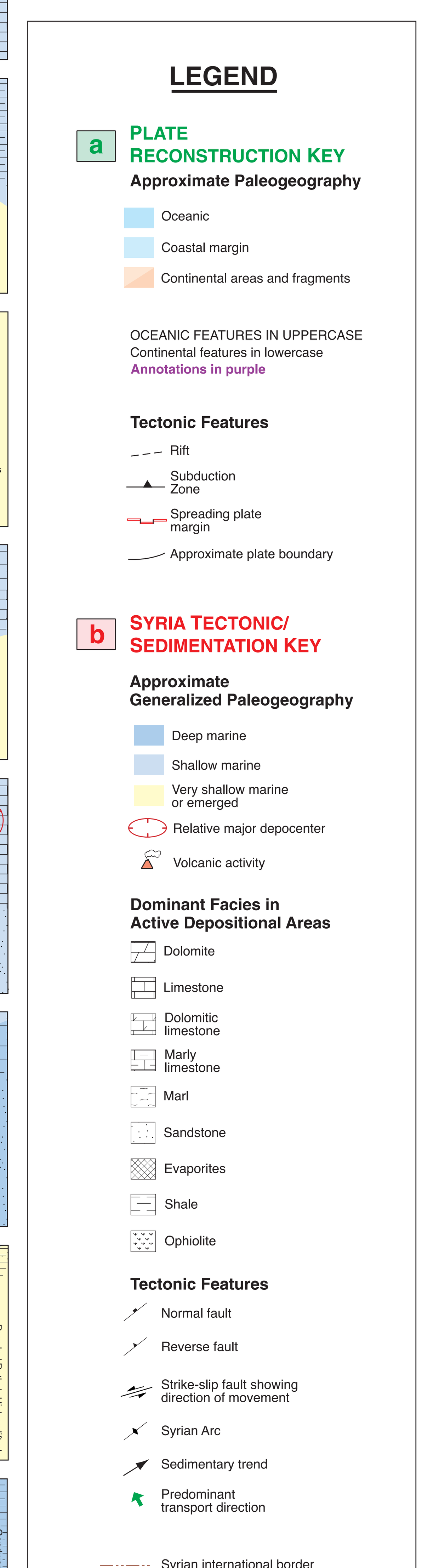
References:

Sharland, P.R., R. Archer, D.M. Casey, R.B. Davies, S.H. Hall, A.P. Heward, A.D. Horbury and M.D. Simmons 2001. Arabian Plate sequence stratigraphy. *GeoArabia* Special Publication 2. Gulf PetroLink, Bahrain, 371 p.

Stampfli, G.M., J. Mosar, P. Favre, A. Pillevuit and J.-C. Vannay 2001. Permian-Triassic evolution of the western Tethyan realm: the NeoTethys/east Mediterranean basin connection. In, W. Cavazza, A.H.F. Robertson and P. Ziegler (Eds.), PeriTethyan rift/wrench basins and passive margins. Memoires du Muséum National d'Historie Naturelle, Paris, PeriTethys Memoir 6.







Published by Gulf PetroLink
P.O. Box 20393,
Manama, BAHRAIN
e-mail: geoarabi@batelco.com.bh
http://www.gulfpetrolink.com

PRINTED AUGUST 2001

A few wells in central and eastern Syria have intersected latest Devonian rocks (Ravn et al., 1994), within which no major hiatus between the Devonian and Carboniferous was observed. This may indicate that incipient subsidence along the Palmyride / Sinjar Trough had begun in eastern Syria by the latest Devonian. However, several deep wells in the Palmyrides intersected Early Silurian strata directly below the Carboniferous, thus indicating that the Palmyride / Sinjar Trough had not undergone large-scale subsidence before the Carboniferous.

Carboniferous (354 Ma to 290 Ma)

In the Carboniferous, the Palmyride / Sinjar depositional trough was fully developed across central Syria, in strong contrast to the relatively uniform and parallel-bedded early Paleozoic deposition. In various forms, this trough continued to be the main depocenter in Syria until Late Cretaceous time, flanked to the northwest by the Aleppo Plateau and to the southeast by the Rutbah-Rawda Uplift. On many seismic lines, the Carboniferous can be seen onlapping the Silurian (Brew et al., 1999) and over 1,700 m of Carboniferous sand, sandy shale, and some minor carbonates, were deposited in the Palmyride / Sinjar Trough (Figure 16, frame 3b). We interpret this Carboniferous trough to be a broad crustal downwarping between anticlinoria identified to the north and south of Syria (Figure 16, frame 3b) (Gvirtzman and Weissbrod, 1984). This Devonian / Early Carboniferous folding could also have been responsible for the major Devonian hiatus observed in Arabia, as discussed above (Husseini, 1992), although as with much of the Paleozoic section, precise dating and correlation is problematic. Sharland et al. (2001) documented this latest Devonian / Carboniferous package as megasequence AP4 (Figure 16).

Alternatively, Stampfli et al. (2001) suggested that the Early Carboniferous was a time of continental rifting along the northern African margin (and consequently in the Palmyride Trough), possibly as a precursor to the formation of the Neo-Tethys. The cause could have been regional stress reorganization after the collision of the Hun superterrane and Laurussia (Figure 16, frame 3a). However, many previous models (e.g. Robertson and Dixon, 1984) envisage no such Carboniferous rifting along northern Gondwana. Hence, while poor seismic data beneath the Palmyrides prevent definitive detection of possible Paleozoic faults, we favor Carboniferous folding rather than initial rifting.

Interestingly, the Carboniferous (and Permian) trough is found along a trend parallel to, but a few tens of kilometers south of, the Mesozoic depocenter and the present Palmyrides. This suggests that the locus of deposition shifted during the formation of the Palmyride Trough, probably in response to differential uplift and subsidence of the bounding Aleppo Plateau and Rutbah-Rawda Uplift. Furthermore, the limit of the Paleozoic and Mesozoic Palmyride Trough is fairly sharply defined to the northwest, whereas it has a more gradual southeastern flank that may indicate a greater interaction of the Rutbah-Rawda Uplift with the Palmyride deformation (McBride et al., 1990).

Permian (290 Ma to 248 Ma)

The opening of the Neo-Tethys in the Permian (Figure 16, frame 4a) led to profound changes in regional tectonics that persisted until its final consumption in the Miocene. On the northern and eastern margin of Gondwana, oceanic spreading separated the Cimmerian superterrane (including present-day Iran) that proceeded to drift northeastward (Stampfli et al., 2001). Megasequence AP5 of Sharland et al. (2001) is cited as a synrift unit associated with this extension. Along the northern African margin, Permian and Early Mesozoic rifting was documented by Stampfli et al. (2001) as being the second phase of the extension that began in the Early Carboniferous. Other authors cite this event as the initiation of faulting (Robertson and Dixon, 1984).

Debate still surrounds the precise timing of tectonics in the eastern Mediterranean region. While consensus has generally been reached concerning the oceanic nature of the eastern Mediterranean crust (see Robertson et al., 1996), the exact start of spreading remains uncertain. Robertson et al. (1996) examined various Neo-Tethys models. They concluded that the most promising reconstruction was similar to that of Robertson and Dixon (1984), who advocated Permian-Triassic rifting, under conditions of northward Paleo-Tethys subduction that led to Triassic sea-floor spreading in the eastern Mediterranean.

The reconstructions that we show (Stampfli et al., 2001) are mostly similar to the model of Robertson and Dixon (1984). One of the main differences is the presence in the Stampfli model of oceanic, rather than continental, crust along north Gondwana at the end of the Permian. This set of models differs markedly from those advocating Early Cretaceous ocean formation in the eastern Mediterranean (e.g., Dercourt et al., 1986). The models of Robertson and Dixon (1984), Stampfli et al. (2001), and others, see the Early Cretaceous as a time of renewed tectonic activity in the eastern Mediterranean, rather than initiation of sea-floor spreading.

We therefore interpret the Late Permian development of the Palmyride Trough to be a consequence of extension along the northern African margin that led to sea-floor spreading in the eastern Mediterranean. In this scenario, the Palmyride rift could be an aulacogen (e.g., Ponikarov, 1966; Best et al., 1993), and we note that the Palmyride rift broadly fits the definition of an aulacogen. The plate reconstructions of Stampfli et al. (2001) favor this interpretation (Figure 16, frame 4a).

An enticing variation to this is the reconstruction by Walley (2001). He argues for two different Permian-Triassic extensional phases, one in the Late Permian to Early Triassic that opened the Palmyride rift, and another in the mid-Late Triassic that led to the opening of the eastern Mediterranean in a slightly different direction. Thus, this model allows for Late Permian rifting of the Palmyrides while not requiring Permian sea-floor spreading of the eastern Mediterranean. Furthermore, in this scenario the Palmyride / Sinjar Trough is not required to be an aulacogen. Additional work concerning the exact timing of faulting will help test this model further.

Synrift Permian-Triassic siliciclastic deposits are preserved only in the Palmyride / Sinjar Trough where they are more than 1,000 m thick. Our hypothesis of the Trough as a Late Permian aulacogen suggests that faulting may be responsible for most of the thickening in the trough, an observation supported by well and seismic data (Chaimov et al., 1992). Furthermore, stratigraphic relationships indicate that the Aleppo Plateau and Rutbah Uplift were emergent throughout the Permian, possibly as uplifted flanks to the rift (Stampfli et al., 2001). Cohen et al. (1990) found Permian-age normal faults in the Levant subparallel to the Palmyrides trend and an increasing sediment thickness westward. This is consistent with the hypothesis of an aulacogen extending from central Syria to the eastern Mediterranean. Beydoun and Habib (1995), also speculated (based on limited data), on the occurrence of a late Paleozoic / Mesozoic aulacogen extending through Lebanon. Unfortunately, poor seismic data limit our ability to better image structure at depth and hence obtain a complete picture of the style of deformation. We conclude that rifting—as opposed to downwarping and subsidence—controlled a significant part, if not most, of Permian-Triassic deposition.

The exception to the pattern of NE-rifting in Syria is the Derro High (Figure 2). This area was a structural high in the Early Triassic and possibly the Carboniferous, and represents the 'Beida Arch' of Kent and Hickman (1997) that connected the adjacent Rawda and Mardin highs (Figure 2). The work of Brew et al. (1997) suggested that the Derro High is a basement uplift, partly bounded by faults.

Triassic (248 Ma to 206 Ma)

From a regional perspective, Syria changed during the Permian-Triassic from being an E-facing to a W-facing passive margin (Best et al., 1993). This occurred as the Levantine passive margin formed in western Syria to a backdrop of the continued formation of the eastern Mediterranean. This margin development, linked to the continued postrift subsidence in the Palmyrides, is shown by the preservation of at least 1,600 m of Triassic-Jurassic sediments along the present coastline. The Triassic strata of Lebanon are very similar to those of Syria. For example, evaporites in the cores of compressional features in offshore Lebanon (Beydoun and Habib, 1995) have a similar mode of occurrence as salt in Syria (Chaimov et al., 1990; Searle, 1994). In northeastern Syria, thickening of the Triassic eastward indicates that the Sinjar region was linked to major basins in Iraq (Sadooni, 1995). These basins were developing along the northern passive margin of Gondwana, as well as being influenced by subsidence along the Palmyride / Sinjar Trough (Brew et al., 1999).

Synrift deposition in the Palmyride Trough appears to have continued into the Early Triassic. The 'Amanous Shale' formation (part of the Doubayat Group of Beydoun (1995), or the Mulussa A of most petroleum explorationists; Figure 9), is the uppermost synrift sequence. It consists of sandstone and shale, with increasing amounts of dolomite and dolomitic limestone upward through the succession in central Syria. The continuity from Amanous Sandstone (Permian) to Amanous Shale (Lower Triassic) sedimentation results in the lack of distinction between these two formations in many wells in central Syrian—a common problem in northern Arabia (Gvirtzman and Weissbrod, 1984).

By the end of the Early Triassic, rifting in the Palmyrides had ceased, whereas spreading in the eastern Mediterranean was still active. This is demonstrated by the 'Amanous Shale' formation that thickens westward in Syria to more than 250 m near the Levantine margin. Furthermore, stratigraphic thickening in the Levant suggests that rifting may have been longer-lived there than in the Palmyrides (Cohen et al., 1990). The cessation of Palmyride rifting could have been a consequence of the eastern Mediterranean spreading ridge moving away along a Levantine transform fault (Stampfli et al., 2001). With the removal of spreading, rifting in the Palmyrides stopped. Alternatively, the hypothesis of Walley (2001) considered the extension in the Palmyrides and eastern Mediterranean as being two separate events explainable by a change in the regional stress direction.

Cessation of Palmyride rifting is indicated by an extensive Early Triassic unconformity in most parts of Syria (Figure 9)—most likely a postrift unconformity, compounded by extremely low sea levels (Haq et al., 1988). The only conformable Permian through Middle Triassic sequence is in central Syria where shaly dolomites of the 'Amanous Shale' formation (Mulussa A) grade into the overlying Kurrachine Dolomite (Mulussa B). This area, with the deepest depocenter, remained submerged while all other areas were exposed and eroded.

Whereas the synrift Permian and earliest Triassic clastics are confined to the Palmyride / Sinjar Trough, the first postrift formation, the Middle Triassic Kurrachine Dolomite (Mulussa B), was spatially extensive over most of Syria (Figure 12c). It shows facies variations between dolomite and limestone, with the increased carbonate content and locally developed pelagic faunas indicating deeper waters. Thus, Middle Triassic formations overlie Permian, Carboniferous, and sometimes even Silurian strata (Figure 12d). This extensive Early to Middle Triassic sedimentation across almost all of Syria indicates that the Paleozoic stratigraphic arrangements we observe today are not a consequence of late Mesozoic or Cenozoic erosion. These postrift strata are predominantly restricted-water carbonates and evaporites (Figure 9). This is a consequence of a drift to lower latitudes (Figure 16, frame 5a), lack of sediment source areas after plate reorganization, and more restricted waters of the postrift environment. Progressively restricted seas in the Triassic are indicated by the general increase up-section of the evaporite content.

Deposition in the Triassic became progressively limited to the internal Palmyride / Sinjar Trough through time (Figures 9 and 12c). However, some transgressions (especially on the Aleppo Plateau, Figure 12c) suggests the influence of minor sea-level variations on a relatively flat platform (Sawaf et al., 2001). This pattern is modified by extensive Late Jurassic and Early Cretaceous non-deposition, and erosion on the Aleppo and Rutbah-Rawda highs that removed much of the lower Mesozoic section. In the Palmyrides, very thick Triassic formations that were locally preserved from erosion had previously been interpreted as evidence of Palmyride Triassic rifting (McBride et al., 1990).

The exception to progressively restricted Triassic sedimentation was in southeastern Syria where Triassic strata onlap approximately along the axis of the Euphrates Fault System. The units of the Mulussa Group progressively onlap the Rutbah-Rawda Uplift to the southeast. A full Triassic sequence is present near to the Bishri Block, but only the Mulussa F is found in the southeast. The Triassic strata onlap Carboniferous and, in the extreme southeast, Silurian strata (Figure 12d) on the persistent Rutbah-Rawda High.

Subsidence curves from within the Palmyride Trough show a decreasing subsidence rate typical of postrift subsidence (Sawaf et al., 2001; Stampfli et al., 2001) and indicate that thermal relaxation probably continued until the Early Cretaceous. Well and seismic data show no widespread Triassic faulting around the Palmyrides, although some local faults are present (Best, 1991). Broad subsidence was the dominant control on the Triassic depocenter.

A sedimentary hiatus before the deposition of the youngest Triassic Mulussa F (Serjelu Formation) is marked by emergence and erosion, especially of the Aleppo and Rutbah-Rawda highs (Figures 9 and 12c). The subsequent Mulussa F shows a distinct facies change, being largely clay and siltstone in contrast to the underlying carbonates and evaporites. These clastics were sourced from the Rutbah Uplift in the south and southwest that remained exposed during the Late Triassic, but with an increasingly calcareous content northward (de Ruiter et al., 1994). The Mulussa F formation marked the beginning of a regional transgression that continued through the Early Jurassic (Mouty, 2000).

Jurassic (206 Ma to 142 Ma)

The transgression that had begun in the latest Triassic continued through the Early Jurassic (MFS J10 of Sharland et al., 2001; near base of megasequence AP7). Characterized by limestone, dolomite, and occasional marl (Mouty, 2000), this type of deposition progressively replaced the Triassic lagoonal-evaporitic deposition with characteristically deeper water facies (Figure 9). The transgression covered all Syria except the Rutbah-Rawda (including the present Euphrates Graben area) and Aleppo / Mardin highs that remained emergent throughout the Jurassic (Mouty and Al-Maleh, 1983; Mouty, 2000). During the Jurassic, the Palmyride / Sinjar Trough extended through SW Syria (up to 2,100 m of Jurassic strata) and Lebanon (up to 2,250 m) toward the still-developing eastern Mediterranean (Walley, 2001).

Liassic tholeiitic basalts in the Anti-Lebanon (Mouty, 1998, 2000) and the Levant (Wilson et al., 1998), illustrate continued rifting activity along the eastern Mediterranean margin. As a possible consequence, the Liassic was a time of renewed regional faulting in the northern Arabian platform (Wilson et al., 1998). Seismic profiles and wells throughout the Palmyrides—especially around the Bishri and Bilas blocks (Figure 4)—demonstrate the presence of Jurassic-age faults (Best, 1991; Chaimov et al., 1992; Chaimov et al., 1993; Litak et al., 1997), that were possibly reactivated Permian rift-bounding faults.

Minor Lower Jurassic thickness changes (a few tens of meters) within southwestern Palmyride anticlines are only a hint of the larger architecture of the time. Stratigraphic relationships preclude these thickness changes as being due to later erosion. Two Jurassic depocenters are evident along strike in the Palmyrides, one centered around the present Bilas Block, and one on the Bishri Block (Sawaf et al., 2001). Widespread Jurassic faulting clearly focused deposition in these areas, with less-significant accumulation in the SW Palmyrides and the Sinjar area. This further indicates that the Jhar and Bishri faults are early Mesozoic structural features.

Regression, beginning at the start of the Bathonian (above MFS J30 of Sharland et al., 2001) (Figure 16, frame 6b), is evidenced by thinning of the Middle Jurassic formations eastward. The presence of the full sequence of Middle Jurassic formations shows that this is not an erosional artifact (Mouty, 2000). However, a more-pronounced regression that was accompanied by widespread erosion, is recorded as beginning in the Kimmeridgian, and most of Syria was subaerially exposed at its end (Mouty, 2000). Jurassic strata are only preserved in the deepest areas of the Palmyride / Sinjar Trough as regions external to this were eroded. Tithonian through Barremian strata are almost entirely absent from Syria (Figure 9), and much of the rest of northern Arabia (see summary in Guiraud, 1998). This corresponds to the boundary between megasequences AP7 and AP8 of Sharland et al. (2001) in the Tithonian (149 Ma) when India broke away from Oman. Heavily karstified surfaces further attest to long-lived exposure of the Jurassic limestone, except in the eastern Mediterranean basin where subsidence continued. Oxfordian to Kimmeridgian alkaline volcanics, with continuing volcanism through to Aptian time, have been identified in the Anti-Lebanon, the Syrian Coastal Ranges, the Palmyrides, and other parts of the eastern Mediterranean (Mouty et al., 1992). Laws and Wilson (1997) combined observations of volcanism, regional tilting, and uplift to suggest mantle plume activity centered in the Syrian region in the Late Jurassic and Early Cretaceous (also see Wilson et al., 1998). Garfunkel (1992) suggested that the Darfur volcanism in North Africa is the present expression of this still-existent hot spot.

Early Cretaceous (142 Ma) to Coniacian (86 Ma)

The Late Jurassic hiatus and erosion continued well into the Cretaceous. This extensive unconformity together with widespread Early Cretaceous volcanics (as far afield as the Euphrates and Sinjar areas) has led to suggestions of continued mantle plume activity (Laws and Wilson, 1997; Wilson et al., 1998). The contemporaneous somewhat accelerated deposition and fault reactivation in the Sinjar area (Brew et al., 1999) and the Palmyrides (Chaimov et al., 1992) may also have resulted from this regional volcanism. In a possibly connected event, accelerated spreading in the eastern Mediterranean may have contributed to the pronounced Late Jurassic to Early Cretaceous faulting (Robertson and Dixon, 1984).

The regional Early Cretaceous transgression covered most areas of the northern Arabian platform with hundreds of meters of fluviodeltaic to shallow-marine sands (>550 m in the Bishri Block). This Cenomanian and Early Cretaceous Rutbah sandstone in eastern Syria has equivalent Aptian and pre-Aptian members in the Palmyrides (Palmyra sandstone, Mouty and Al-Maleh, 1983), Lebanon (Gres de Base, Dubertret, 1966; Tixier, 1972) and Aafrin Basin (Al-Maleh, 1976). The only region of Syria not covered by the Rutbah sandstone or equivalent was the Rutbah-Rawda Uplift (Figure 12b and Figure 16, frame 7b). This area was still elevated, as it had been for most of the Phanerozoic, and Carboniferous and Permian sandstone eroded from it was the probable source of Cretaceous sand (Figures 12c and 12d).

Several interesting facies variations within the Lower Cretaceous sandstones reveal ambient paleogeographic conditions. Palmyra sandstone mapped in the Coastal Ranges is generally much more marly than in the Palmyrides, indicating deeper water to the west. The ‘Gres de Base’ sandstone thickens significantly toward Lebanon, with the presence of limited amounts of limestone indicating occasional shallowing of the basin (Tixier, 1972). This fits within a scenario of a continually subsiding eastern Mediterranean passive margin. The Rutbah and Palmyra sandstones become progressively more shaly and carbonaceous to the north, reflecting increasing distance from their sediment source in the Rutbah Uplift.

In central and western Syria, slow subsidence continued after the sandstone deposition. In general, this broad Albian to end Turonian carbonate-platform deposition (sometime referred to as the ‘Middle Cretaceous’, Mouty and Al-Maleh, 1983) is distinctly different from the underlying sandstones and overlying Senonian strata. The Zbeideh and Abou Zounar formations (Figure 9) mark two cycles of a shallowing depositional environment superimposed on a general trend of decreasing water depth that suggests a decreasing rate of subsidence. As with most of the Cretaceous and Jurassic strata, these formations show clear trends indicating deeper water, less-restricted circulation, and a smaller proportion of clastics in the west and southwest. For example, in the Euphrates Graben in eastern Syria, the Cenomanian-Turonian Judea limestone (Figure 9) indicates marginal to shallow-water depths and calm conditions of deposition. The equivalent Palmyride strata (Abou Zounar, Abtar, and Halabat formations) show medium-depth to shallow-marine conditions in three major sedimentary cycles (Mouty and Al-Maleh, 1983). The Cenomanian in the Coastal Ranges and Anti-Lebanon contains increasing amounts of marl and occasional planktonic foraminifera and pelagic, open-marine facies (Slenfeh and Bab Abdallah formations). The northwestern Kurd Dagh region records hemipelagic strata. A maximum ‘Middle Cretaceous’ transgression is recorded at about the early Cenomanian to early Turonian (top of megasequence AP8, Sharland et al., 2001), and prior to ophiolite obduction in eastern Arabia.

Formation of the Euphrates Fault System

The first hint of Euphrates rifting activity comes in Turonian-Coniacian time as a widespread unconformity and associated volcanics and anhydrite (base of megasequence AP 9, Sharland et al., 2001). The underlying Judea Formation was eroded and dolomitized. This could mark the prerift unconformity created by initial heating and uplift of the lithosphere under conditions of incipient rifting and plate flexure due to ophiolite obduction. Subsequent redbed deposition was restricted to eastern Syria (Derro redbeds, Figure 9) and western Iraq.

The exact cause of the Euphrates rifting is still unclear. Alsdorf et al. (1995) suggested that latest Cretaceous continental collision along the northern margin of the Arabian Plate caused tensional forces orthogonal to the collision, thus creating the Euphrates Fault System and Abd el Aziz-Sinjar faulting. However, the much earlier initiation of faulting in the Euphrates Graben and the increasing tectonism away from the collision tend to invalidate this suggestion. Lovelock (1984) was the first to suggest slab-pull as a possible passive rifting mechanism. By Senonian time, subduction in the NeoTethys was approaching the Arabian margin, and it continued until the end-Cretaceous collision (Figure 16, frames 8–10a). This, together with progressive loading due to ophiolite obduction, could explain the increasing extension with time, and the cessation of rifting with the collision of the trench and the northern Arabian margin during the Maastrichtian. However, the stresses created by such a distant trench may not have been sufficient to cause the observed extension. Furthermore, the presence of the prerift unconformity and volcanics might favor an active rifting scenario. This could be associated with the Early Cretaceous phase of plume activity observed in western Syria.

Santonian (86 Ma) to Campanian (71 Ma)

Palmyride Area

The Senonian was a time of subsidence throughout the northern Arabian platform, due to subsidence resulting from ophiolite obduction and other tectonic factors. In the Palmyrides, sedimentary facies suggest a clear increase in water depth after Turonian time. The upper Campanian Soukhne Group (Rmah and Sawwaneh formations, their base in the Coniacian) exhibits an increased marl and decreased calcareous content. A locally phosphatic limestone bed marks the top of the Group (Al-Maleh and Mouty, 1988). Studies by Mouty and Al-Maleh (1983) show differentiation between pelagic and hemipelagic strata recorded in the Bilas area, and shallower conditions on the southern margin of the Palmyrides that was not completely submerged until the late Senonian. This caused the preferential development of phosphatic deposits along the southern margin (Al-Maleh and Mouty, 1994).

Significant Late Cretaceous faulting in the Palmyrides is only observed in the Bishri area. Even so, central Syria at this time was undergoing accelerated regional subsidence that covered all areas. This was possibly due to the influence of NE-directed tensile stress that we have invoked as the cause of formation of the Euphrates Fault System formation (as discussed above).

On a regional scale, Bartov et al. (1980) reported significant Santonian structural inversion in northern Sinai. However, Guiraud and Bosworth (1997) noted that this was an isolated case, and was generally minor compared to later events. They claimed that no widespread compression of the 'Syrian Arc' (inverted structures subparallel to the eastern Mediterranean coast from Sinai to Syria, see Walley, 2001) occurred before the Maastrichtian.

Abd el Aziz-Sinjar Area

Although the Senonian was the time of significant rifting in the Euphrates Fault System (discussed below), similar large-scale faulting did not occur in the Abd el Aziz-Sinjar area until the Maastrichtian. Deposition in the northeast of Syria was limited during the Late Cretaceous (excluding Maastrichtian), so that, in places, not more than a few hundred meters of strata are present. The depositional environment was calm, with shelf carbonates prograding from Turkey in the north and mudstone deposition farther south (Kent and Hickman, 1997). Deposition in the southwest of the area was controlled by the NW-striking faults of the Euphrates Fault System (Brew et al., 1999).

Euphrates Fault System

The Euphrates Fault System rifted across oblique-slip normal faults from the Santonian onward, although the system was most active during the Campanian and early Maastrichtian. The first graben-fill was the Rmah chert in the west (equivalent to the Palmyride Rmah chert), and the Derro redbeds in the east (Figure 9) deposited during transgression. Progressively deeper water carbonate facies of the synrift sequence then filled the graben. This culminated in the accumulation of up to 2,300 m of pelagic marly limestone of the Shiranish Formation. At this time, the Euphrates Fault System and Bishri depocenters were linked by a fault-controlled topographic low (Figure 10).

We suggest, as originally proposed by Lovelock (1984), that Euphrates rifting was driven by slab-pull in the approaching subduction zone in the NeoTethys (Figure 16, frames 9a,b). The Wadi Sirhan graben in Jordan (Figure 1) shows a very similar orientation and timing of evolution to the Euphrates Fault System (Litak et al., 1997). This suggests that the tensional forces responsible for transtension in the Euphrates were transmitted across the Arabian Plate and were causing similarly oriented extension in Jordan.

Aafrin Basin and Coastal Ranges Area

During the Late Cretaceous the Aafrin Basin formed in the northwestern corner of the Arabian platform, roughly along the line of the present Syrian-Turkish border. The basin has subsequently been inverted to form the Kurd Dagh Mountains (Figure 2). As in other areas of Syria, subsidence and deposition in the Aafrin Basin increased throughout the Senonian. The basin fill contains progressively deeper water facies from this period (Al-Maleh, 1976; 1982). Hemipelagic open-marine strata of Santonian age lie beneath pelagic Campanian rocks. The beginnings of a recognizable Aafrin Basin developed in the Campanian. Again, this may be related to the increased stress within the platform as a consequence of subduction approaching from north and northeast. It may also be related to the loading of ophiolites that were being progressively obducted onto the northern Arabian margin a short distance north of the Basin. Surface mapping shows a typical preserved Santonian-Campanian section more than 200 m thick (Al-Maleh, 1976). At this time, pelagic open-marine strata were deposited in the Coastal Range area, although it was not a significant depocenter compared to the Aafrin Basin.

Maastrichtian (71 Ma to 65 Ma)

Palmyride Area

The early Maastrichtian was marked by accelerated deposition throughout the Palmyrides. This was the start of a major phase in the development of the Palmyride Trough as recorded by the deposition of the carbonate pelagic Maastrichtian to Lower Eocene Bardeh Formation (Mouty and Al-Maleh, 1983). The Formation (its lower part equivalent to the Shiranish of the Euphrates and NE Syria, Figure 9) has been studied extensively in outcrop (e.g. Al-Maleh and Mouty, 1988; El-Azabi et al., 1998). It shows great contrast to the depositional environment of most Senonian Palmyride strata. The Bardeh is a monotonous marl containing very few quartz grains and some planktonic and benthic foraminifera, indicating great water depths in a low-energy, open-marine setting (Al-Maleh and Mouty, 1988; El-Azabi et al., 1998). Thickness changes within the Bardeh emphasize the continuous development of the Palmyrides with the thickest strata recorded in the central areas.

Minor compression and uplift are well documented in the Palmyrides and the foothills of Turkey (Chaimov et al., 1992) in the latest Cretaceous. A coincident minor sedimentary hiatus at the Cretaceous-Tertiary boundary is present in the Bardeh Formation (El-Azabi et al., 1998). This is regarded as one of two prominent phases in the development of the Syrian Arc that caused inversion of Permian-Triassic normal faults along the Levant margin (Guiraud and Bosworth, 1997). This transition from an extensional to a compressional regime was due to collision of the Arabian Plate with the intraoceanic subduction trench in the north and east (Figure 16, frame 10b), as first suggested by Lovelock (1984). This event was related to widespread Maastrichtian southward obduction of ophiolites along the northern and northeastern margin of Arabia (Hempton, 1985). It was not the final Eurasian-Arabia collision, however, and the Neo-Tethys Ocean, with associated subduction, persisted to the north and east (Figure 16, frame 10a).

Abd el Aziz-Sinjar Area

The significant period of Late Cretaceous deformation in northeastern Syria began in the latest Campanian or earliest Maastrichtian (Brew et al., 1999). The boundary between the Soukhne (Massive Limestone), and the synextensional Shiranish Formation is unconformable. Kent and Hickman (1997) suggested this is the major preextensional unconformity. The Shiranish is predominantly marly limestone with some sandy units derived by erosion from exposed areas to the north (Kent and Hickman, 1997). It correlates with the Shiranish in the Euphrates Fault System. Extension took place on W-striking faults that are limited westward by the Euphrates faulting, and coalesce with Zagros deformation to the east in Iraq (Figure 12b). This extension created the Abd el Aziz and Sinjar half grabens (Figure 5). This faulting and half-graben formation ultimately led to the deposition of as much as 1,600 m of Shiranish strata (Figure 10).

We suggest that these E-W oriented faults formed as a consequence of tension created by subduction located along the northern and northeastern margins of the Arabian Plate, and of continuing ophiolite obduction (Figure 16, frame 10a). Perhaps the strain was accommodated in the Abd el Aziz-Sinjar area because it represented a structurally weak zone of thick sedimentation on the northern edge of the Palmyride / Sinjar Trough. A gradual shift in the orientation in this subduction zone might explain the transition from general NW-trending extensions in the early Senonian (Euphrates and Wadi Sirhan grabens) to more N-S extension in the Maastrichtian (Adb el Aziz and Sinjar half grabens). This was also the time of maximum extension in the W-trending Anah Graben (Figure 16, frame 9b) (Ibrahim, 1979). The relative southerly advance of ophiolitic nappes that were being obducted onto the northern margin could have contributed to normal faulting in northeastern Syria through loading.

Facies changes (Kent and Hickman, 1997), and the abrupt termination of faulting at the top Cretaceous level, together with a post-extension unconformity, signaled the end of Late Cretaceous extension in NE Syria. This was caused when Arabia collided with the Neo-Tethys subduction zone, as discussed above. This event is equivalent to the end of the plate-wide megasequence AP9 of Sharland et al. (2001).

Euphrates Fault System

While a vast thickness of the Shiranish Formation continued to be deposited in the Euphrates Fault System during the Maastrichtian, subtle indications suggest a reorientation of the stress direction, and a slowing of extension before final cessation of the rifting. Litak et al. (1997) reported that strike-slip features are more common amongst the NW-striking faults of the Euphrates deformation, than amongst the WNW-striking features. Furthermore, faulting ceased before the end of the Cretaceous, and an unconformity is present within the Shiranish Formation (Litak et al., 1998). These observations could be explained by reorientation of extension from SW-NE to N-S in conjunction with changes in extension in the Abd el Aziz-Sinjar area, and in Neo-Tethys subduction (Figure 16, frame 10a).

Aafrin Basin and Coastal Ranges Area

The early Maastrichtian was a time of continued subsidence and pelagic deposition in the NE-trending depocenter of the Aafrin Basin. More than 600 m of Maastrichtian strata are found in measured sections exposed by Cenozoic basin inversion (Al-Maleh, 1976). However, during the Maastrichtian, ophiolite nappes encroached on the northwestern margin of the basin to the extent that it shallowed considerably. To the southeast and especially the southwest, the basin remained and Maastrichtian turbidities deposited there contain considerable ophiolitic detritus (Al-Maleh, 1976). Clastic lenses within the uppermost Cretaceous strata stratigraphically above the ophiolite indicate transgression after ophiolite emplacement.

In the Coastal Ranges, Campanian depositional trends continued into the early Maastrichtian with the deposition of marly strata and only limited subsidence. The late Maastrichtian was marked by the initial uplift of the Coastal Ranges (Brew et al., 2001), as recorded stratigraphically by an angular unconformity between Maastrichtian and Paleocene strata (Ponikarov, 1966). This uplift occurred as part of the development of the ‘Syrian Arc’ that resulted from plate collision along the northern Arabian margin.

Paleocene (65 Ma) to Oligocene (24 Ma)

The Paleogene was largely a time of quiescence in the northern Arabian platform. Most areas remained under marine conditions with extensive pelagic deposition. In the Euphrates and Wadi Sirhan grabens, widespread thermal subsidence followed Late Cretaceous rifting (Figure 16, frame 11b). The Paleocene Kermev Formation in the Euphrates Graben contains more chert than the underlying Shiranish. Progressive shallowing is indicated throughout the Paleogene section here and in the Abd el Aziz-Sinjar area.

During the Paleogene, the prominent subsidence in the Palmyrides area that had begun in the Maastrichtian continued together with deposition of the Bardeh Formation. The Paleocene consists of a monotonous succession of pelagic marly limestone. The Lower Eocene Arak flint formation is a carbonate and silicic facies, deposited in much-shallower water than the previous cycle. In the Middle Eocene, low-energy pelagic carbonate deposition formed chalk, chalky limestones, and marls rich in microfossils and nanofossils.

For most of the Upper Eocene and Oligocene, the Palmyride region was characterized by nummulitic sandy limestone and sandstone, and major lateral changes suggest regression linked to tectonic uplift (Yzbek, 1998). Mouty and Al-Maleh (1983) studied the Middle Eocene through Oligocene sequence and named it the Abiad Group (Figure 9). In other parts of Syria, specifically the Anti-Lebanon, and the Aafrin Basin, the time-equivalent unit lacks the sandy lithology characteristic in the Palmyrides.

Although Chaimov et al. (1992) documented minor tectonism in the SW Palmyride fold and thrust belt in Middle Eocene time, the Late Eocene was clearly the main stage of Syrian Arc deformation (Guiraud and Bosworth, 1997). This included uplift of the Syrian Coastal Ranges (Brew et al., 2001) that is recorded as a stratigraphic gap during the Late Eocene and Oligocene in the coastal area. This 'Syrian Arc' development led to the formation of the major topographic elements in Lebanon (Walley, 1998). Lebanese structures were later modified as part of the restraining-bend architecture of the Dead Sea Fault System during the Neogene (Chaimov et al., 1990). Minor shortening in southern Turkey (Hempton, 1985), very minor transpression in the Euphrates Fault System, and minor compression in the Abd el Aziz uplift (Kent and Hickman, 1997), are all reported for this time period.

Hempton (1985) documented the Middle to Late Eocene as the initial period of final collision on the northern Arabian margin. This final obliteration of oceanic lithosphere formed the Bitlis Suture along the western part of the northern Arabian margin (Figure 16, frame 11a). The plate-wide compression caused by this suturing can explain the numerous instances of mid-Late Eocene compressional tectonics mentioned above. This is the start of the megasequence AP11 of Sharland et al. (2001) (34 Ma).

Miocene (24 Ma) to Holocene

The Miocene witnessed the final transition to continental conditions in Syria. However, it occurred at different times in various parts of the country due to partitioning by tectonic uplift. In particular, the uplifted Aleppo Plateau separated long-lived marine conditions in the northwest from more exposed regions elsewhere in Syria.

Miocene restricted-marine strata, including appreciable anhydrite and salt deposits of the Lower Fars and Dibbane formations, dominated the east and southeast of Syria. Furthermore, Miocene uplift and erosion created well-developed intramontane continental basins of the Al-Daww and Damascus basins (Figure 2) in, and around, the Palmyrides. These small basins contain continental strata with limited amounts of interbedded lacustrine carbonates and basalt.

To the northwest, deeper more open-marine conditions prevailed throughout the Miocene and Pliocene. In particular, the Aafrin Basin and adjacent areas along the northwestern margin of Arabia record substantial sedimentary deposition. The Miocene in parts of this area is more than 800 m thick and is composed mainly of argillaceous limestone and marl, with some turbidites. Basaltic layers, particularly of Middle Miocene age, indicate volcanic activity. Better exposures of volcanics occur farther south on the Aleppo Plateau (Figure 15). Hiatuses and deposition of evaporites that were contemporaneous with the Mediterranean Messinian salinity crisis record relative sea-level regression in Late Miocene times. Pliocene strata are as much as 450 m thick in some parts of the northwest, as in the Nahr al Kebir al Shamali Basin. The Pliocene sequence shows a progression toward continental deposition with some basaltic volcanism (for example, in the Aafrine Basin).

From a regional tectonic perspective, after the Middle to Late Eocene suturing of Africa-Arabia to Eurasia, convergence between the plates was accommodated in part by the shortening and thickening of the Arabian continental margin (Hempton, 1985). The stress created by the ongoing convergence continued to form the compressional features begun in the mid-Late Eocene, but at a slower rate. This stress regime was changed again by the beginning of continental stretching and rifting in the Red Sea in the Late Oligocene-Early Miocene. Rifting here led to the first phase of movement along the southern Dead Sea Fault System (Hempton, 1987). This, in turn, hastened the still-ongoing uplift of the Palmyrides (Chaimov et al., 1992).

By the mid-Late Miocene the colliding edge of the northern Arabian continental margin had reached a maximum crustal thickness. This occurrence is regarded as the terminal suturing of Arabia to Eurasia. In the model of Hempton (1987), the collision can be correlated in time with the cessation of the first phase of Red Sea rifting and movement on the Dead Sea Fault System. He also showed that at about the end of the Miocene, the North and East Anatolian faults formed to accommodate the continued convergence of Arabia and Eurasia. In his model, this coincided with a resumption of extension in the Red Sea that led to full-scale sea-floor spreading, and the second phase of movement on the Dead Sea Fault System. This episode caused a shift in the path of the fault in northern Levant to form the Syrian part of the Dead Sea Fault System (Chaimov et al., 1990).

Late Miocene onward is marked as a time of increased compression in Syria, presumably caused by the cessation of shortening along the northern margin. Evidence for increased compression includes accelerated basin inversion of the Palmyride fold and thrust belt (Chaimov et al., 1992), and minor shortening in the northwestern part of the Euphrates Fault System, the Turkish foot hills, the Zagros region (Litak et al., 1997), and the Abd el Aziz uplift (Kent and Hickman, 1997). In addition, Feraud et al. (1985) used dikes and volcanic alignments as paleostress indicators in western Syria to document a shift in maximum stress direction from roughly NW-SE to N-S at about the end of the Miocene.

Full-scale inversion of the Abd el Aziz and Sinjar uplifts did not take place until the Late Pliocene (Brew et al., 1999). Fault-propagation folds forming above reactivated Late Cretaceous W-striking normal faults have created the current W-trending topography. Although small outcrops of Senonian strata are found on the Abd el Aziz structure, Cretaceous rocks are more extensively exposed on the Sinjar Uplift in Iraq owing to increasing fault inversion to the east. Inversion in the Euphrates Fault System, however, is very minor and transpression is largely limited to the northwestern segment of the system. This could be a consequence of the Abd el Aziz-Sinjar structures accommodating most of the late Cenozoic strain. Also, the oblique angle that the Euphrates Fault System forms in relation to the Alpine collision favors strike-slip reactivation that is difficult to detect in subsurface data. Seismicity, Quaternary volcanism (Figure 15), and very minor Quaternary faulting suggest that the aborted grabens in eastern Syria are still actively inverting (Ponikarov, 1966).

To the northeast of the Sinjar area, sediment thickness increases rapidly into the Mesopotamian Foredeep (Figure 12a). This depression resulted from flexure of the Arabian Plate beneath Eurasia. In Syria, some small Zagros-related folding is observed, with deeper structures reminiscent of the Sinjar Graben. Well data indicate at least 1,300 m of Neogene clastic fill (Figure 10), shed partly from the uplifting Zagros since the terminal continental collision on this margin in the mid-Late Miocene.

Volcanic rocks were extruded from 24 to 16 Ma throughout western Syria with the exception of the Coastal Ranges. As noted by Mouty et al. (1992), this period coincides approximately with the final stages of Arabian-Eurasian convergence. Interestingly, an absence of volcanism from about 16 to 8 Ma roughly corresponds to the episode of no Red Sea spreading, and no movement on the Dead Sea Fault (Hempton, 1987). Penecontemporaneous with renewed movement on the Dead Sea transform, the volcanism shifted from the Aleppo Plateau to locations along the Fault in Syria. In particular, the formation of the northern Ghab Basin appears to have focused the most recent volcanism there from 1 to 2 Ma (Devyatkin et al., 1997). Holocene volcanic centers south of Damascus show strong NW-trending alignments (Figure 15). This could be reflecting a modern NNW-SSE stress direction (Feraud et al., 1985), or evidence for reactivation of the underlying Wadi Sirhan structures that strike in a very similar direction (Figure 1). Although the cause of the volcanism remains enigmatic, it is clearly linked in some way to the collision along the northern Arabian margin.

Currently, the Palmyride region is deforming by dextral transpression (Chaimov et al., 1990; Searle, 1994), under the influence of compression from the north and northwest (Figure 16, frame 12b). Evidence for active deformation on the Jhar Fault includes small Quaternary offsets (Ponikarov, 1966) and seismicity. Additional, possible dextral strike-slip faults on the Aleppo Plateau, (Figure 15) have also been identified (McBride et al., 1990). Our analysis suggests that the NE-trending faults mapped from the Bishri Block toward the Abd el Aziz structure (Figures 2 and 12b) could be acting to translate right lateral shear away from the Palmyride region. The exact interaction between the Palmyrides, Euphrates, and Sinjar tectonic zones is still unclear.

HYDROCARBON HABITAT

Estimated recoverable hydrocarbon reserves from Syria are about 2.5 billion barrels of oil and 8.5 trillion cubic feet of gas (Oil & Gas Journal, December 1999). Most discoveries (Figure 17) have been made in three of the four major Syrian tectonic zones (Figure 2). The exception is the Dead Sea Fault System. Although it is host to some hydrocarbons in the Levant—particularly in the Jurassic section—none has been found so far in this zone in Syria. This may be attributed to the lack of suitable source rocks. The three hydrocarbon-bearing zones are all abandoned rifts that have varying degrees of subsequent structural inversion. As a gross generalization, source and reservoir rocks were deposited under late Paleozoic and Mesozoic extension, and Mesozoic extension and late Cenozoic compression formed traps (Figure 18).

Source rocks in the Palmyrides have generally been buried to greater depths relative to sources elsewhere in Syria (Figure 12c) and this zone is largely gas and condensate bearing. Alternating carbonate / evaporite deposits in the Mesozoic section form viable reservoir / seal pairs. Most of the gas is found in the Triassic carbonate section, especially the Middle Triassic Kurrachine dolomite; fracturing largely controls porosity as primary porosity (3 to 10%) is poor (Al-Otri and Ayed, 1999). This reservoir is sealed by the Kurrachine anhydrite, and was charged by Permian-Triassic and Carboniferous shale containing from 0.8 to 5 percent total organic content (TOC) (Al-Otri and Ayed, 1999). Another important reservoir / seal pair is the Upper Carboniferous Makada sandstones (up to 25% porosity) sealed by Permian shales. Traps have been created in late Paleozoic-Mesozoic fault blocks and in folds created during structural inversion and shortening (Figures 18 and 19).

Both oil and gas are produced from the Bishri Block (Figure 2) in the transition between the Euphrates and Palmyride petroleum systems. Lower Cretaceous (Palmyra-Rutbah) sandstone, Triassic carbonates, and Carboniferous sandstones are the most common reservoirs, and fault blocks and anticlines the most usual traps. Potential Upper Cretaceous source rocks (Arak marl and Shiranish Formation) may not have been sufficiently buried to reach full maturity in the Bishri Block, and are positioned structurally higher than the reservoirs (Figures 12a and 12b). In this case, the charge may have come from the adjacent Euphrates Graben, or from Permian-Triassic shales in the Bishri area.

Discoveries in the Abd el Aziz-Sinjar area are mostly correlated with current topography (Figure 2 and Figure 17). The main trapping mechanism is Late Pliocene fault-propagation folding that requires very recent migration, whereas some deeper traps are fault blocks (Figure 18). Folds of this type also form prolific traps in Iraq, but faulting in Turkey has breached many of the fault-propagation fold reservoirs. Source rocks in northeast Syria are commonly of Cretaceous (Soukhne Formation) and Triassic age (Ala and Moss, 1979). Reservoirs are predominately Mesozoic and Cenozoic fractured carbonates and many fields have multiple objectives in the Miocene (Jeribe Formation), Cretaceous (Shiranish and Soukhne formations), and Triassic (Kurrachine dolomite) (Figure 18). Seals are shale and evaporites that are distributed throughout the Mesozoic and Cenozoic succession.

The Mesopotamian Foredeep, in far northeastern Syria is the longest-established production area in the country with many different fields (see well distribution in Figure 8). Traps occur in the simply folded Late Cretaceous and Cenozoic strata and are charged from Late Cretaceous and Triassic sources. Late Cretaceous fault blocks may be trapping deeper reserves.

Although mostly unknown before the 1980s, the Euphrates Graben harbors the most important hydrocarbon plays in Syria. More than 400,000 barrels of light, sweet crude are estimated to be produced daily from the graben, out of a national average of 540,000 barrels (Oil & Gas Journal, December 2000). The bulk of the production is from the Lower Cretaceous Rutbah sandstone (Figure 18). This is a high

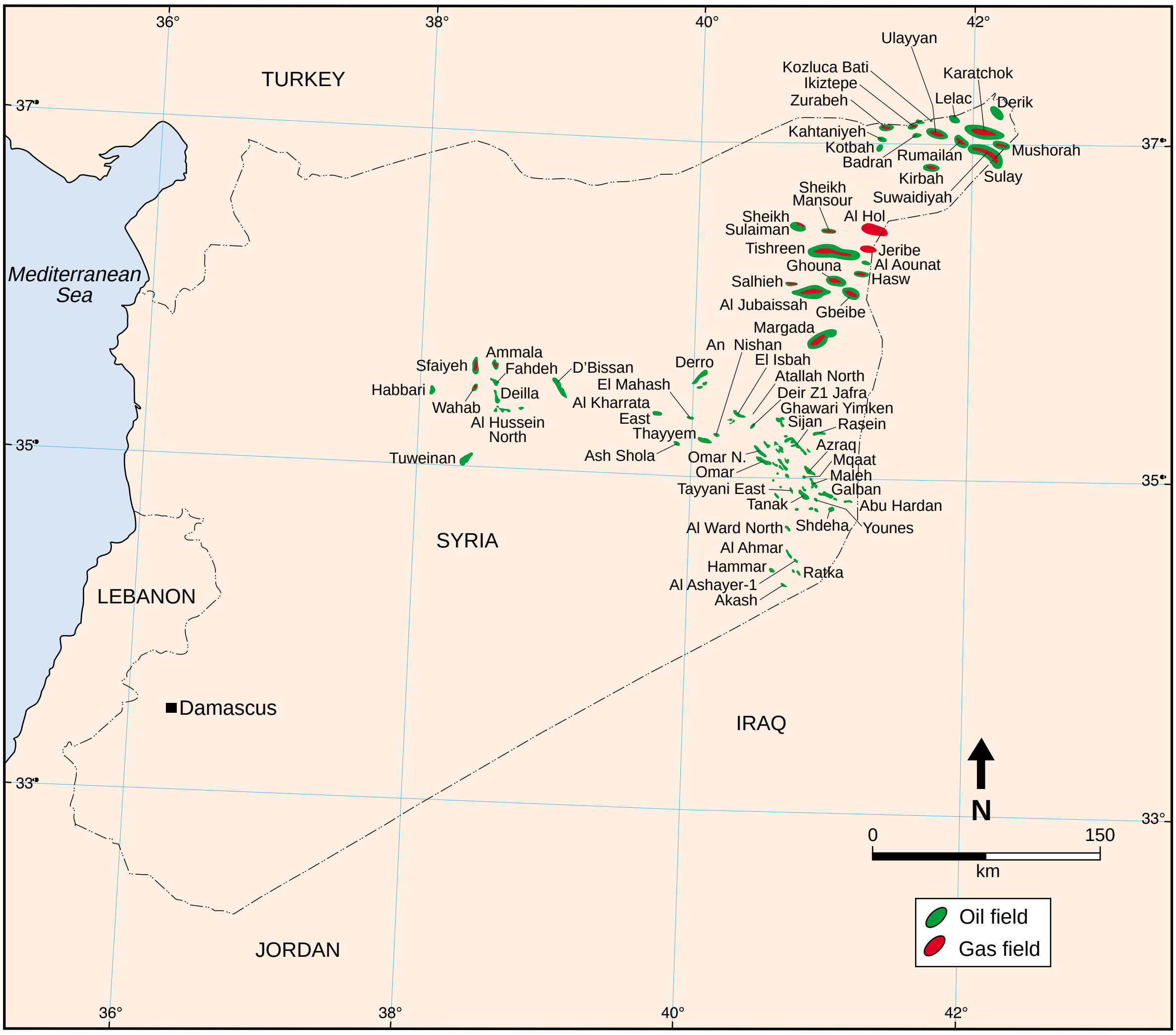


Figure 17: Oil and gas fields of Syria.

porosity (up to 20%) fluviodeltaic sandstone with well-maintained permeability that was deposited during the Neocomian transgression in eastern Syria (Figure 16, frame 7b). The Triassic Mulussa F sandstone is also a very important reservoir (de Ruiter et al., 1994). Both charge and seal are provided by the Upper Cretaceous marly limestone of the Shiranish Formation (up to 1.7% TOC) and the Rmah chert and Arak marl formations (average TOC 4%, locally up to 19%; Al-Otri and Ayed, 1999). These sources, deposited under widespread extension in eastern Syria (Figure 16, frame 9b), were juxtaposed with the Rutbah by the latest Cretaceous normal faulting that created the rotated fault-block traps (Figure 19). Although appreciable structural inversion in the northwest of the region may have breached some reservoirs, farther to the southeast traps has been enhanced by the very gentle folding that resulted from the Cenozoic compression. Alternating Triassic carbonates and evaporites (Figure 9) have created a series of potential reservoir/seal pairs, and minor oil shows occur in Carboniferous sandstones, for example in the Doubayat Group (de Ruiter et al., 1994).

Declining production in Syria has pushed deeper the search for hydrocarbons, and exploration now focuses on Paleozoic plays. Graptolitic shales, such as the Silurian Tanf Formation and Lower Ordovician Swab Formation (Figure 18), and their equivalents, are source rocks found through most of the Middle East (Sharland et al., 2001). Tests show from 2 to 5 percent TOC in the Tanf formation increasing southward to as much as 16 percent TOC in Iraq (Aqrawi, 1998). The Tanf beneath the Rawda High is immature to early mature (A. Horbury, personal communication, 2001), whereas beneath the Rutbah Uplift the Formation is over-mature.

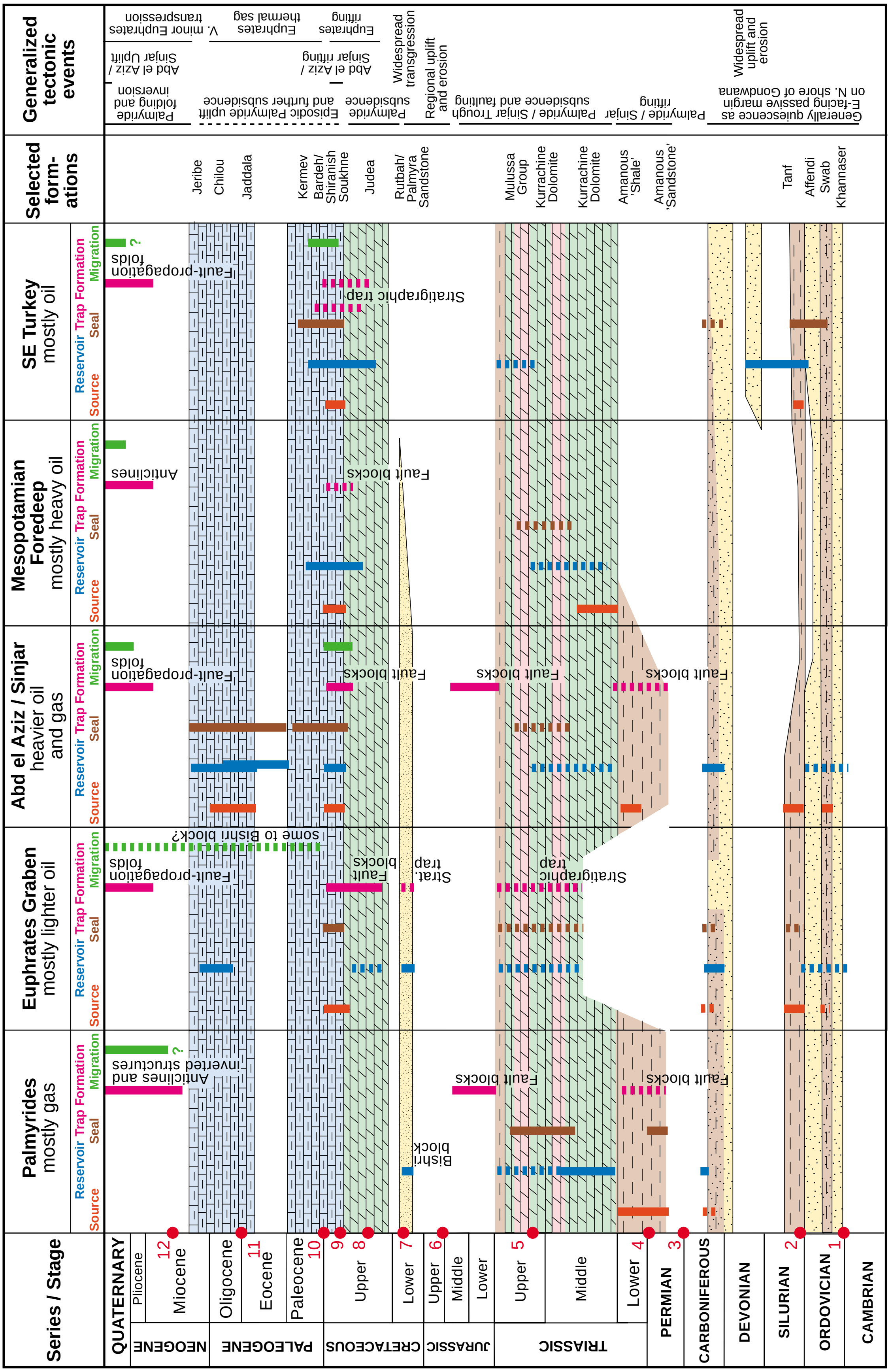


Figure 18: Generalized stratigraphy and selected structural elements in various hydrocarbon provinces of Syria and SE Turkey. Proven features related to hydrocarbon accumulation are shown as solid lines; dashed lines where uncertain. Tectonic events generalized from Figure 16. Red dots refer to time points of Figure 16. Note that formation names change between Syria and Turkey. Lithology as for Figure 9.

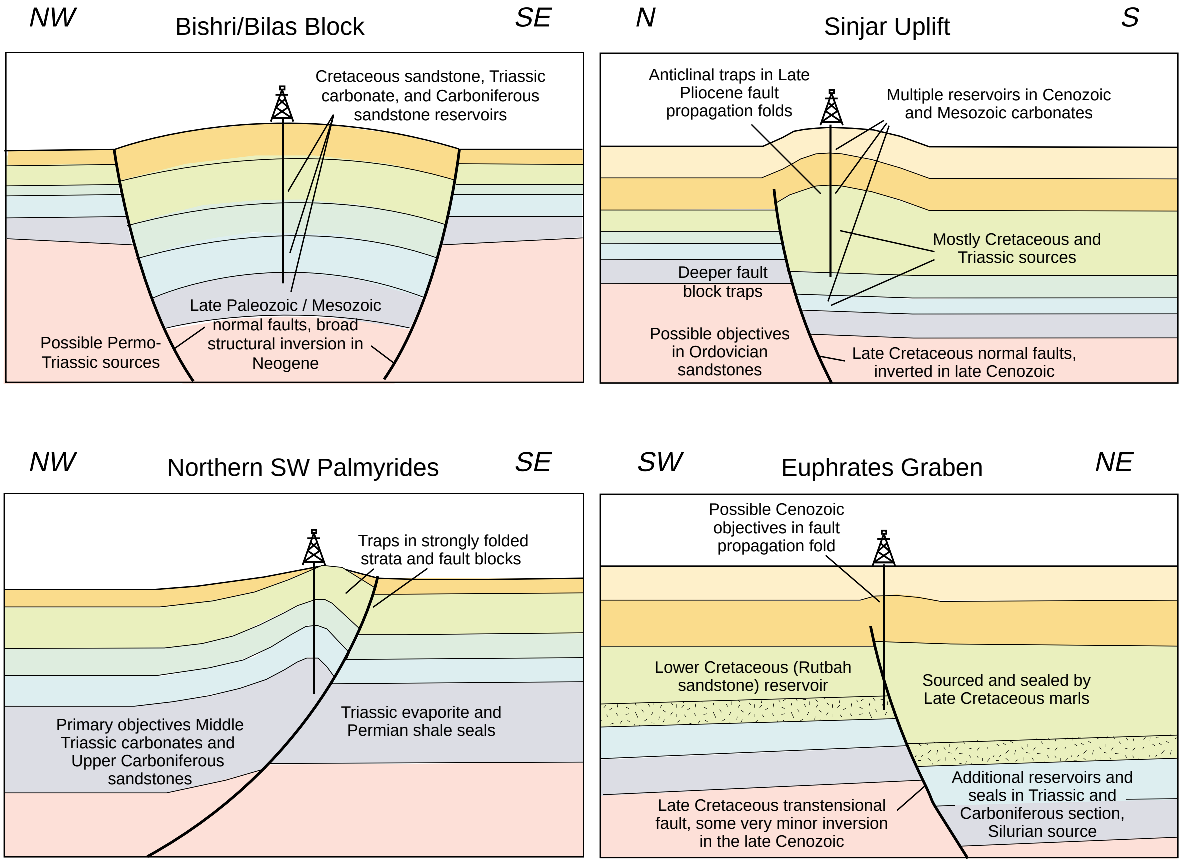


Figure 19: Highly schematic cross-sections of examples of trapping configurations in some typical oil fields of Syria.

Paleozoic reservoir rocks in Syria could include Permian-Carboniferous and Ordovician sandstones (Makada, Affendi and Khannaser formations, of up to 25% porosity) that are present at various depths over most of the region (Figure 12d). Evidence exists for viable Paleozoic plays in SE Syria. The Akkas oil shows from a Lower Silurian sandstone and gas from the Upper Ordovician sourced and sealed by Lower Silurian shales occur in Iraq (Aqrawi, 1998). Paleozoic discoveries sourced from the Silurian Tanf Formation in the Euphrates Graben (de Ruiter et al., 1994) confirm the viability. The presence of suitably timed structural traps and sealing lithologies could be the main controls on this play. The Maghlouja well on the Abd el Aziz structure (Figure 5) had shows of gas in the Silurian section, and limited shows of relatively light oil (39° API) in the Upper Ordovician Affendi Formation (Kent and Hickman, 1997). However, if this oil has a Silurian source and migrated after fault inversion juxtaposed that unit with the Ordovician in the Pliocene, insufficient time may have elapsed for an economically adequate charge to have accumulated.

SUMMARY

By integrating vast amounts of detailed geophysical and geological data with previous knowledge, we have composed a new regional geologic evolutionary model for Syria. Tectonic deformation within specific Syrian tectonic zones was often contemporaneous with deformation in other adjacent zones. Moreover, in almost all cases these episodes of tectonism can be related to activity on nearby margins of the Arabian Plate, as reflected in the sequence stratigraphy of the entire Arabian Plate (see Sharland et al., 2001).

After cratonic accretion of the Arabian-Nubian Shield had taken place in the Proterozoic, Syria was part of the northern passive margin of Gondwana bordering the Tethys Ocean for most of the Phanerozoic. Gentle early Paleozoic subsidence of this E-facing margin led to the regional accumulation of thick clastic deposits eroded from nearby areas of the Precambrian Shield. This was followed by fluvioglacial and marginal-marine conditions that changed to a shelf environment during frequent transgressions. Later, regional compression followed by extension related to the opening of the Neo-Tethys led to the formation of the Palmyride-Sinjar Trough in which more than 2,000 m of Late Carboniferous and Permian-Triassic clastics accumulated.

As the plate moved into lower latitudes in the Mesozoic, extensive carbonate platforms developed on the wide northern Arabian epicontinental shelf. Thermal subsidence above the Permian-Triassic Palmyride rift accommodated a thick Triassic and Jurassic succession in the Palmyrides, enhanced by periods of reactivated faulting. Development of the eastern Mediterranean, W-facing, Mesozoic passive margin also concentrated deposition in that area. Extensive Late Jurassic to Early Cretaceous uplift, widespread volcanism, and renewed fault activity may indicate contemporaneous mantle plume activity.

Barremian to Aptian transgression deposited thick fluviodeltaic sands across much of Syria. In the Late Cretaceous a NE–SW regional extension formed the Euphrates Fault System, and accelerated subsidence elsewhere. An increasingly N–S extensional direction in the Maastrichtian caused the opening of the Abd el Aziz, Sinjar, and Anah grabens. Collision along the northern plate margin in the latest Cretaceous and associated ophiolite emplacement, terminated extension and caused a slight uplift of the Syrian Arc, including the SW Palmyrides.

Thick, marly carbonate sequences continued to form in the Paleogene, with some uplift and compression in mid-Late Eocene time related to the beginning of the final collision phase of the Arabian Plate with Eurasia. Neogene clastics indicate the shift to the continental conditions that prevail today, and this occurred in tandem with renewed compressional tectonics. The tectonics were associated with terminal suturing on the northern margin that caused most of the Palmyride uplift and inversion of the Abd el Aziz-Sinjar structures. Pliocene development of the northern Dead Sea Fault System led to the creation of the Ghab Basin.

This geologic evolution of Syria has created conditions most suitable for the preservation of hydrocarbons. Reservoirs were formed in the extensive clastic and carbonate deposits, most particularly in the Mesozoic, with source rocks throughout the section. The traps are mostly structural in the form of fault blocks or fault-propagation folds.

ACKNOWLEDGMENTS

We thank the Syrian Petroleum Company for providing the data used in this study. Mikhail Mouty of Damascus University deserves very special thanks for his scientific input and advice regarding many aspects of Syrian lithostratigraphy. Abdul Nassar Darkel, also of Damascus University, was indispensable during fieldtrips. Francisco Gomez and Dogan Seber, both at Cornell University, provided valuable comments and suggestions when reviewing an early draft of this manuscript. Three anonymous reviewers and GeoArabia's editorial staff are thanked for their very professional treatment of this publication. The drafting of the final graphics was by Gulf PetroLink staff.

REFERENCES

Ala, M.A. and B.J. Moss 1979. Comparative petroleum geology of southeast Turkey and northeast Syria. Journal of Petroleum Geology, v. 1, no. 4, p. 3–27.

Al-Maleh, K., 1976. Etude stratigraphique, petrographique, sedimentologique et geochimique du Cretace du N.W. Syrien (Kurd Dagh se environs d'Aafrine): les aspects petroliers de la region. Universitie Pierre et Marie Curie (Paris 6). 620 p.

Al-Maleh, K., 1982. Evolution de la sedimentation Carbonatee dans le Nord–ouest de la Syrie pendant le cretace. Mémoire Géologique, v. 4, University of Dijon, p. 437–479.

Al-Maleh, K. and M. Mouty 1988. The sedimentation and paleogeographic evolution of the Palmyridean region during the Jurassic and Cretaceous (Central part of Syria). Third Jordanian Geology Conference, Amman, p. 213–244.

Al-Maleh, K. and M. Mouty 1992. The Senonian in the Palmyridian Chaine. Final Report AECG-G / FRSR63. Atomic Energy Commission, Damascus, Syria. 43 p.

Al-Maleh, K. and M. Mouty, 1994. Lithostratigraphic characteristics of phosphorite deposits and the regional sedimentational and paleogeographic framework of their formation in the Palmyrides mountain chain, Middle Syria. Proceedings of the 29th International Geological Congress, part C, VSP, p. 225–235.

Al-Otri, M. and H. Ayed 1999. Evaluation of hydrocarbon potentials of the sedimentary basins in Syria. Evaluation of hydrocarbon potential in Arab sedimentary basins. École Nationale Supérieure des Pétroles et Moteurs, France.

Al-Saad, D., T. Sawaf, A. Gebran, M. Barazangi, J. Best and T. Chaimov 1992. Crustal structure of central Syria: the intracontinental Palmyride mountain belt. Tectonophysics, v. 207, no. 3–4, p. 345–358.

Alsdorf, D., M. Barazangi, R. Litak, D. Seber, T. Sawaf and D. Al-Saad 1995. The intraplate Euphrates depression-Palmyrides mountain belt junction and relationship to Arabian plate boundary tectonics. Annali Di Geofisica, v. 38, no. 3–4, p. 385–397.

Aqrawi, A.A.M. 1998. Paleozoic stratigraphy and petroleum systems of the western and southwestern deserts of Iraq. GeoArabia, v. 3, no. 2, p. 229–248.

Barazangi, M., D. Seber, T. Chaimov, J. Best, R. Litak, D. Al-Saad and T. Sawaf 1993. Tectonic evolution of the northern Arabian plate in western Syria. In, E. Boschi, E. Mantovani and A. Morelli (Eds.), Recent Evolution and Seismicity of the Mediterranean Region. Kluwer Academic Publishers, p.117–140.

Bartov, Y., Z. Lewy, G. Steinitz and I. Zak 1980. Mesozoic and Tertiary stratigraphy, paleogeography and structural history of the Gebel Areif en Naqa area, Eastern Sinai. Israel Journal of Earth Sciences, v. 29, no. 1–2, p. 114–139.

BEICIP 1975. Gravity maps of Syria: Damascus (Syria). Bureau d'etudes Industrielles et de Cooperation de l'Institut Français du Petrole, France, 96 p.

Best, J.A., 1991. Crustal evolution of the northern Arabian platform beneath the Syrian Arab Republic. Unpublished PhD thesis, Cornell University, Ithaca, New York. 152 p.

Best, J.A., M. Barazangi, D. Al-Saad, T. Sawaf and A. Gebran 1990. Bouguer gravity trends and crustal structure of the Palmyride Mountain belt and surrounding northern Arabian platform in Syria. Geology, v. 18, no. 12, p. 1235–1239.

Best, J.A., M. Barazangi, D. Al-Saad, T. Sawaf and A. Gebran 1993. Continental margin evolution of the northern Arabian platform in Syria. American Association of Petroleum Geologists Bulletin, v. 77, no. 2, p. 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, 77 p.

Beydoun, Z.R. and J.G. Habib 1995. Lebanon revisited: new insights into Triassic hydrocarbon prospects. Journal of Petroleum Geology, v. 18, no. 1, p. 75–90.

Brew, G., M. Barazangi, T. Sawaf and K. Al-Maleh 2000. Tectonic map and geologic evolution of Syria: the role of GIS. The Leading Edge, v. 19, no. 2, p. 176–182.

Brew, G., R. Litak, M. Barazangi and T. Sawaf 1999. Tectonic evolution of northeast Syria: regional implications and hydrocarbon prospects. GeoArabia, v. 4, no. 3, p. 289–318.

Brew, G.E., R.K. Litak, D. Seber, M. Barazangi, A. Al-Imam and T. Sawaf 1997. Basement depth and sedimentary velocity structure in the northern Arabian platform, eastern Syria. Geophysical Journal International, v. 128, no. 3, p. 617–631.

Brew, G., J. Lupa, M. Barazangi, T. Sawaf, A. Al-Imam and T. Zaza 2001. Structure and tectonic development of the Dead Sea Fault System and Ghab Basin in Syria. Journal of the Geological Society, London, v. 158, p. 665–674.

Chaimov, T., M. Barazangi, D. Al-Saad and T. Sawaf 1993. Seismic fabric and 3-D upper crustal structure of the southwestern intracontinental Palmyride fold belt, Syria. American Association of Petroleum Geologists Bulletin, v. 77, no. 12, p. 2032–2047.

Chaimov, T., M. Barazangi, D. Al-Saad, T. Sawaf and A. Gebran 1990. Crustal shortening in the Palmyride fold belt, Syria, and implications for movement along the Dead Sea fault system. Tectonics, v. 9, no. 6, p. 1369–1386.

Chaimov, T., M. Barazangi, D. Al-Saad, T. Sawaf and A. Gebran 1992. Mesozoic and Cenozoic deformation inferred from seismic stratigraphy in the southwestern intracontinental Palmyride fold-thrust belt, Syria. Geological Society of America Bulletin, v. 104, no. 6, p. 704–715.

Cohen, Z., V. Kaptsan and A. Flexer 1990. The tectonic mosaic of the southern Levant: implications for hydrocarbon prospects. Journal of Petroleum Geology, v. 13, no. 4, p. 437–462.

de Ruiter, R.S.C., P.E.R. Lovelock and N. Nabulsi 1994. The Euphrates Graben, Eastern Syria: a new petroleum province in the northern Middle East. In, M.I. Al-Husseini (Ed.), Middle East Petroleum Geosciences, GEO'94. Gulf PetroLink, Bahrain, v. 1, p. 357–368.

Dercourt, J., L.P. Zonenshain, L.-E. Ricou, V.G. Kazmin, X. LePichon, A.L. Knipper, C. Grandjacquet, I.M. Sbortshikov, J. Geyssant, C. Lepvrier, D.H. Pechersky, J. Boulin, J.-C. Sibuet, L.A. Savostin, O. Sorokhtin, M. Westphal, M.L. Bazhenov, J.P. Lauer and B. Biju-Duval 1986. Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. Tectonophysics, v. 123, no. 1–4, p. 241–315.

Devyatkin, E.V., A.E. Dodonov, E.V. Sharkov, V.S. Zykin, A.N. Simakova, K. Khatib and H. Nseir 1997. The El-Ghab rift depression in Syria: its structure, stratigraphy, and history of development. Stratigraphy and Geological Correlation, v. 5, no. 4, p. 362–374.

Dubertret, L., 1955. Carte Géologique du Liban. Ministere des Travaux Publics, Beyrouth.

Dubertret, L., 1966. Liban, Syria et bordure des Pay Voisines: I, tableau stratigraphique et carte au millionieme. Extrait de Notes et Memoire Moyen-Orient VIII, Muséum National d'Histoire Naturelle, Paris.

El-Azabi, M.H., A.K. Al-Maleh and M.K. Yzbek 1998. Facies characteristics and depositional environments of the Maastrichtian-Paleocene succession in Jabal El-Bardeh and Jabal Anter, Kasr Al Heir-Turfa area, southern Palmyridian region, Syria. Middle East Research Center, Ain Shams University, Earth Sciences, v. 12, p. 1–20.

Feraud, G., G. Giannerini and R. Campredon 1985. Dyke swarms as paleostress indicators in areas adjacent to continental collision zones: examples from the European and northwest Arabian Plates. Mafic Dyke Swarms, International Lithosphere Program, University of Toronto, Canada, p. 273–278.

Freund, R., Z. Garfunkel, I. Zak, M. Goldberg, T. Weissbrod and B. Derin 1970. The shear along the Dead Sea rift. Philosophical Transactions of the Royal Society, London, v. 267, no. 1, p. 107–130.

Garfunkel, Z. 1992. Darfur-Levant array of volcanics—a 140 Ma-long record of a hot spot beneath the African-Arabian continent, and its bearing on Africa's absolute motion. Journal of Israeli Earth Sciences, v. 40, p. 135–150.

Gradstein, F. M. and J. Ogg 1996. A Phanerozoic time scale. Episodes, v. 19, p. 3–5.

Guiraud, R. 1998. Mesozoic rifting and basin inversion along the northern African Tethyan margin: an overview. In, D.S. Macgregor, R.T.J. Moody and D.D. Clark-Lowes (Eds.), Petroleum Geology of North Africa. Geological Society, London, Special Publication no. 132, p. 217–229.

Guiraud, R. and W. Bosworth 1997. Senonian basin inversion and rejuvenation of rifting in Africa and Arabia: synthesis and implications to plate-scale tectonics. Tectonophysics, v. 282, no. 1–4, p. 39–82.

Gvirtzman, G. and T. Weissbrod 1984. The Hercynian geanticline of Helez and the late Palaeozoic history of the Levant. In, J.E. Dixon and A.H.F. Robertson (Eds), Geological Society, London, Special Publication no. 17, p. 177–186.

Haq, B.U., J. Hardenbol and P.R. Vail 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In C.K. Wilgus, B.S. Hastings, C.A. Rosset al (Eds.), Sea-level changes; an integrated approach. Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 72–108.

Hempton, M. 1985. Structure and deformation of the Bitlis suture near Lake Hazar, southeastern Turkey. Geological Society of America Bulletin, v. 96, no. 2, p. 233–243.

Hempton, M. 1987. Constraints on Arabian plate motion and extensional history of the Red Sea. Tectonics, v. 6, no. 6, p. 687–705.

Husseini, M.I. 1989. Tectonic and deposition model of late Precambrian-Cambrian Arabian and adjoining plates. American Association of Petroleum Geologists Bulletin, v. 73, no. 9, p. 1117–1131.

Husseini, M.I. 1992. Upper Palaeozoic tectono-sedimentary evolution of the Arabian and adjoining plates. Journal of the Geological Society, London, v. 149, no. 5, p. 419–429.

Ibrahim, M.W. 1979. Shifting depositional axes of Iraq: an outline of geosynclinal history. Journal of Petroleum Geology, v. 2, no. 2, p. 181–197.

Kent, W.N. and R.G. Hickman 1997. Structural development of Jebel Abd Al Aziz, northeast Syria. GeoArabia, v. 2, no. 3, p. 307–330.

Kohn, B., M. Eyal and S. Feinstein 1992. A major Late Devonian-Early Carboniferous (Hercynian) thermotectonic event at the NW Margin of the Arabian-Nubian Shield: evidence from zircon fission track dating. Tectonics, v. 11, no. 5, p. 1018–1027.

Laws, E.D. and M. Wilson 1997. Tectonics and magmatism associated with the Mesozoic passive continental margin development in the Middle East. Journal of the Geological Society, London, v. 154, no. 3, p. 459–464.

Litak, R.K., M. Barazangi, G. Brew, T. Sawaf, A. Al-Imam and W. Al-Youssef 1998. Structure and evolution of the petroliferous Euphrates graben system, southeast Syria. American Association of Petroleum Geologists Bulletin, v. 82, no. 6, p. 1173–1190.

Litak, R.K., M. Barazangi, W. Beauchamp, D. Seber, G. Brew, T. Sawaf and W. Al-Youssef 1997. Mesozoic-Cenozoic evolution of the intraplate Euphrates fault system, Syria: implications for regional tectonics. Journal of the Geological Society, London, v. 154, no. 4, p. 653–666.

Lovelock, P.E.R. 1984. A review of the tectonics of the northern Middle East region. Geological Magazine, v. 121, no. 6, p. 577–587.

McBride, J.H., M. Barazangi, J. Best, D. Al-Saad, T. Sawaf, M. Al-Otri and A. Gebran 1990. Seismic reflection structure of intracratonic Palmyride fold-thrust belt and surrounding Arabian platform, Syria. American Association of Petroleum Geologists Bulletin, v. 74, no. 3, p. 238–259.

McClusky, S., S. Balassanian, A. Barka, C. Demir, S. Ergintav, I. Georgiev, O. Gurkan, M. Hamburger, K. Hurst, H. Kahle, K. Kastens, G. Kekelidze, R. King, V. Kotzev, O. Lenk, S. Mahmoud, A. Mishin, M. Nadariya, A. Ouzounis, D. Paradissis, Y. Peter, M. Prilepin, R. Reilinger, I. Sanli, H. Seeger, A. Tealeb, M.N. Toksöz, and G.Veis 2000. Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus. Journal of Geophysical Research, v. 105, no. B3, p. 5695–5719.

Mouty, M. 1998. Le Jurassique du Mont Hermon (Anti-Liban). Decouverte de Trias et de Lias. Archives des Sciences et Compte Rendu, Geneve, v. 51, no. 3, p. 295–304.

Mouty, M. 2000. The Jurassic in Syria: an overview. Lithostratigraphic and biostratigraphic correlations with adjacent areas. In, S. Crasquin-Soleau and E. Barrier (Eds.), New data on PeriTethyan sedimentary basins. Memoires du Muséum National d'Historie Naturelle, Paris, PeriTethys Memoir 5, p. 159–168.

Mouty, M. and Al-Maleh, K., 1983. The geological study of the Palmyridian chain using ideal geological sections for exploration purposes and geological survey. General Establishment of Geology and Mineral Resources, Syrian Ministry of Petroleum and Mineral Resources, Damascus, Syria, 'Unigeoconsult', no. 140, 4 volumes, 950 p.

Mouty, M., M. Delaloye, D. Fontignie, O. Piskin and J.-J. Wagner 1992. The volcanic activity in Syria and Lebanon between Jurassic and Actual. Schweizerische Mineralogische und Petrographische Mitteilungen, v. 72, no. 1, p. 91–105.

Ponikarov, V.P. 1966. The geology of Syria. Explanatory Notes on the Geological Map of Syria, scale 1:200 000. Ministry of Industry, Syrian Arab Republic.

Quennell, A.M. 1984. The western Arabia rift system. In, J.E. Dixon and A.H.F. Robertson (Eds.), The Geological Evolution of the Eastern Mediterranean. Geological Society, London, Special Publication no. 17, p. 775–788.

Ravn, R.L., B. McPhilemy, M. Rutherford, S. Talli and G. Bahra 1994. Late Devonian and Early Carboniferous palynostratigraphy and its applications in northeastern Syria. In, M.D. Simmons (Ed.), Micropalaeonology and Hydrocarbon Exploration in the Middle East. Chapman & Hall, p. 5–21.

Ricou, L.E. 1995. The plate tectonic history of the past Tethys Ocean. In, A.E.M. Nairn, L.-E. Ricou, B. Vrielynck and J. Dercourt (Eds.), The Ocean Basins and Margins: the Tethys Ocean. Plenum Press, v. 8, p. 3–70.

Robertson, A.H.F. and J.E. Dixon 1984. Aspects of the geological evolution of the Eastern Mediterranean. In, J.E. Dixon and A.H.F. Robertson (Eds.), The Geologic Evolution of the Eastern Mediterranean. Geological Society, London, Special Publication no. 17, p. 1–74.

Robertson, A.H.F., J.E. Dixon, S. Brown, A. Collins, A. Morris, E. Pickett, I. Sharp and T. Ustaomer 1996. Alternative tectonic models for the Late Paleozoic-Early Tertiary development of the Tethys in the Eastern Mediterranean region. In, A. Morris and D.H. Tarling (Eds.), Paleomagnetism and tectonics of the Mediterranean region. Geological Society, London, Special Publication no. 105, p. 239–263.

Sadooni, F.N. 1995. Petroleum prospects of Upper Triassic carbonates in northern Iraq. Journal of Petroleum Geology, v. 18, no. 2, p. 171–190.

Sawaf, T., G.E. Brew, R.K. Litak and M. Barazangi 2001. Geologic evolution of the intraplate Palmyride Basin and Euphrates fault system, Syria. In, W. Cavazza, A. Robertson and P. Ziegler (Eds.), PeriTethyan rift / wrench basins and passive margins, Memoires du Muséum National d'Historie Naturelle, Paris, PeriTethys Memoir 6.

Sawaf, T., D. Al-Saad, A. Gebran, M. Barazangi, J.A. Best and T. Chaimov 1993. Structure and stratigraphy of eastern Syria across the Euphrates depression. Tectonophysics, v. 220, no. 1–4, p. 267–281.

Searle, M.P. 1994. Structure of the intraplate eastern Palmyride Fold Belt, Syria. Geological Society of America Bulletin, v. 106, no. 10, p. 1332–1350.

Seber, D., M. Barazangi, T. Chaimov, D. Al-Saad, T. Sawaf and M. Khaddour 1993. Upper crustal velocity structure and basement morphology beneath the intracontinental Palmyride fold-thrust belt and north Arabian platform in Syria. Geophysical Journal International, v. 113, no. 3, p. 752–766.

Seber, D., D. Steer, E. Sandvol, C. Sandvol, C. Brindisi and M. Barazangi 2000. Design and development of information systems for the geosciences: an application to the Middle East. GeoArabia, v. 5, no. 2, p. 269–296.

Sharland, P.R., R. Archer, D.M. Casey, R.B. Davies, S.H. Hall, A.P. Heward, A.D. Horbury and M.D. Simmons 2001. Arabian Plate sequence stratigraphy. GeoArabia Special Publication 2. Gulf PetroLink, Bahrain, 371 p.

Stampfli, G.M., J. Mosar, P. Favre, A. Pillevuit and J.-C. Vannay 2001. Permian-Triassic evolution of the western Tethyan realm: the NeoTethys / east Mediterranean basin connection. In, W. Cavazza, A.H.F. Robertson and P. Ziegler (Eds.), PeriTethyan rift / wrench basins and passive margins. Memoires du Muséum National d'Historie Naturelle, Paris, PeriTethys Memoir 6.

Steckler, M. and U. ten Brink 1986. Lithospheric strength variations as a control on new plate boundaries: examples from the northern Red Sea. Earth and Planetary Science Letters, v. 79, no. 1–2, p.120–132.

Stoeser, D.B. and V.E. Camp 1985. Pan-African microplate accretion of the Arabian shield. Geological Society of America Bulletin, v. 96, no. 7, p. 817–826.

Tixier, B., 1972. Le 'Gres de Base' Cretace du Liban: Etude stratigraphique et sedimentologique. Notes et Memoires Moyen-Orient, Muséum National d'Histoire Naturelle, Paris, v. 12, no. 2, p. 187–215.

Trifonov, V.G., V.M. Trubikhin, Z. Adzhamyan, S. Dzhallad, Y. El' Khair and K. Ayed 1991. Levant fault zone in northeast Syria. Geotectonics, v. 25, no. 2, p. 145–154.

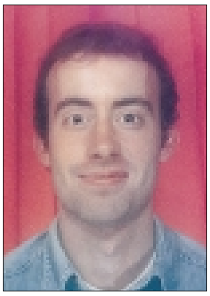
Walley, C. 1998. Some outstanding issues in the geology of Lebanon and their importance in the tectonic evolution of the Levantine region. Tectonophysics, v. 298, no. 1, p. 37–62.

Walley, C. 2001. The Lebanon passive margin and the evolution of the Levantine Neotethys. In, W. Cavazza, A.H.F. Robertson and P. Ziegler (Eds.), PeriTethyan rift / wrench basins and margins. Memoires du Muséum National d'Historie Naturelle, Paris, PeriTethys Memoir 6.

Wilson, M., R. Guiraud, C. Moureau and Y. Bellion 1998. Late Permian to Recent magmatic activity on the African-Arabian margin of Tethys. In, D. MacGregor, R. Moody and D. Clark-Lowes (Eds.), Petroleum Geology of North Africa. Geological Society, London, Special Publication no. 132, p. 231–263.

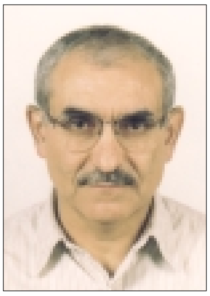
Yzbek, M.K. 1998. Calcareous nannofosil zonation and micofacies studies on the Eocene sediments of the Palmyridian and Anti-Lebanon region, Syria. Unpublished PhD thesis, Cairo University, 342 p.

ABOUT THE AUTHORS



Graham Brew *is a Research Scientist at Cornell University. He has a BSc in Geophysics (1995) from University College, London, and a PhD in Geophysics from Cornell University (2001). He worked for a short time with RTZ Mining and Exploration in Santiago, Chile. Graham's research with the Cornell Syria Project is focused on interpretating the tectonic evolution of the nerthern Arabian platform from geophysical data, through geophysical analysis.*

E-mail: geb3@cornell.edu



Muawia Barazangi *is a Professor in the Department of Geological Sciences at Cornell. He is also Associate Director of the Institute for the Study of the Continents, and is the leader of the Cornell Syria Project. He has a BS in Physics and Geology from Damascus University, an MS in Geophysics from the University of Minnesota, and a PhD in Seismology from Columbia University's Lamont-Doherty Earth Observatory. His research includes global tectonics, seismotectonics of continental collision zones, intracontinental mountain belts, and Middle East tectonics.*

Corresponding author: Institute for the Study of the Continents, Cornell University, Ithaca, New York 14853, USA

E-mail: mb44@cornell.edu

Ahmad Khaled Al-Maleh *is a Professor in the Geology Department at Damascus University, Syria. He has been Head of Geology Department, Damascus University, Head of the Division of Nuclear Ores Exploration with the Syrian Atomic Energy Commission, and General Director of the Syrian General Establishment of Geology and Mineral Resources. He has published widely in French, Arabic, and English, and is currently focusing on issues of the Mesozoic development of Syria, especially in relation to phosphate deposition.*

Tarif Sawaf *works for the Al-Furat Oil Company in Syria. He has a BS in Applied Geology from Damascus University. Previously he was a Senior Geologist and Associate Head of the regional mapping department of the Syrian Petroleum Company. Before that he worked for seven years with Sonatrach, Algeria.*

Manuscript Received February 19, 2001

Revised May 4, 2001

Accepted May 6, 2001