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Crustal Structure of Central Syria: The Intracontinental Palmyride Mountain Belt

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ABSTRACT

Along a 450 km transect across central Syria seismic reflection data, borehole information, potential field data and surface geologic mapping have been combined to examine the crustal structure of the northern Arabian platform beneath Syria. The transect is surrounded by the major plate boundaries of the Middle East, including the Dead Sea transform fault system along the Levantine margin to the west, the Bitlis suture and East Anatolian fault to the north, and the Zagros collisional belt to the northeast and east. Three main tectonic provinces of the northern Arabian platform in Syria are crossed by this transect from south to north: the Rutbah uplift, the Palmyra fold-thrust belt, and the Aleppo plateau. The Rutbah uplift in southern Syria is a broad, domal basement-cored structure with a thick Phanerozoic (mostly Paleozoic) cover of 6-7 km. Isopachs based on well and seismic reflection data indicate that this region was an early Paleozoic depocenter. The Palmyra fold-thrust belt, the northeastern arm of the Syrian Arc, is a northeast-southwest trending intracontinental mountain belt that acts as a mobile tectonic zone between the relatively stable Rutbah uplift to the south and the less stable Aleppo plateau to the north. Short wavelength en echelon folds characterized by relatively steep, faulted southeast flanks dominate in the southwest, most strongly deformed segment of the belt, while a complex system of deeply rooted faults and broad folds characterize the northeast region, described in this study. The Aleppo plateau lies immediately north of the Palmyride belt, with a combined Paleozoic and Mesozoic sedimentary section that averages 4-5 km in thickness. Although this region appears relatively undeformed on seismic reflection data when compared to Palmyride deformation, a system of near vertical, probable strike-slip faults crosscut the region in a dominantly northeasterly direction.

Gravity and magnetic modeling constrains the deep crustal structure along the transect. The crustal thickness is estimated to be approximately 38 km. Interpretation of the gravity data indicates two different crustal blocks beneath the Rutbah uplift and the Aleppo plateau, and the presence of a crustal-penetrating, high-density body beneath the northeast

Palmyrides. The two distinct crustal blocks suggest that they were accreted possibly along a suture zone and/or a major strike-slip fault zone located approximately in the present-day position of the Palmyrides. The age of the accretion is estimated to be Proterozoic or early Cambrian, based on the observation of a pervasive reflection (interpreted as the Middle Cambrian Burj limestone) in the Rutbah uplift and in the Aleppo plateau and by analogy with the well-mapped Proterozoic sutures of the Arabian shield to the south.

Introduction

This paper discusses a crustal scale cross section, located roughly parallel to but west of the Euphrates River (Figs. 1a, b), that provides a new comprehensive interpretation of crustal architecture and elucidates the structural and stratigraphic history of the northern Arabian platform beneath Syria. Major active tectonic systems outline the boundaries of the Arabian plate on its northern flank (Fig. 1a): the Dead Sea transform fault system along the Levantine margin to the west, the East Anatolian fault system and Bitlis suture to the north, and the Zagros suture and fold belt to the east and northeast. Each of these systems has contributed to the development of the tectonic framework of Syria.

The database for this transect includes detailed geologic maps (Ponikerov, 1966b), a composite seismic reflection profile compiled from nine industry seismic reflection lines provided by the Syrian Petroleum Company, well information from nine exploratory wells near the seismic lines, and Bouguer gravity (BEICIP, 1975) and aeromagnetic (Filatov and Krasnov, 1959) maps of Syria. The 450 km composite seismic profile draws information from an additional 1500 km of seismic reflection data distributed within a 100 km wide corridor along the transect. The seismic data generally span 4-5 seconds two-way travel-time, and most stacks are unmigrated. None of the seismic sections was available in digital format, so no further processing was possible. Data were collected by a number of companies over an approximately 10 year period, so their quality is variable, but, for the most part, they image well at least the shallow section to about 2-3 seconds (5-7 km), and in some cases provide good reflections to 5 seconds (about 15 km).

The goal of this study is to construct along the NW-SE transect a geological cross section from the surface to the base of the crust. The reflection data, well control, and magnetic data constrain the shallow sedimentary section and mid crust, whereas gravity data are modeled to estimate the nature of the deeper crust. Modeling results indicate a probable Proterozoic crustal accretion episode, possibly along a suture, in Syria, as well as the presence of a high-density and highly magnetized crustal-scale body beneath the northeastern block of the Palmyrides that could be associated with early Paleozoic extension, as is documented to the south in Saudi Arabia (Husseini,1989).

Tectonic Setting

The intracontinental Palmyride fold-thrust belt is the northeastern arm of the "S"-shaped Syrian Arc that includes the Negev folds in central Sinai. Shortening in the Palmyride belt has been minor, about 20-25 %, and has taken place intermittently along with the Negev folds since Late Cretaceous time, about 40 m.y. prior to the initiation of the main phase of left slip along the Dead Sea fault system that bisects the Syrian Arc (Chaimov et al., 1990). The evolution of the Palmyrides has been influenced by the surrounding Arabian plate boundaries, including the Red Sea and Dead Sea fault system on the west, the Bitlis suture zone and left-lateral East Anatolian fault to the north, and the Zagros suture zone to the east. Specifically, it appears that uplift in the Palmyrides can be attributed to stresses transmitted from the northern Arabian plate boundary into the interior of the Arabian platform (Chaimov et al., 1991).

With an abundance of surface and subsurface geological information, the Palmyrides provide a special opportunity to study the nature of intracontinental deformation. Best et al. (1990) modeled the Bouguer gravity signature of Syria to resolve the deep crustal structure beneath Syria, and McBride et al. (1990), Chaimov et al. (1990) and Al-Saad et al. (1991) have described the shallow structure of the region. This study integrates all available data and known studies to describe the regional structure of the northern Arabian platform from surface to the Moho. However, among the outstanding unresolved questions for future investigations are those concerning (1) the relation between the Palmyrides and the similar Sinjar trough to the northeast across the Euphrates depression in eastern Syria and western Iraq, (2) the nature and amount of strike-slip displacements in the northern Arabian platform and adjacent regions, (3) the nature of crustal thickening (ductile vs. brittle) beneath intraplate mountain belts, and (4) the exact mechanism of transmitting stresses from the plate boundary to the plate interior, whether by mid- or deep-crustal or shallower detachments.

Stratigraphy and structure of the Rutbah uplift

The Rutbah uplift is a broad, basement-cored dome located in central southern Syria near the Jordan-Iraq border (Fig. 1b) manifest in the thick Paleozoic and thin overlying Mesozoic sedimentary section (6-7 km total). Paleozoic rocks there are an interbedded sand/shale sequence, deposited in a near shore to shallow marine environment. Isopachs from exploratory wells indicate that the Rutbah uplift region was a Paleozoic depocenter (Fig. 5) (Gvirtzman and Weissbrod, 1984; Lovelock 1984; Sawaf et al., 1988; Best, 1991). The Mesozoic section onlaps the northern flank of the uplift facing the Palmyride belt (at about 3.3 sec. in Fig. 2), indicating subsequent uplift relative to the Palmyride trough in the early Triassic (Best, 1991). Four prominent, subhorizontal regional reflections observed on seismic data in the Rutbah uplift represent major Paleozoic unconformities (McBride et al., 1990). These reflections dip gradually northward and disappear beneath the highly deformed Palmyride belt (Fig. 2). Seismic reflection data reveal thickened Mesozoic and Cenozoic sections to the east in the Euphrates depression (from 0.2-0.5 sec in Fig. 3).

The northeast sector of the Palmyra belt

The Palmyra fold-thrust belt, a northeast-southwest trending, intracontinental mountain belt (Powers et al., 1966; Bender, 1975), separates the Rutbah uplift to the south from the Aleppo plateau to the north (Fig. 1b). The Palmyrides attain a maximum height of 1,385 meters at their southwestern end near the Anti-Lebanon ranges in Lebanon and plunge to the northeast beneath the flat-lying Cenozoic sediments of the Euphrates valley. A system of broad folds and long, complex fault zones characterize the northeastern sector, whereas short wavelength, en echelon folds, typically with relatively steep, faulted southeast flanks dominate in the southwest portion of the belt (Ponikarov, 1966a, b, and 1967; Lovelock, 1984; McBride et al., 1990; Al-Saad et al., 1991; Chaimov et al., 1991). The southwestern and northeastern regions are separated by the Jhar fault, identified as a major E-W striking strike-slip fault of indeterminate displacement (Fig. 1b).

The northeastern sector of the Palmyrides, crossed by the transect, is divided into two structural blocks by a northwest trending system of folds and faults (arc-shaped in map view) identified as a strike-slip fault zone in outcrop and on seismic data (Figs. 1b and 3). A recent earthquake associated with these faults indicated right-lateral oblique reverse motion (Chaimov et al., 1990). Additionally, correlation of seismic sections across the fault system can be interpreted to yield a 5 km minimum estimate of right-lateral movement along the strike-slip fault zone (Fig. 4).

Cretaceous outcrop roughly coincides with the topographic relief of the Palmyride mountain belt. Around the perimeter of the Palmyrides, Paleogene section crops out, creating a rough symmetry to the belt outcrop pattern. Isopachs and well correlation diagrams in the Palmyrides and adjacent regions show that the sedimentary section in the Palmyrides comprises a thickened Mesozoic section associated with minor extension (Fig. 5). This "rift" environment was inverted to that of the present-day transpressive regime mainly during the Cenozoic, probably as a response to the Late Cretaceous to present collision between the Arabian and Eurasian plates (Chaimov et al., 1991), with the main component of uplift restricted to the Mio-Pliocene (Ponikarov, 1966b). Neogene to Recent movement completed the present structural framework of the belt (Horowitz, 1979; Murris, 1980; Lovelock, 1984; McBride et al., 1990). Minor recent seismicity indicates that the belt is still active.

The Palmyride belt is the northeastern arm of the Syrian Arc, a much larger S-shaped deformed belt that stretches from the Negev folds of central Sinai through the Palmyrides to their northeastern limit where they meet the Euphrates depression. Detailed seismic stratigraphic analysis indicates that the Palmyrides have been uplifted intermittently since Late Cretaceous time along with the Negev fold belt. Hence, the Syrian Arc clearly predates the Miocene Dead Sea fault system (Chaimov et al., 1991).

Stratigraphy and structure of the Aleppo plateau

The Aleppo Plateau of northwest Syria (Fig. 1b) is a broad, platform-like region similar to the Rutbah uplift in its absence of substantial internal deformation. However, the sedimentary section in the region is composed of Paleozoic, Mesozoic and Cenozoic rocks, unlike the predominantly Paleozoic section in the Rutbah uplift. Seismic profiles from these two regions reveal a thicker Paleozoic section in the Rutbah uplift than in the Aleppo plateau, but thicker Mesozoic in the Aleppo plateau than in the Rutbah uplift (Fig. 5). Thus, the differences in sedimentary thicknesses between the two relatively stable blocks indicate large-scale differential uplift through time. Additionally, several northeast-southwest trending probable strike-slip fault zones apparent on seismic reflection data only from the Aleppo plateau (Fig. 6) are evidence of subtle differences in internal structure between the Aleppo plateau and Rutbah uplift.

Geophysical Database

Seismic reflection data

The seismic reflection data used in the transect sample numerous seismic surveys acquired by different companies for hydrocarbon exploration from 1972 through 1980. Thus, variations exist in acquisition parameters and processing routines; however, most of the seismic sections have four to five second record lengths (two-way travel time). Data acquisition and/or processing problems were commonly encountered over unusually rugged terrain and over faulted exposures of resistant Cretaceous carbonate rocks that, moreover, are often karstic. This indicates that vibroseis source coupling and signal penetration may have been a problem when collecting seismic data on exposed carbonate surfaces.

Seismic reflection character in the predominantly carbonate Mesozoic and Cenozoic sedimentary sections is more coherent and continuous than in the mainly clastic Paleozoic section. Coherent reflections are recorded from the Mesozoic and Cenozoic sedimentary succession from near the surface to approximately 2.0 sec. The Paleozoic section, in general below about 2.0 sec. (~5 km), is less reflective, with the most continuous reflections associated with unconformities in the Carboniferous, Silurian, Upper Ordovician and Lower Ordovician in the Aleppo and Rutbah uplifts (Figs. 2, 3, and 6). Whereas Mesozoic and Cenozoic rocks are mainly limestone with minor interbedded dolomite and evaporites, the lithology of the Paleozoic section is predominantly sandstone and shale interbedded and deposited in a near shore to shallow marine environment. Beneath the Palmyride belt the Paleozoic section is not well imaged. This may be due to the combination of low acoustic impedance contrasts in the Paleozoic sand/shale sequence and/or seismic signal distortion due to complex near surface structure in the mountain belt.

Gravity data and modeling

Gravity measurements were recorded over most of the Syrian Arab Republic in the form of 19 regional surveys acquired from 1948 to 1972 by Iraqi, Syrian and Soviet scientific groups, with different base stations used for each survey. The station density for the surveys varies from one point in 1.8 to one point in 4.0 . In order to combine the data from these surveys into a common format, the Bureau d'Etudes Industrielles et de Cooperation de l'Institut Francais du Petrole (BEICIP, 1975) was commissioned in 1975 to construct a smoothed Bouguer gravity map of Syria. Based on analysis of geophysical well logs and well cores, an average reduction density of 2.53 g/cm3 was used in the calculation of the Bouguer anomaly. Results from a refraction study to the south in Jordan (El-Isa et al., 1987) were used for an initial estimate of crustal thickness for the gravity models. The variation in the long wavelength components of the Bouguer gravity were then used to model variations in the thickness and/or density of the crustal section, an unresolvable ambiguity because of the lack of deep crustal information, such as regional seismic refraction data, in Syria.

The Bouguer gravity values along the transect range from -44 mGals to -10 mGals. Regionally, the Bouguer gravity signatures of the three tectonic provinces traversed by the transect can be characterized as follows: the Rutbah uplift is characterized by Bouguer gravity values ranging from -44 to -30 mGals; the northeast Palmyra belt has slightly higher gravity values at -30 to -10 mGals; and the Aleppo plateau has gravity values ranging from -20 to -10 mGals (see Fig. 7).

Gravity models for the transect were constructed using the U.S. Geological Survey two-dimensional Hypermag program (Saltus and Blakely, 1983), which is based on the gravity equations of Grant and West (1965). The program is a 2-D and 2.5-D interactive modeling package that calculates a gravity profile along a user specified crustal model composed of polygonal bodies with relative density contrasts. The viability of the model is based on comparison between the computed model gravity values and the observed gravity profile along the transect. Many different models were constructed, and the proposed model (Fig. 7) offers the advantage of simplicity in structure and an associated synthetic gravity anomaly that fits the data closely. The detail in the shallow part of the gravity model is well-constrained by structural interpretations based mainly on seismic reflection profiles. Interpretation of the gravity data indicates the following: (1) two distinct crustal blocks marked by a northward increasing gravity gradient, (2) the presence of a crustal-penetrating, high-density body beneath the northeastern Palmyrides, and (3) possible Precambrian sediments represented by a relatively negative anomaly that trends subparallel to the northeastern Palmyrides.

The two distinct crustal blocks suggest a possible suture zone and/or a major strike-slip fault zone of Proterozoic or early Cambrian age located along the present-day site of the Palmyrides. A prominent deep (~3 sec.) reflection correlated with the Middle Cambrian Burj limestone is observed in both the Aleppo plateau and in the Rutbah uplift. For this pervasive Burj limestone to have been deposited regionally, the Rutbah uplift and Aleppo plateau must have been joined prior to the Middle Cambrian, hence a Lower Cambrian or, by analogy with the Proterozoic sutures of the Arabian shield to the south (e.g., Johnson et al., 1987), a Proterozoic time of accretion is inferred (Best et al., 1990). The hypothesized suture or fault zone may have acted as a long-lived zone of weakness along which early Mesozoic rifting and subsequent Cenozoic inversion of the Palmyrides occurred. The high-density crustal body may be an intrusive complex associated with rifting. The obvious association would be with Mesozoic Palmyride rifting, however, the bulls-eye anomaly in the northeast Palmyrides appears to be part of a trend of nearly circular Bouguer anomalies, here referred to as the Rmah trend, that diverge from the mountain belt toward the southwest. The Rmah trend may be associated with an earlier Cambrian rifting phase (Best et al., 1990) recognized to the south in Saudi Arabia and Jordan (Husseini, 1988), or alternatively with the Precambrian rifting in northern Egypt and the Sinai peninsula (Stern, 1985) that is truncated by the Najd fault system. The northern Arabian platform beneath Syria may record an early tectonic history similar to that recorded in the exposed Arabian shield to the south, marked by Proterozoic convergence and early Paleozoic rifting.

Magnetic data and modeling

An aeromagnetic survey of Syria was carried out during 1957-58 by a Soviet scientific group (Filatov and Krasnov, 1959). Flight lines were oriented across strike of the major geological structures of Syria. The survey routes were flown at an altitude of only 200 meters.

Magnetic modeling of the observed total magnetic intensity along the transect was carried out using the U.S. Geological Survey 2-D Hypermag Program (Saltus and Blakely, 1983). Much like the Hypermag gravity modeling program, the magnetics program, based on the equations of Grant and West (1965), accepts a user-specified crustal model composed of polygonal bodies with different relative magnetization (susceptibility). Many models were constructed and tested to determine the best fit between the calculated and observed anomalies along the transect. The preferred model fits the observed magnetic data relatively well (Fig. 8), but has limited geologic significance. Seismic reflection data provide a much more useful medium for interpretation of the shallow crustal structure. While the magnetic model elucidates little about the geology along the transect, qualitative interpretation of the magnetic signature across the whole of Syria (e.g., Filatov and Krasnov, 1959) yields the following: (1) A relatively quiet magnetic field of low intensity associated with the northern slope of the Arabian platform and the Rutbah uplift is consistent with the observed thick sedimentary cover on top of crystalline basement. (2) A positive circular magnetic anomaly correlates with a high density body (probably an intrusive body) beneath the northeastern part of the Palmyrides (see Figs. 7 and 8). (3) Other small circular anomalies correlate with shallow (a few km) regions of disruption on the seismic data and may represent smaller intrusions. (4) A positive anomaly in the northeastern Aleppo plateau at the foot of the Kurd Dagh mountains is probably associated with ferrous deposits northwest of the city of Aleppo (see Fig. 8).

Summary

An interpretive northwest-southeast crustal cross section across Syria is shown in Figure 9. The various structural levels of the cross-section were constrained by different data sets. The shallow section of the model was constrained by over 2000 km of seismic reflection data in a 100 km wide corridor along the NW-SE transect through Syria. These sections were interpreted and correlated with nine deep exploratory wells (all >2.5 km) within that corridor (Figs. 1b and 5). Basement and the deep crustal variations in the final cross section are based primarily on gravity modeling and refraction data from Jordan, whereas the shallow section is based mainly on the seismic and well data.

The crustal cross section across Syria documents several stages in the evolution of the northern Arabian platform, summarized as follows (Figs. 9 and 10):

1) The Aleppo plateau may represent a distinct crustal block that accreted to the Rutbah uplift (the Arabian plate proper) along a Proterozoic suture zone and/or a major strike-slip fault zone that became the site of subsequent Mesozoic rifting and Cenozoic inversion of the Palmyrides.

2) A crustal-penetrating, high-density body is present beneath the northeastern block of the Palmyrides and may represent an intrusive complex associated with Early Paleozoic rifting.

3) Mesozoic rifting of the Palmyrides resulted in deposition of a thickened Mesozoic sedimentary section between the Aleppo plateau and the Rutbah uplift.

4) Inversion of the Mesozoic basin since early Cenozoic time has spawned both thrust and strike-slip faulting, and has reactivated older faults in the Palmyrides. The inversion process is still active today.

5) Strike-slip faults of indeterminate slip are present in the relatively stable Aleppo plateau and are not as prevalent in the more stable Rutbah uplift.

The late Permian-early Mesozoic rifting in the Palmyrides accompanied opening of the Eastern Mediterranean basin, from the western desert of Egypt to southern Turkey and northern Iraq (Abu-Jaber et al., 1989; May, 1991), to the development of the Levantine margin. The Mesozoic Palmyride depression may have formed as an aulacogen (e.g., Ponikarov et al, 1967; O'Keefe and Sengör, 1988; McBride et al., 1990), accumulating approximately 5 km of Mesozoic and Cenozoic carbonates. Inversion of the Palmyrides was probably effected by the late Cretaceous and early Tertiary Alpine collision between the Arabian and Anatolian plates. Multiple episodes of Cenozoic onlap and angular unconformities, which indicate recurrent episodes of inversion, were recorded in the Al-Daww depression of Syria (Chaimov et al., 1991; Ponikerov, 1967) and in the western desert of Egypt (Regan et al., 1986), indicating intermittent periods of ongoing uplift and quiescence.

Conclusions

This study proposes that the Precambrian-Early Cambrian crustal construction of the northern Arabian platform beneath Syria was similar to the crustal mosaic framework recognized in the Arabian shield along the eastern margin of the Red Sea, especially in Saudi Arabia (e.g., Johnson et al., 1987; Husseini, 1989), with Proterozoic accretion and Paleozoic rifting represented in both regions. The similarity between the northern Arabian platform and the Arabian shield ended in the Mesozoic with the development of the Levantine margin to the west of Syria and the development of an associated sedimentary trough, or rift, along the location of the postulated Proterozoic suture zone in central Syria. Late Mesozoic and Cenozoic northward convergence of the Arabian plate relative to the Eurasian plate (e.g., Nur and Ben-Avraham, 1978; Sengör et al., 1985) signaled the onset of the inversion and transpression that continues today in the Palmyrides.

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Figures and Captions

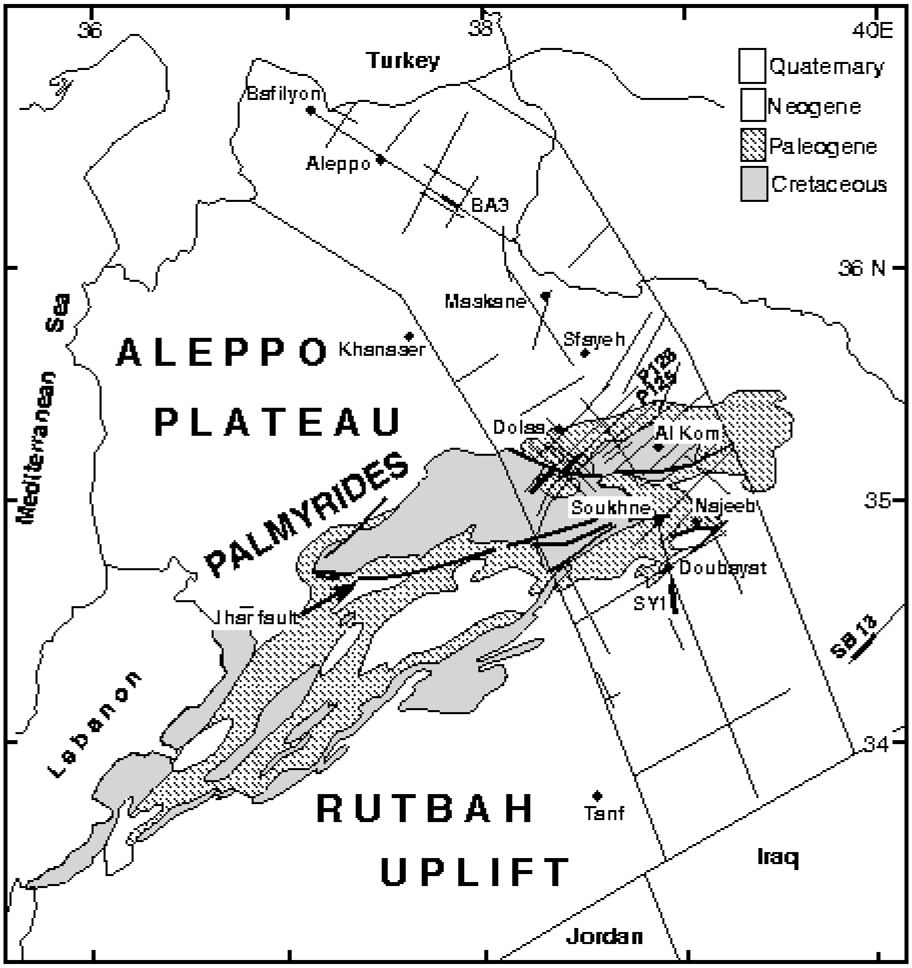

Fig. 1. a) Generalized tectonic map of the Arabian Platform and surrounding regions. DSF=Dead Sea transform fault system. **b)** Map showing the western part of Syria including generalized geology of the Palmyride fold belt and location of the central Syria transect that is the subject of this paper. Circles represent wells used for correlation with seismic reflection profiles (narrow lines).

Fig. 2. Portion of seismic line SY-1 showing the boundary between the Rutbah uplift and the Palmyra mountain belt. See Fig. 1b for location. "A" represents the base of the Cretaceous, "B/C" the unconformity that marks the top of the Ordovician, and "D" the Infracambrian Burj limestone. Note how the Paleozoic reflections, especially "D," weaken and disappear beneath the first signs of Palmyride deformation.

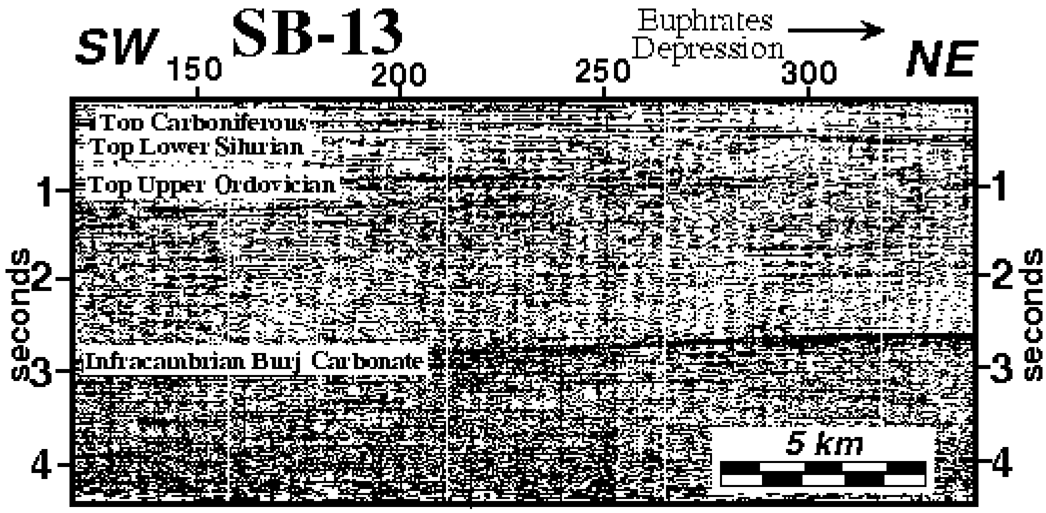

Fig. 3. Portion of seismic line SB 13 showing the thickening of Mesozoic and Cenozoic strata (upper 0.5 sec) in the direction of the Euphrates depression to the east and the onlap of Silurian and Upper Ordovician rocks onto the Lower Ordovician. See Fig. 1b for location.

Fig. 4. Portions of seismic lines P126 and P125 demonstrating the correlation across the northwest/southeast trending strike-slip fault after restoration of about 5 km of right-lateral motion. See Fig. 1b for location.

Fig. 5. Stratigraphic correlation of drill-holes along the transect highlighting the thickened Mesozoic section in the Palmyra mountain belt. See inset and Fig. 1b for location of drill holes.

Fig. 6. Portion of seismic line BA-3 on the Aleppo plateau showing a negative flower structure (transtension). See Fig. 1b for location.

Fig. 7. Best fit gravity model to the observed data along the transect, the shallow section of which is constrained by seismic reflection and well data. Density values are in g/cm3. Note that the density of the crust beneath the Aleppo plateau is higher than that beneath the Rutbah uplift (assuming constant thickness). Alternatively, the Aleppo plateau may be thinner than and of a similar density as the Rutbah uplift.

Fig. 8. Best fit magnetic model to the observed total intensity along the transect. Magnetic susceptibility units are in emu/cm3. Sensitivity of magnetic measurements does not permit interpretation below the mid-crustal level, here about 18 km. Geologic significance of bodies is limited relative to the more reliable gravity model of Fig. 7.

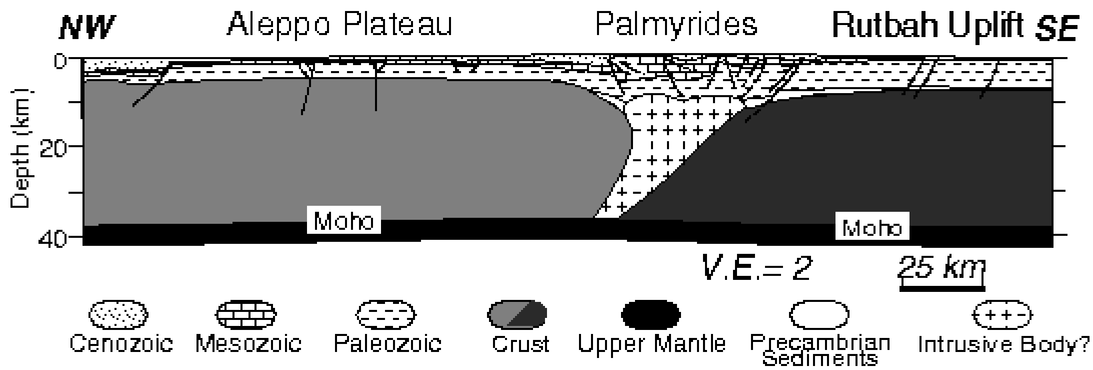

Fig. 9. Interpretive cross section to Moho (see Fig. 1b for location of transect). The high-density intrusive body may be associated with early Paleozoic extension. The nature of the difference between the Rutbah and Aleppo crusts is uncertain because of the ambiguity plateau is either thinner or denser than Rutbah crust.

Fig. 10. Schematic tectonic evolution of the Palmyrides and adjacent crustal blocks, with formation lithologies and regional facies variations.