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Upper crustal velocity structure and basement morphology beneath the intracontinental Palmyride fold-thrust belt and north Arabian platform in Syria

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SUMMARY

The intracontinental Palmyride fold-thrust belt, which is the site of an inverted Mesozoic rift, is sandwiched between two crustal blocks, the Aleppo plateau in the north and the Rutbah uplift in the south. The 400 x 100 km belt merges with the Dead Sea fault system in the southwest and gradually ends near the Euphrates depression in the northeast. Very dense (i.e., 100 m geophone spacing), reversed and multifold seismic refraction profiling was carried out to map approximately the upper 15 km of the crust in the early 1970s. These refraction data are utilized to model sedimentary rock thickness, seismic velocity, and basement morphology. Extensive data coverage also enables identification of the major faults of the region. A 2-D ray tracing technique is used in the modeling. Interpretation of these data indicates that five distinct velocity layers characterize the upper crust of the northern Arabian platform in Syria. The P-wave velocities within these layers are (in km s^{-1}): 2.0-2.8, 4.0-4.4, 5.2-5.3 , 5.5-5.7, corresponding to sedimentary rocks from Quaternary to late Precambrian in age, and 5.9-6.0, corresponding to metamorphic basement. A comparison of the velocity models with the available drill hole information and seismic reflection profiles shows strong velocity variations in a given geologic formation, depending on the depth and location of the formation. The depth to metamorphic basement beneath the Palmyride fold belt clearly shows a deep trough, filled with Phanerozoic sedimentary rocks. These rocks decrease in thickness from about 11 km in the southwest to about 9 km in the central segment of the belt. The basement depth is about 6 km in the Aleppo plateau and not less than 8 km in the Rutbah uplift. Deeper basement in the Rutbah uplift is probably the result of a Precambrian rifting episode, clearly identified to the south in Jordan and Saudi Arabia. Cenozoic crustal shortening of about 20-25% across the southwestern segment of the Palmyride belt has not been sufficient to substantially reduce the size of the basement trough beneath this mountain belt. Finally, northeast decreasing basement depth in the Palmyrides supports the idea that the Palmyride Mesozoic rifting was developed as an aulacogen of the rifted Levantine margin along the eastern Mediterranean.

Key words: Seismic refraction, P-wave velocity, basement morphology, Palmyride mountain belt, Arabian platform, Syria.

Abbreviated title: Velocity structure of north Arabian platform

INTRODUCTION

A seismic refraction survey was conducted in the northern Arabian platform in Syria, in 1972-73 by Syrian and Soviet scientists to investigate the upper part of the crust (<15 km). The seismic refraction experiment, similar to the Soviet Deep Seismic Sounding (DSS) experiments in design, collected data over 9 transects, seven of which are a few hundred kilometers long; the remaining two are less than 100 km long. The two shorter profiles, one in the Aleppo plateau and one in the southwestern Palmyrides, and a regional profile traversing Syria from Jordan to Turkey, have been available and form the refraction database for this study (Figures 1 and 2). The data are analyzed to obtain the upper crustal P-wave seismic velocities, basement morphology and sedimentary rock thickness in western Syria using 2-D ray tracing and recently obtained geologic information from previous studies. The first interpretation of the data was made by the Soviet scientists in 1974 using classical interpretation techniques of refraction data (Ouglanov, Tatlybayev & Nutrobkin, 1974). However, this interpretation did not benefit from modern computerized techniques and today's better understanding of the geologic evolution of the region. Our results differ substantially from those of the Soviet scientists especially in thicknesses of sedimentary layers and basement velocities throughout the region. The earlier interpretation, for example, shows basement velocities as high as 7 km s^{-1} and about 4-5 km thick sedimentary rock thickness in the Rutbah uplift. Our results, however, show that basement velocities do not exceed 6 km s^{-1} and the sedimentary column is thicker than 8 km in the central Rutbah uplift.

Many researchers have focused their attention on the major plate boundaries of the region, especially on the Dead Sea fault system and the Red Sea area. For example Quennell (1958) and Freund *et al.* (1970) discussed the Dead Sea rift system from a morphological and structural point of view, and tried to explain its geological history. Le Pichon & Francheteau (1978) and Hempton (1987) studied the opening of the Red Sea and its role in the plate tectonic evolution of the region. Intraplate structures have recently received attention. Beydoun (1981) and Lovelock (1984) discussed the stratigraphy and structure of Lebanon and the northern Arabian plate. Walley (1988) studied the strike-slip zone of the Dead Sea and its extension toward the interiors of the plate. More recently, subsurface data have become available, and seismic stratigraphy and gravity anomalies of the northern Arabian plate have been studied (Best *et al.* 1990, McBride *et al.* 1990, Chaimov *et al.* 1990,1992, and Al-Saad *et al.* 1992). These studies show that the complex and inter-related plate boundaries have profoundly affected the intraplate structures of the region (e.g., evolution of the Palmyride fold belt).

Two different views exist in the literature about the formation of the Palmyra fold-thrust belt. According to one view, the Palmyride belt was formed because of the restraining bend in the left-lateral Dead Sea transform fault (Walley, 1988; Lovelock, 1984, and Quennell, 1984). According to the other view, which is constrained by subsurface data, the fold-thrust belt predates the deformation along the Dead Sea fault, and was formed as a result of the collision between the Arabian and Eurasian plates (McBride *et al.* 1990, and Chaimov *et al.* 1990, 1992). Knowing the exact thickness of sedimentary rocks and metamorphic basement geometry in the Palmyrides and surrounding platforms will constrain the geologic history, and help in understanding the evolution of this intracontinental mountain belt.

Information about the geologic history of Syria is derived primarily from surface geology, exploratory wells and seismic reflection profiles. Since little pre-Cretaceous outcrop exists within Syria, exploratory wells and seismic lines play a crucial role in determining the geological history of the region. Subsurface data, however, are limited to early Paleozoic or younger lithologies. No wells penetrate into Precambrian basement, and the deepest seismic reflector that can provide some structural constraints on the older sedimentary rocks is the so-called "D reflector" (McBride *et al.* 1990), which is most probably the mid-Cambrian Burj limestone. Thus, determining the early Paleozoic and especiallyPrecambrian geologic history of the region is problematic. In this study we attempt to overcome this problem by determining upper crustal velocities and thicknesses of sedimentary layers, especially those of early Paleozoic and late Precambrian in age, as well as basement morphology throughout the region. Obtaining basement depth beneath an intracontinental mountain belt is a challenging task. To constrain our results, seismic reflection and well data acquired for hydrocarbon exploration in the region along with

Bouguer gravity and surface geology information will be integrated with the refraction data.

GEOLOGIC SETTING

The geology of Syria has been affected by movements along the nearby boundaries of the Arabian plate (Figure 1). Syria, located in the northwestern part of the Arabian plate includes the following major geological structures in its western segment: The Aleppo plateau in the north, the Rutbah uplift in the south, the intracontinental Palmyride fold and thrust belt sandwiched between these two blocks, a portion of the Dead Sea fault system in the west, marking the boundary between the Arabian and Levantine plates, and the Euphrates depression in the east (Figure 2).

The Aleppo plateau, a relatively stable platform, occupies the northern segment of the country. Although some strike-slip faults are identified, structural deformation is minor compared to the Palmyrides. The plateau is covered by Phanerozoic (mostly Paleozoic) sedimentary rocks. The Rutbah uplift, in the south, is identified as a Paleozoic depocenter. A thick Paleozoic sedimentary section is overlain by thin Mesozoic sedimentary rocks, predominantly Cretaceous in age. Onlapping of Mesozoic sedimentary rocks in the northern flank of the Rutbah uplift, close to the southern Palmyrides, indicates an early Mesozoic relative uplift of the Rutbah block (Al-Saad *et al.* 1992). The NE-SW oriented Palmyride fold belt, about 400 x 100 km in size is the site of an inverted Mesozoic rift. Chaimov *et al.* (1992) showed that termination of rifting was initiated in the late Cretaceous due to the collision of the Arabian plate with an island arc system or with the Anatolian plate. The belt is composed of small basins and uplifted blocks (Ponikarov, 1967). Deformation in the belt includes strike-slip faults and NE-SW striking fold-thrust structures. Approximately 20-25% crustal shortening is documented in the southwestern segment of the belt (Chaimov *et al.* 1990). The shortening gradually decreases towards the northeast and reaches only a few percent in the northeastern end of the belt. Proterozoic suturing beneath the Palmyrides was postulated by Best *et al.* (1990) based on gravity modeling, although it was not uniquely constrained. The Euphrates depression, controlled by strike-slip faults, developed during the transpression episode of the Palmyrides and shows minor inversion compared to the Palmyride fold belt (Sawaf *et al.* 1993). It has about 7 km of sedimentary cover.

Basement rocks are not exposed in Syria. A possible exception is in the northwest region near the Turkish border where amphibolic schists of pre-Cambrian (?) age are observed. However, metamorphic basement exposures are seen in the surrounding countries. To the south, in Jordan, basement rocks are exposed at the surface near the southern Dead Sea fault. A refraction survey in Jordan (El-Isa *et al.* 1987) revealed that basement rocks have P-wave velocities of 5.8-6.5 km s^{-1}, and their depths are 2-2.5 km in the north of Amman, and more than 5 km in central Jordan. In Turkey, to the north, basement is also exposed near the Bitlis suture. In Iraq, to the east, seismic and magnetic survey results showed that in the western desert of Iraq the metamorphic basement is 7-8 km deep, and it reaches 15 km in the Mesopotamian foredeep (Ismail, 1987).

DATA AND ANALYSIS

The locations of the three available seismic refraction profiles in the region are shown in Figure 2. The lengths of Profiles I, II and III are 92 km, 83 km, and 380 km, respectively. Data from 90 forward and reverse shots in these three profiles are analyzed. The shot receiver offset averages about 40 km, ranging from 25 km to 55 km. Geophone spacing for Profiles I and III is 100 m and for Profile II is 150 m. Overlapping forward and reverse shot points provide up to 8-fold data coverage in some regions (Figure 3a), which helps in obtaining reliable and unique velocity-depth models. Average charge size varied from 200 kg to 1000 kg in the Aleppo and Rutbah regions and was usually twice as large in the Palmyride region (Figure 3b), mainly because of a thicker and more deformed sedimentary section. Charge sizes were picked strictly from this graph within ± 20 -30 % tolerance limits (Ouglanov *et al.* 1974). Charge depths for these shots varied from 30 m to 50 m.

Interpretation was carried out using a 2-D ray tracing software developed by Luetgert (1988). Approximately 25,000 first arrivals of original, analog, photographic paper records were digitized and interpreted. First arrivals were generally easy to identify from the high quality original records (Figure 3c). At some occasions first arrivals were ambiguous due to faulting and/or lack of energy transmission. In those instances, however, the ambiguous first arrivals were usually followed by strong second arrivals (mainly wide-angle reflections). Instead of digitizing unclear first arrivals, we digitized clear and unambiguous second arrivals in order to avoid any possible misinterpretation of the data. An attempt to search and digitize all possible second arrivals on each record failed mainly because of the limited recording time on paper records following the first arrivals. Digitizing errors in arrival times are approximately 20 msec or less. A great deal of care was taken to use a single, and as simple as possible model to explain all the observations from different shot points and distances. Initial models were constrained by surface geology, nearby well logs and/or seismic reflection profiles, and forward modeling was conducted for a single shot until a good fit was obtained. The corresponding data for the reverse shot were then introduced to the model. After obtaining a good fit for both forward and reverse shots, other consecutive pairs of forward and reverse shots were incorporated into the model and necessary changes were made, always maintaining consistency with the previous shots. The models described in the next sections satisfy at least 80% of all of the observations within ±0.1 s. The velocity values were obtained within ± 0.1 km s^{-1} limits. Maximum error in the depth estimation is about 500 m for the deeper sections, based on the error estimates given above, and it is much less for the shallow sections. Because of the large number of shot points, it is not possible to show the calculated travel times and their fits to the observed travel times for all shot points. Instead, samples from the critical segments of the profiles such as across faults, particular uplifts etc., will be shown, and complete summary of velocity-depth models will be presented for each profile.

Profile I

Profile I is a 92 km long, NW-SE trending profile located in the Aleppo plateau. The profile traverses mostly Cenozoic sedimentary rocks, with only a small portion (~ 10 km) crossing on Cretaceous outcrop near the Khanasser-1 well (Figure 2). Data from twelve shots, six forward and six reverse, along this profile were analyzed. Shot point separation averaged about 9.2 km. Digitized first arrivals of the data with a 6 km s^{-1} reduction velocity are shown in Figure 4. Elevation over this region varies only slightly along the profile (< 100 m); hence topographic effects were ignored in this model.

The final velocity-depth model for this profile, obtained after considerable iteration, is shown in Figure 4. This model explains all the observations within ± 0.1 s limits. Up to 8-fold data coverage allows ray sampling of about 80 for a given 1x1 km^2 vertical area near the surface. Observed and calculated arrival times of the traced rays from shot points 1 and 6 are shown in Figure 5. In addition to refracted arrivals, wide-angle reflections, when available, are also modeled. The model has a three-layered sequence in the upper 1 km, with increasing velocities from 2.0 to 3.8 km s^{-1}, corresponding to Cenozoic and Cretaceous sedimentary rocks. This sequence, confirmed by the Khanasser-1 well, forms the first velocity layer in this model (Figure 4). Even though different surface geological units are traversed, no lateral velocity variation is observed. The boundary between this three-layered sequence and the underlying layer with a velocity of about 4.8 km s^{-1} corresponds to the Mesozoic-Paleozoic boundary as inferred from the Khanasser-1 well. Beneath this layer lies another sedimentary layer with a velocity of about 5.2 km s^{-1}, which corresponds to lower Paleozoic sedimentary rocks. The Khanasser-1 well bottoms at about 3800 m in the lower Cambrian. The refraction model indicates a velocity boundary at about 4000 m in this region. Approximately 1.7 km lies between the bottom of the well and the top of basement, amounting to a total sedimentary thickness of 5.5 km. The deepest sedimentary layer on top of the metamorphic basement has a velocity of 5.5 km s^{-1}, and is interpreted as early Paleozoic and late Precambrian sedimentary rocks equivalent or similar to those documented to the south in Jordan (e.g., Husseini 1989; Abed 1985). The last boundary on the refraction model, representing the sedimentary-metamorphic basement boundary, occurs at a depth of 5.5-6.0 km in this region (Figure 4). The basement velocity is about 5.9-6.0 km s^{-1}.

An offset in the velocity-depth model beneath the southeastern end of Profile I (Figure 4) is interpreted as a fault. Nearby seismic reflection profiles (Figure 6) and gravity trend and 2D modeling of the Bouguer gravity anomaly over this profile (Figures 7 and 8) confirm this interpretation. A clear gravity signature with more than 10 mgal variation from NW to SE marks the location of the fault zone on the Bouguer map (Figure 7). The gravity trend suggests that this zone may extend to the southwest following the northern boundary of the Homs depression (Figure 7). This fault probably developed as a splay - about 200 km long- off the Dead Sea fault system from about 100 km north of Lebanon. The seismic reflection profiles show near surface deformation suggesting that the fault experienced some recent (Quaternary) movement. No surface expression has yet been mapped for this structure, although satellite imagery shows a lineament with the same orientation of the proposed fault. The refraction data, due to low ray sampling over the fault, do not provide a unique solution to how deep this fault extends. However, gravity modeling requires that the fault penetrates into the metamorphic basement, and in the reflection sections the fault is traceable down to 3 s, suggesting that it is a crustal scale structure.

Profile II

Profile II is an 83 km long, NW-SE trending profile located in the southwestern segment of the Palmyrides, where the maximum shortening of 20-25% across the fold belt is observed.

The profile crosses various geological formations as well as the major faults of the mountain belt (Figure 2). Data from 16 shot points, 8 forward and 8 reverse, were modeled (Figure 9). A clear difference between the data sets of Profile I and Profile II can be seen. Arrival times in Profile II are usually 0.5 s later than those in Profile I and they are more varied and complex. This is mainly due to the structural deformation of the region. We accounted for the topography in our model for this profile, since significant variations (~ 400 m) are observed along the profile.

After modeling the arrival times of every shot point, the final velocity-depth model for this profile was obtained (Figure 9). The model includes the same five distinct velocity layers observed in Profile I with some lateral velocity variations. The major mapped faults of the region are also observed in the model. The Cheriffe-2 well located on this profile provides information down to about 3100 m where it bottomed in Triassic rocks. The first layer, with a velocity of about 2.0 km s^{-1}, represents young (Quaternary) and/or surface exposed sedimentary rocks. The second layer, with a velocity of about 2.6 to 3.6 km s^{-1}, corresponds to Cretaceous rocks. A much thicker underlying layer with a velocity of about 5.0 - 5.4 km s^{-1}, corresponds to lower Triassic and late Paleozoic sedimentary rocks, as indicated by the Cheriffe-2 well. The fourth layer, with a velocity of about 5.4 - 5.7, km s^{-1} , is probably composed of early Paleozoic and late Precambrian sedimentary rocks also identified in Profile I. The deepest layer is the metamorphic basement. Wide-angle reflections are crucial in identifying the basement along this profile, because these reflections, not the refractions, are usually the first arrivals seen on the records at long offsets in this region. A possible explanation for the missing or very weak refracted arrivals is that the severe deformation of the basement surface due to Cenozoic shortening may be scattering and diffracting the refracted rays. The wide-angle reflections, however, reflect off a small portion of the basement and are affected much less by basement morphology.

The deepest metamorphic basement is observed beneath this profile. An 11 km thick sedimentary column overlies the metamorphic basement in the severely deformed southwestern segment of the Palmyrides. Some sample ray tracings are shown in Figure 10. This very thick sedimentary column formed mainly in the Mesozoic as a result of the Palmyride rifting (Best *et al.* 1992). Approximately upper 6 km of sedimentary rocks in this region is composed of Mesozoic and Cenozoic strata (Best *et al.* 1992). The remaining part is a combination of Paleozoic and Precambrian sedimentary rocks. The minimum Bouguer gravity values in the region (-70 mgal) are also observed in the vicinity of the profile. Gravity modeling of Best *et al.* (1990), which does not show a major crustal thickening in this area, suggested a very thick sedimentary column beneath the Palmyrides, consistent with the present results. A basement uplift beneath the SE end of the profile (Figure 9) is probably the result of the shortening process. Since the uplift is poorly sampled, its shape remains unknown.

Profile III

Profile III is a 380 km long, N-S trending regional profile traversing Syria from Turkey in the north to Jordan in the south. It crosses three major structural units: The Aleppo plateau, Palmyride belt, and Rutbah uplift. Data from 62 different shots, 33 forward and 29 reverse, were analyzed. Shot point separation averages about 12 km along this profile. A section of missing receivers near the intersection of Profiles I and III, divides the profile into two segments. Shot points, however, exist in this section and help to fill the gap between the north and south sections of the profile.

Rays for each shot point were traced and a final model satisfying most of the observations within ±0.1 s limits was constructed. A portion of the model, where the transition from the Palmyrides to the Rutbah uplift occurs, is shown in Figure 11 along with the corresponding observations. The complete model is also shown in Figure 15 with the other models for a comparison. The model consists of the five characteristic layers that are also identified in Profiles I and II. A low 2.0-2.8 km s^{-1} velocity layer near the surface is underlain by sedimentary layers having velocities of about 4.4-4.5 km s^{-1}, 5.2-5.3 km s^{-}

^{1}, and 5.4-5.7 km s^{-1} , and basement with a velocity of about 6.0 km s^{-1}. Lateral velocity variations are obvious in the model, especially at locations where major faults are crossed. Considerable variations in basement morphology are observed along the profile. Each structural unit (Aleppo plateau, Palmyrides, and Rutbah uplift) displays its own characteristic sedimentary layer thickness and depth: An average basement depth of about 6 km in the Aleppo region, and 9-10 km in the Palmyrides. The Rutbah uplift also shows considerable variation in basement structure. In the northern portion of the Rutbah uplift, adjacent to the Palmyrides, a basement depth of about 6.5 km is obtained. Farther south the basement deepens steeply and becomes undetectable because of the absence of the 6 km s^{-1} basement identifying branch in the travel-time observations. This may be due either to decreasing basement velocities towards the south nearing that of the overlying layer or more probably to a steep increase in basement depth towards the south. Some examples of ray tracing are shown in Figure 12.

The Tanf-1 well, which is located near the southern end of the profile, helps in interpreting the upper section of the sedimentary rocks in the Rutbah uplift. At this locality, the upper layer in the model corresponds to sedimentary rocks from Neogene to Carboniferous in age. The second layer covers the Silurian and upper Ordovician sections. The well bottoms at 3365 m in the lower Ordovician section. A comparison of the refraction model with nearby reflection data (line MO-17) shows that the bottom of the third layer in the refraction model corresponds to the so-called "D reflector" (McBride *et al*. 1990), interpreted as the mid-Cambrian Burj limestone, which is the deepest reflector that can be clearly identified from the available seismic reflection sections. At least 2 km of sedimentary rocks lie between "D" and basement in the Rutbah uplift. In the northern segment, there is no available well information to constrain the refraction interpretation. A seismic reflection line (LA-8), however, is available and helps in interpreting this segment of the profile. The first two layers in the velocity-depth model correspond to Cenozoic and Mesozoic sedimentary rocks (Figure 13). The following two layers, bounded by prominent reflections, correspond to Paleozoic unconformities. Basement depth at this locality is identical to that of the "D reflector" as seen from Figure 13. This is due either to very thin or non-existent early Paleozoic and/or late Precambrian sedimentary rocks. In the south, however, in the Rutbah uplift, the "D" reflector is well above basement. These thicker sedimentary rocks in the south suggest that there was a rifting event and/or subsidence that took place before the middle Cambrian. The idea of a possible Precambrian or early Paleozoic rifting event in Jordan and Saudi Arabia has been suggested by several researchers (e.g., Husseini 1989; Abed 1985). Best *et al.* (1990) also mentioned the apparent effects of an Infracambrian rifting event on the gravity anomalies of Syria. Best *et al.* (1990) showed that a relatively thicker sedimentary section in the Rutbah uplift compared to the Aleppo plateau is required to explain the Bouguer gravity anomalies at about 100 km east of refraction Profile III. For these reasons, it is believed that the missing basement refractions in most of the Rutbah uplift are due to steep dip in basement morphology towards the south. Some of the reflection profiles in the Rutbah uplift also show layered reflections below the "D" reflector (McBride *et al.* 1990), possibly imaging the sedimentary layers associated with the Infracambrian rifting episode.

DISCUSSION

Very densely acquired refraction data, collected by the Syrian Petroleum Company and Soviet scientists in the early 70s, allowed detailed analysis of upper crustal velocities, thicknesses of sedimentary layers and basement morphology in the north Arabian platform in Syria. Multiple fold in data acquisition and dense geophone spacing (~100 m) form a unique database for accurate estimates of velocity structure on a scale similar to surface geology. Also, the velocity models obtained for Profile I and Profile III agree very well at their intersection, allowing us to correlate each velocity layer from one profile to the other. Very large charge size for all shot points enabled accurate and precise identification of first arrivals. Integration of available seismic reflection, Bouguer gravity, well log, and surface geology information with the refraction data allowed geological interpretation of the velocity-depth models.

The results of this investigation are summarized in Figure 15. There is no other direct estimate of the total sedimentary thickness in Syria with which we can compare our results. Most of the available information on the Cenozoic, Mesozoic and late Paleozoic sedimentary sections come from exploratory wells and seismic reflection profiles (Best *et al.* 1993). The deepest portion of the basement (~ 11 km) was observed in the intracontinental Palmyride fold-thrust belt beneath Profile II. A relatively deep (~ 9 km) section is also observed in the central Palmyrides beneath Profile III. These results suggest more pronounced extension in the southwestern segment of the Palmyride belt, which is consistent with gravity and geological observations. Relative vertical basement deformation of about 5 km beneath the Palmyrides gives us a minimum estimate of the degree of extension. Cenozoic shortening, however, may have partially inverted the original rift-related basement deformation. A basement uplift seen in the Profile-II model is possibly an example of the shortening effects. Presently, there still remains a considerable trough beneath this mountain belt.

Although we see about 5 km variation in basement morphology (from the Aleppo plateau to the Palmyride belt) resulting from Mesozoic rifting, there is no related volcanism at the surface. Some of the drill holes in the Palmyride region, however, penetrated volcanic flows mainly in the lower Cretaceous or upper Jurassic levels. Basaltic flows in the southern and northern segments of the Palmyrides (Ponikarov 1966) are Neogene and Quaternary in age, much younger than the rifting. There are inferred magmatic intrusions in the south of the Palmyrides identified in the Bouguer gravity and magnetic maps, referred to as the Rmah trend by Best *et al.* (1990). However, these intrusions are interpreted by Best *et al.* (1990) as a result of Infracambrian rifting. Under these observations one can speculate that rifting in the Palmyrides did not reach a mature level before Cenozoic shortening. The Palmyride trough may have developed as an aulacogen to the Mesozoic Levantine margin in the west as suggested by Beydoun (1981) and Lovelock (1984).

There is at least one exploratory well located on each profile (Figure 2). This gives us a unique opportunity to correlate refraction velocities with sonic logs and geologic formations. The refraction velocities are generally in good agreement with the sonic log velocities, even though the well logs indicate low velocity channels. As shown in Figure 14, considerable velocity variations are observed for each geologic formation depending on the depth and location of the formation. An increase in velocity values with depth rather than age is evident. For example, the shallower upper Paleozoic sedimentary rocks near the Tanf-1 well area have low velocities (2.8 km s^{-1}), and the deeper Triassic rocks near the Cheriffe-2 well have much higher velocities (~ 5.3 km s^{-1}). However, near-surface sedimentary rocks near the Khanasser-1 and Cheriffe-2 wells have similar velocities. The implication of these results is that velocity models obtained for the three profiles do not correspond to similar geological boundaries beneath these profiles. It appears that the depth of a formation in the sedimentary section in central Syria is considerably more important in determining velocity than variations in lithology and age. This may be due to the variations of porosity under different pressures.

CONCLUSIONS

Interpretation of the seismic refraction profiles indicates that sedimentary rock thickness in the northern Arabian platform in Syria varies from 5.5 km in the Aleppo plateau to 11 km in the Palmyride belt (Figure 15, 16). No significant variation in basement velocities of the Rutbah uplift and Aleppo plateau were observed. An average velocity of 6 km s^{-1} characterizes the metamorphic basement in western Syria. Beneath the Palmyrides, basement velocities are slightly higher (~ 6.5 km s^{-1}). Available refraction data are insufficient to map the basement structure in detail beneath the Rutbah uplift. Interpretation shows that the Rutbah uplift has a sedimentary thickness of about 6.5 km adjacent to the Palmyrides and no less than 8 km in the southern segment.

The existence of a potentially important, possibly strike-slip, fault in the Aleppo plateau is documented by the refraction data, and supported by seismic reflection and Bouguer gravity data. A comparison of the velocity models with well data shows that for a given geologic formation, P-wave velocities vary considerably with depth and location. This may be interpreted to be a result of porosity variations due to pressure effects. Structural deformation may also contribute to these variations. The obtained geometry of the Palmyride trough supports the idea that rifting in the Palmyrides developed as an aulacogen during the evolution of the Mesozoic Levantine margin along the eastern Mediterranean, forming a weakness zone which was later subjected to compression because of the collision of Arabian and Anatolian plates along the Bitlis suture in southern Turkey. The Cenozoic shortening of the Palmyrides slightly closed the Mesozoic Palmyride trough, and formed the fold-thrust belt. Despite the crustal shortening since the Mesozoic, a basement trough filled with 9-11 km thick Phanerozoic sedimentary rocks still remains beneath the intracontinental Palmyride fold belt, in contrast to the relatively shallow basement of the adjacent Rutbah uplift and Aleppo plateau.

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Figure Captions

Figure 1. Location of Syria relative to simplified tectonic units of the Arabian plate, modified from Beydoun (1991). The Dead Sea fault forms the northwest boundary, the Bitlis and Zagros sutures form the north and east boundaries, respectively, and the Red Sea, Gulf of Aden and Arabian Sea spreading centers form the west and south boundaries of the Arabian plate.

Figure 2. Locations of the seismic refraction and reflection profiles and well information relative to the major tectonic units of western and central Syria. The solid circle on seismic line LA-8 marks the location of the seismic section shown in Figure 13.

Figure 3. (a) Example of configuration of data acquisition technique. Overlapping forward and reverse shots enable detailed velocity-depth estimation. (b) Graph showing explosive charge size used during data collection (after Ouglanov et al. 1974), (c) Data sample from the Rutbah uplift showing the quality of first arrivals, which can easily be recognized and digitized.

Figure 4. Reduced travel times of first breaks and wide angle reflections (when available) for all shot points on Profile I. Arrival times from forward and reverse shots are shown as black and gray lines, respectively. Phase correlations were made on the analog records before digitization. In each shot record (forward or reverse) there are about 400 picks corresponding to arrival times of either first breaks or wide angle reflections. Shot points are numbered 1 through 6. Individual shot points are also marked on the ground level of the velocity model. The final velocity-depth section (in km s^{-1}) is shown at the bottom. Zero

level on the model corresponds to sea level. The location of the Khanasser-1 well (KH-1) is indicated on the model. **A** marks the location of an inferred fault on the refraction model.

Figure 5. Examples of ray tracings of reversed shot points 1 and 6 for Profile I. Small dots represent observed arrivals. Velocity values are in km s^{-1}. The crosses are calculated travel times of refracted rays; plusses are calculated travel times for wide-angle reflections. Only some selected rays are shown for each shot point as a comparison with observations. A major disturbance on the velocity layers near the southeastern end of the profile is interpreted as a fault.

Figure 6. Two seismic reflection profiles near refraction Profile I (see Figure 2 for location) showing a fault zone marked as B and C on HR-8 and HR-40, respectively. An interpreted line drawing is also shown for the region marked on the HR-8 section. The thicker lines depict the main fault plane. A clear disturbance of continuous reflections is observed on each side of the profiles. Near surface deformation suggests recent (Neogene or younger) movement along the fault plane.

Figure 7. A close up of the locations of refraction Profile I and reflection profiles HR-8 and HR-40, and also the Bouguer gravity anomalies (in mgals) of the region. The letters **A**,**B**,**C** mark the location of the fault on each profile. The dashed line represents the approximate location of the fault. Bouguer gravity signature is clear and suggests that the fault zone might be extending towards the southwest.

Figure 8. Bouguer gravity modeling over Profile I showing the effect of the proposed fault in the Aleppo plateau. The model is slightly modified version of the refraction model. Upper sedimentary rock densities are constrained by the Khanasser-1 well; the density of the metamorphic basement was adopted from Best *et al.* (1990). Since we are modeling

only the upper crustal section, i.e. no Moho modeling, a level adjustment on the calculated gravity values was applied, assuming a flat Moho beneath this profile.

Figure 9. Reduced travel times of first breaks and wide angle reflections (when available) for all shot points on Profile II. Arrival times from forward and reverse shots are shown as black and gray lines, respectively. Phase correlations were made on the analog records before digitization. In each shot record (forward or reverse) there are about 400 picks corresponding to arrival times of either first breaks or wide angle reflections. Shot points are numbered 1 through 8. Individual shot points are also marked on the ground level of the velocity model. The final velocity-depth section (in km s^{-1}) is shown at the bottom. Zero level on the model corresponds to sea level. The location of the Cheriffe-2 well (CH-2) is also marked on the profile.

Figure 10. Examples of ray tracings of some shot points on Profile II. Velocity values are in km s^{-1}. The small dots are the observed arrivals. The crosses are calculated travel times of refracted rays; plusses are calculated travel times for wide-angle reflections. Clearly identified wide-angle basement reflections constrain the depth to basement. Shallower basement depth in the SE is probably a result of Cenozoic crustal shortening. The data require about 2 km vertical uplift of basement rocks in the SW segment. They are, however, not sufficient to obtain the actual geometry of the transition zone from deep basement to relatively shallow basement.

Figure 11. Reduced travel times of first breaks and wide angle reflections (when available) for some shot points on Profile III at a location where transition from the Palmyrides to the Rutbah uplift occurs. Arrival times from forward and reverse shots are shown as black and gray lines, respectively. Phase correlations were done on the analog records before digitization. In each shot record (forward or reverse) there are about 400

picks corresponding to arrival times of either first breaks or wide angle reflections. Shot points in this range are numbered 1 through 9. Individual shot points are also marked on the ground level of the velocity model. The final velocity-depth section (in km s^{-1}) is shown at the bottom. Zero level on the model corresponds to sea level.

Figure 12. Examples of ray tracings of some shot points on Profile III. The small dots are the observed arrivals. The crosses are calculated travel times of refracted rays; plusses are calculated travel times for wide-angle reflections. Velocity values are in km s^{-1}. The apparent offset in the arrival times of the forward shot between 270 and 280 km can be explained with a lateral velocity variation in the second layer from about 4.7 to 5.1 km s^{-1} . The forward shot shows an apparent offset in the arrival times due to laterally decreasing velocities, while the reverse shot does not show a significant anomaly due to laterally increasing velocities with distance.

Figure 13. A comparison of the refraction model for a segment of Profile III with the LA-8 reflection profile (See Figure 2 for location). Calculated two-way reflection travel times obtained using the refraction model are compared to the LA-8 seismic reflection line. A very close correlation is observed between the calculated and the observed reflection times. "D" on the reflection profile marks the mid-Cambrian Burj limestone, which is a thin but very reflective layer. This is the only region where basement coincides with the "D" reflector, suggesting that in this region early Paleozoic or late Precambrian sedimentary rocks, which are observed farther to the south, are missing or very thin below the Burj limestone formation.

Figure 14. Correlation diagram of velocity models with nearby well information. Locations of the wells are shown in Figure 2. Sonic log velocities (shown in km s^{-1}) and refraction-derived velocities agree quite well, although the logs indicate some low velocity

channels. The correlation suggests that velocities vary with depth and location. Increasing depth causes the velocity to increase in a specific formation possibly due to pressure effects. It is quite clear that velocity models do not correlate with individual geologic formations. Same geologic formations can have different velocities depending on the depth and location.

Figure 15. Interpreted velocity models for all three refraction profiles. The thinnest sedimentary column is beneath Profile I in the Aleppo plateau, and the thickest sedimentary column is beneath Profile II in the southwestern segment of the Palmyride fold belt. Profile III shows the geometry of the central Palmyrides trough. The major faults are easily identified from the velocity models. In these models each velocity layer does not necessarily correspond to one specific geologic formation. Since formations have different velocities depending on the depth and location, they may have different geometries than these velocity layers.

Figure 16. A simplified map showing metamorphic basement depth in western Syria. The deepest basement is beneath the Palmyrides and the shallowest is beneath the Aleppo plateau. Depth values (bold numbers) are in kilometers.