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Tectonic evolution of the NE Palmyride mountain belt, Syria: the Bishri crustal block

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Abstract: Investigation of the Bishri block, centrally positioned amid the diverse tectonic and structural zones of Syria, reveals details of the intraplate Phanerozoic development of the northern Arabian platform. The Bishri block is a broad NE-plunging inverted basin located at the NE portion of the Palmyride mountain belt where the mountains intersect the Euphrates fault system. Well and seismic data show that subsidence and sedimentation in the Bishri area was generally continuous from Carboniferous to Paleocene time, with the Bishri block part of the extensive Palmyride–Sinjar trough. Major bounding faults and a rift-type environment are documented in the Permo-Triassic, Jurassic and Cretaceous. The present Bishri structural and topographic high has been formed through transpressive structural inversion since the Mid-Miocene; high-angle Mesozoic bounding normal faults now have net reverse offsets with a significant dextral strike-slip component. East of the Bishri block, towards the Euphrates fault system, NNW–SSE-striking normal faults exhibit less reverse movement. This deformation history correlates with the opening and closing of the nearby NeoTethys ocean that has driven the evolution of intracontinental Syria.

Keywords: Palmyride mountain belt, Syria, seismic methods, tectonics, sedimentary basins.

Syria is a well-documented region of long-lived and diverse intraplate deformation (e.g. Best *et al*. 1993; Brew *et al*. 2001; Sawaf *et al*. 2001). Herein, we interpret the geological evolution of an uplifted area in central Syria called the ‘Bishri block’, which forms the NE portion of the intracontinental Palmyride mountain belt (Fig. 1). Using extensive seismic reflection and well data we show that the Bishri block exhibits traits of tectonic development similar to both western and eastern Syria. The Bishri block subsided as part of the Palmyride trough of central and western Syria for most of the Late Palaeozoic and Mesozoic; during the Jurassic and Cretaceous the deposition appears to have been largely fault-bounded when the Bishri region resembled a typical rift. During the Late Cretaceous the area experienced rapid deposition linked to the nearby Euphrates rifting and basin formation in eastern Syria. Since the Mid-Miocene regional transpression has led to structural reactivation and the Bishri block has become a typical ‘positively’ inverted structure *senso stricto* (Williams *et al*. 1989).

These results give new insight into the development of intracontinental mountain belts, and especially the regional tectonics of the northern Arabian platform. For instance, whereas the early Mesozoic history of the Palmyride mountain belt was approximately similar along its length, the Cenozoic development of the belt in the NE (i.e. the Bishri block) is interpreted to be in strong contrast to that in the same mountain belt in the SW. Significant variations of style and timing of inversion along strike in the Palmyrides mountain belt are revealed and well documented, ranging from thin-skinned deformation in the SW to thick-skinned inversion in the Bishri area. Regionally, Bishri block extensional events are found to correlate with the opening of the NeoTethys and the eastern Mediterranean, whereas subsequent compressional episodes are contemporaneous with collisions of Arabia with Eurasia along the northern Arabian margin in Turkey and NW Iran. A staggered series of compression events within the northern Arabian platform is revealed, supporting the hypothesis of a progressive west–east final continent–continent collision between Arabia and Eurasia. We have incorporated these observations into models of Phanerozoic Arabian plate evolution. This shows a picture of long-living structural inheritance where tectonic activity is repeatedly focused in a small number of intraplate tectonized zones, such as the Palmyride mountain belt and the Euphrates fault system. The activity within these zones is controlled by nearby plate boundary events and, critically, the orientation of the tectonized zone with respect to prevailing far-field stresses.

Geological setting

The current plate tectonic setting of the northern Arabian platform places Syria close to Arabia–Eurasia continental collision, with active plate boundaries occurring to the west, north and east (Fig. 1, inset). These plate boundaries include the Zagros fold and thrust belt, the Bitlis suture, the North and East Anatolian faults, the Dead Sea fault system, and the Red Sea–Gulf of Aden spreading centres.

The Palmyride mountains stretch across central Syria from the Anti-Lebanon range in the SW to the Euphrates fault system in central Syria (Best *et al*. 1993) (Fig. 1). Beginning in the Carboniferous and continuing through the Mesozoic, subsidence and rifting occurred along a NE–SW-trending axis through central and NE Syria that now contains several kilometres of Upper Palaeozoic and Mesozoic rocks. The Late Cretaceous

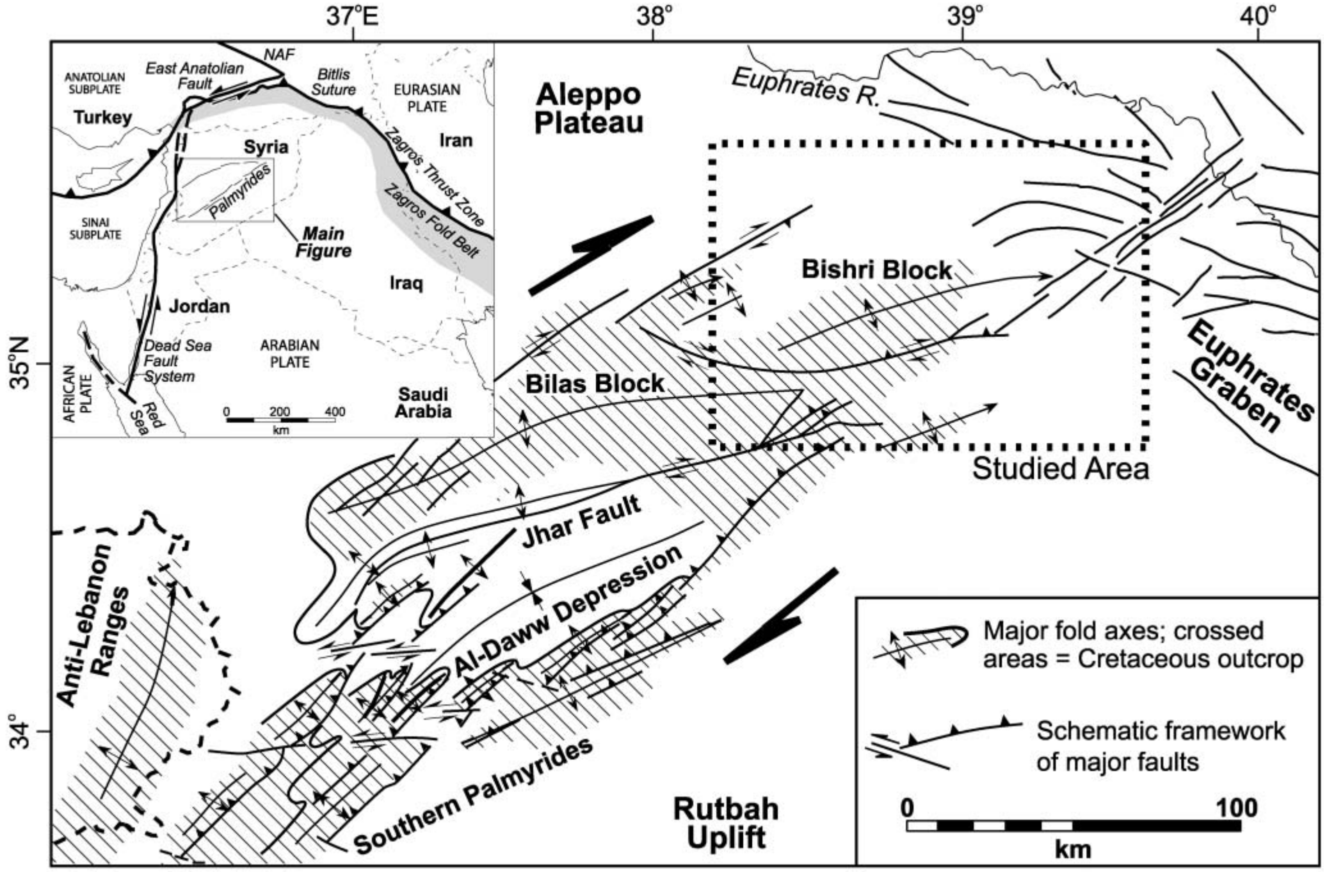

Fig. 1. Main figure shows schematic structure of the Palmyride mountain belt, including Mesozoic exposures (generally indicating higher topography), and major faults (modified from Sawaf *et al.* 2001). Dashed box indicates area studied in this paper. Inset map shows the regional setting of Syria within the northern Arabian platform. NAF, North Anatolian Fault.

Euphrates fault system decoupled western and eastern Syrian deformation, such that the Late Cretaceous and Cenozoic evolution of the Palmyrides is very distinct from the deformation in NE Syria (Brew *et al.* 1999). Minor inversion of the SW Palmyride rift initiated as early as the Late Cretaceous (Chaimov *et al.* 1992). Transpression accelerated during the Miocene contemporaneous with suturing of Arabia to Turkey and Iran and rifting in the Red Sea (Hempton 1987).

The Palmyride mountain belt can be divided into three structural domains: the southern Palmyride fold belt, the Bilas block and the Bishri block (Fig. 1). The southern Palmyrides is a series of narrow, en echelon, asymmetric folds with a SE vergence, cored by reverse faults with Cretaceous outcrops at their crest (Ponikarov 1966; Lovelock 1984; Chaimov *et al.* 1992). In some areas these faults sole out at depth along a Triassic evaporite detachment surface, although this is only locally developed (Chaimov *et al.* 1990). The Bilas and Bishri blocks are larger-wavelength anticlinoria with Cretaceous exposure, forming the central highlands in the NE segment of the mountain belt (Fig. 1). The term ‘Bishri block’ has been used in the geological literature at least since the work of Ponikarov (1966) to describe the easternmost province of the uplifted Palmyride mountains. The topographic expression of the Bishri block takes two forms: a NE-plunging anticlinorium (maximum elevation *c.* 800 m) and a structural saddle that connects to the Bilas block in the west (Fig. 2a). The Bishri and Bilas blocks are separated by a series of small ridges, which form an arcuate boundary along the SSW edge of the Bishri block (the South Bishri fault, Fig. 2a). The oldest outcrops in the Palmyrides are Lower Cretaceous strata exposed in the SW of the study area. The age of exposures decreases from Paleogene to Neogene along plunge to the NE, and away from the axis of the anticlinorium to the NW and SE.

Database and mapping

The primary data for this work were *c.* 2500 km of 2D seismic reflection profiles, and more than 110 exploration and field wells (Fig. 2a). The seismic data consist largely of 1980s post-stack migrated hardcopy data. All the wells penetrate Mesozoic strata, and 40 wells penetrate Palaeozoic strata. P-wave sonic velocity logs were available from 16 wells (locations shown in Fig. 2a), allowing for the generation of synthetic seismograms and providing direct sampling of rock properties.

From well data, ties to outcrop (Ponikarov 1966) and previous studies (e.g. Mouty 2000), we generalized a stratigraphic column that is representative of the Bishri area. In summary, predominantly clastic Palaeozoic rocks reflect open marine deposition. In the Mesozoic, and into the Paleocene, limestone and dolomite interbedded with shale, clay and anhydrite prevailed in a more restricted, shallow marine to lagoonal environment. The Mesozoic section contains several major unconformities, the most long-lived and widespread of which occurred in the Late Jurassic and Early Cretaceous, leading to an absence of Callovian to Barremian strata throughout central and eastern Syria (Mouty 2000). A shallowing of marine conditions is marked by an increased influx of clastic

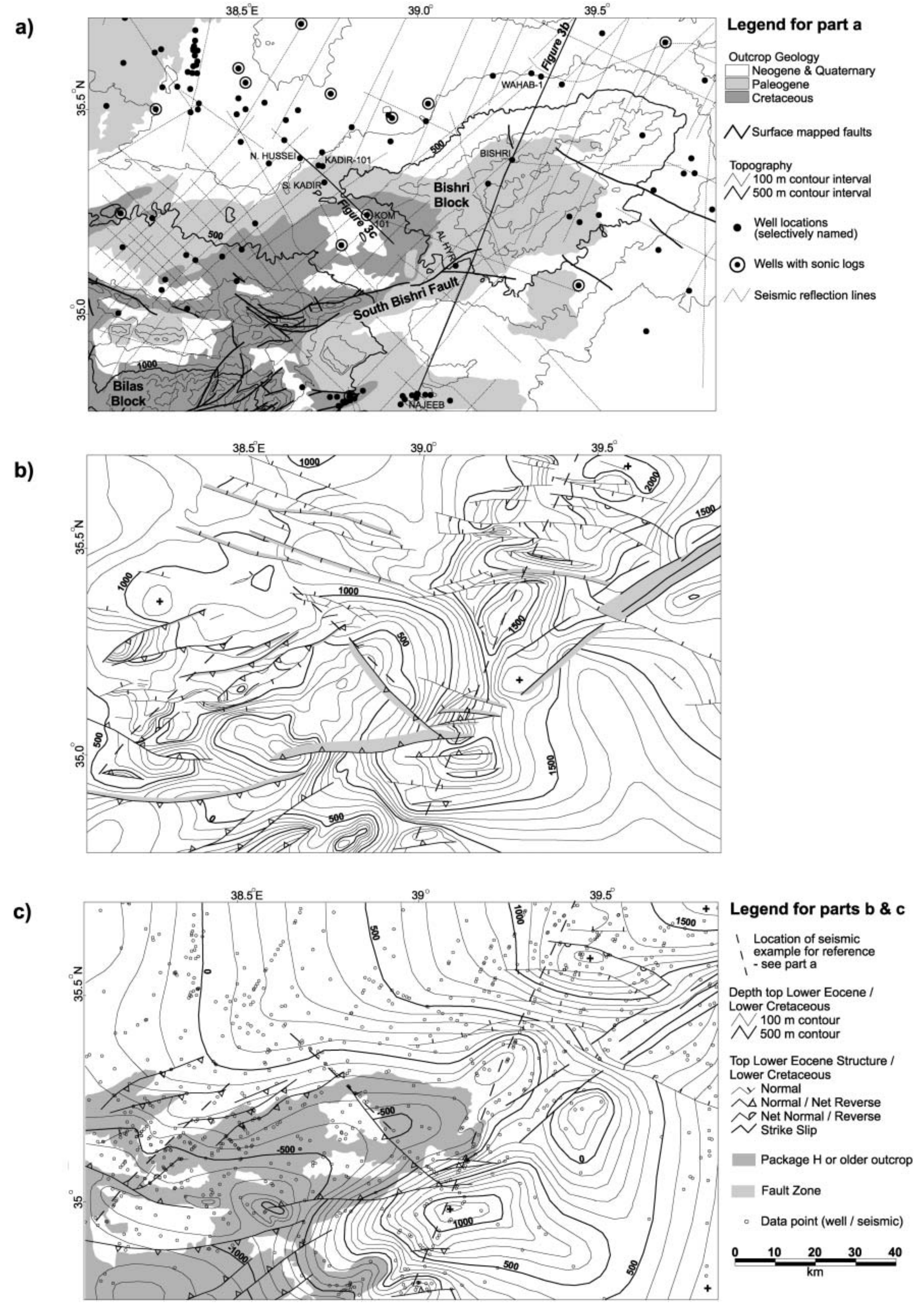

Fig. 2. (**a**) Map showing smoothed topography contours, simplified outcrop geology and faults, and seismic reflection profiles and well data, in the studied area (location is indicated in Fig. 1). Locations of seismic reflection examples used in this paper are marked (Fig. 3); named wells correspond to those shown in the seismic examples. (**b**) Depth structure map on the base Upper Cretaceous (package F). (**c**) Depth structure map on the base Middle Eocene (package H); or topographic surface in areas of older exposure. In (**b**) and (**c**) depth contours are shown in metres below sea level, and significant faults are shown with current sense of throw at the objective level. +, contour maxima; ○, locations of data points used in the construction of these maps.

material in the Eocene. In Neogene and Quaternary time a shift in depositional environment occurred, from shallow-water marine in the Early Miocene, Helvetian and Tortonian (sandstones, limestones, dolomites, gypsum and clay) to continental–lacustrine in the Late Miocene and Pliocene (conglomerate, sandstones and clays with minor gypsum).

For the purposes of interpretation, we divided the stratigraphic column into a series of 10 unconformity-bounded packages (labelled A–J), each with relatively homogeneous lithological and physical properties (Table 1). The horizons chosen for mapping on seismic sections were the tops of these 10 packages. In general, the Mesozoic and Cenozoic alternating carbonate–clastic formations are highly reflective and easily interpretable. In contrast, the overwhelmingly clastic Palaeozoic section is largely unreflective and seismic reflection interpretation of Palaeozoic horizons is highly speculative in many areas. Few faults are shown on the geological maps (scale 1:200 000, Ponikarov 1966). However, numerous faults are imaged by the seismic reflection data throughout the region. Imaging around these faults is often poor owing to difficult surface conditions (steep topography and carbonate outcrop) and lateral velocity variations.

Seismic interpretation began with the generation of synthetic seismograms and subsequent ties to seismic data. From the sonic logs, typical seismic velocities for each of the interpreted packages were established (Table 1), and used to tie-in the wells lacking in sonic data. Minor residual adjustments to the wells lacking velocity information were made based on reflection travel-times to prominent marker horizons, in particular the base Upper Cretaceous (package F). Typically, these residual corrections were small (<100 ms), attesting to the lateral homogeneity of velocities within localized areas. Strong lateral velocity variations were observed within some of the packages, predominantly between areas with distinctly different tectonic histories. The final smoothed velocity model was used for the depth conversion of the interpreted time-sections.

After mapping the chosen horizons throughout the study area, we constructed selected isopachs and structure maps. Based on their significance to the development of the Bishri block, two detailed structure maps are presented. The first (Fig. 2b) is the base Upper Cretaceous (package F), and the second (Fig. 2c) is near the base Middle Eocene (package H).

Structure of the Bishri block

The structure maps (Fig. 2b and c) reveal that the majority of subsurface faults strike between east–west and NE–SW. A secondary trend (WNW–ESE) is also observed in the east of the study area. Faults are interpreted with strike-slip, normal and reverse sense of offset on seismic reflection profiles; many faults show a changing sense of motion with time. A large number of faults cut the Lower Cretaceous horizon (Fig. 2b). Whereas most of these faults were initially normal (based on observations of synextensional deposition), subsequent compression has reactivated them in a reverse sense. Thus many exhibit a net sense of reverse displacement at the base Upper Cretaceous level (designated normal/net reverse in the legend); for example, faults near Al Hyr well in Figure 3b. The Cenozoic section, although cut by relatively few faults (Fig. 2c), has been strongly affected by compression and shows many anticlinal structures developed above deeper reverse faults (e.g. Fig. 3c beneath the Kadir 101 well). Such folding is typical of positive structural inversion (Mitra 1993). The vast majority of faults throughout the Bishri area are interpreted to be steep and deeply penetrating. The high angle of these and other faults in the study area (generally >70°) results in very minor shortening associated with the compressional reactivation (Fig. 4). This is in marked contrast to the southern Palmyrides, where a locally developed Triassic detachment surface is interpreted (Chaimov *et al*. 1990). Furthermore, total shortening in the NE Palmyrides, where deformation is thick-skinned (Best 1991), is significantly less than in the southern Palmyrides (Chaimov *et al*. 1990). These observations illustrate the strong variations in structural style along strike in the Palmyride mountain belt.

We now consider in detail the trends and expressions of faults in and around the Bishri block. The most prominent faults in the subsurface are along the south and SW boundary of the Bishri block. These correspond to an arcuate surface trend of en echelon faults (the South Bishri fault, Fig. 2a) exposing Campanian strata. This fault trend has characteristics of strike-slip faults on reflection profiles, appearing as positive ‘flower structures’, with opposite dips on either side of the faults in the deeper section (Fig. 3b). These faults currently exhibit net reverse motion at all structural levels with subtle hints of older normal activity; for instance, a slight thickening of Jurassic and Upper Triassic strata into the fault seen in Figure 3c and in nearby wells. Thus, we interpret these faults as originally Mesozoic normal faults that were later reactivated in a strike-slip and reverse sense in a Late Cenozoic transpressive regime.

This main trend of faults is continuous around the southern margin of the Bishri block and towards the NE, whereupon the faults strike SW–NE and exhibit much clearer strike-slip characteristics, with little apparent reverse offset. The different align-

Table 1. *The stratigraphic column has been divided into 10 ‘packages’ for the purposes of this interpretation; strata older than Carboniferous are not considered*

Interpretation package	Age	Generalized lithology	Maximum thickness[1] (m)	Seismic velocity[2] (km s^{-1})
J	Neogene and Quaternary	Limestones, anhydrite topped by sandstone and conglomerate	1280	2.1–3.4
I	Late Paleocene	(Marly) limestone	1030	2.5–3.8
H	Latest Cretaceous and Early Paleocene	Marls, shale, limestone	2240	2.3–3.8
G	Late Cretaceous	Marl, shale, limestone, dolomite	1280	3.8–5.0
F	Early Cretaceous	Sandstone, minor basalt	650	3.5–4.5
E	Jurassic	Dolomite and limestone	1080	5.3–5.5
D	Latest Triassic	Dolomite with shale	510	4.5–5.1
C	Late Triassic	Dolomite with shale	320	5.2–5.8
B	Mid-Triassic	Dolomite, shale, anhydrite	1370	5.9–6.5
A	Carbo-Permo-Triassic	Sandstone, shale, some limestone	2390	4.0–4.2

[a] Maximum thickness in well data.

[b] Range of typical seismic velocities within studied area.

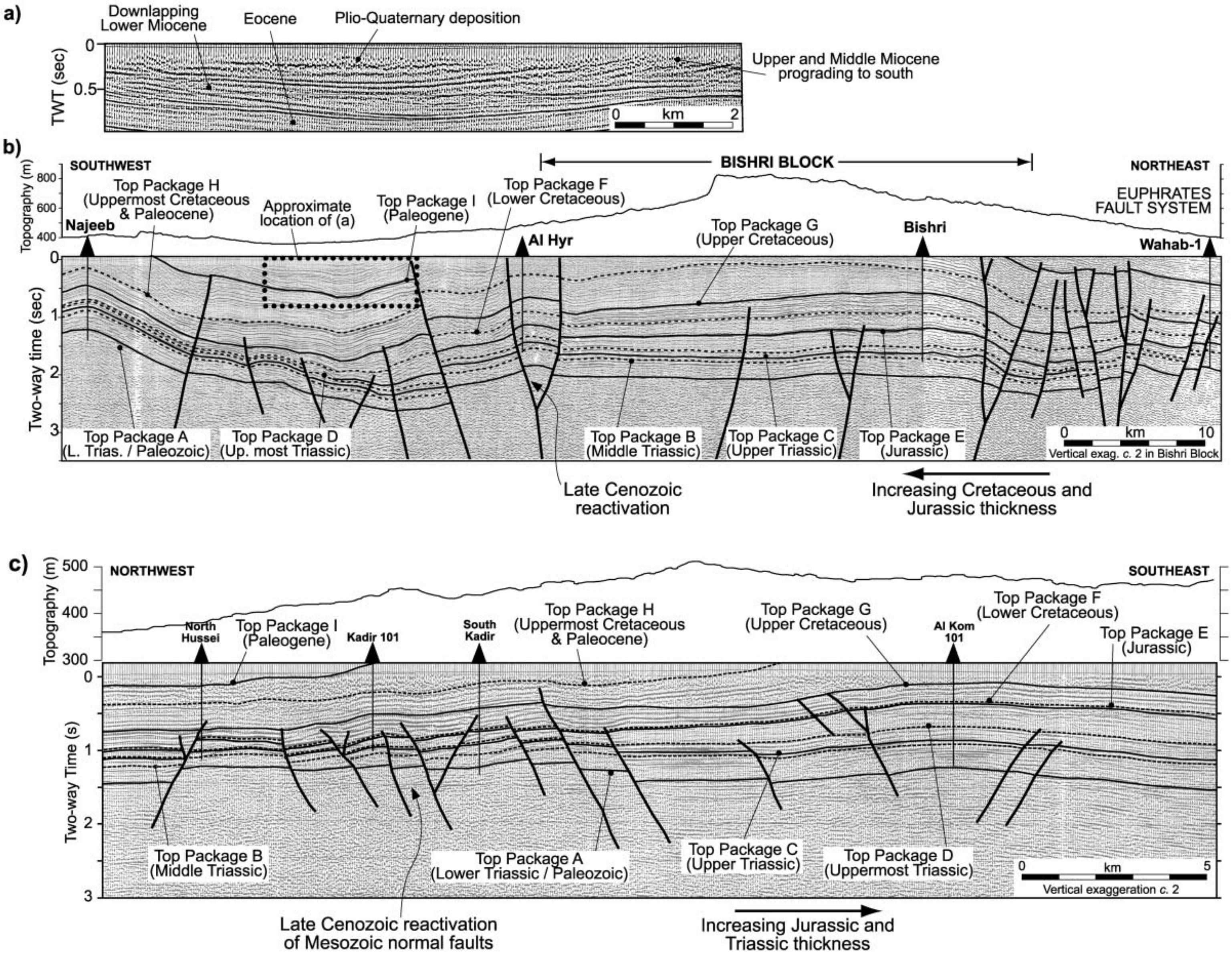

Fig. 3. (**a**) Small portion of seismic line P106EXT showing stratigraphic relationships in the Cenozoic section; position shown in (**b**). (**b**) Composite cross-section showing seismic reflection example from SW to NE across the Bishri structure (seismic profiles ALAN 90-10 and AB-2052). Location is shown in Figure 2a. The loss of reflections across major structural zones, mainly because of poor surface conditions, should be noted. The faults near the Al Hyr well are the subsurface expression of the South Bishri fault. Limited throw on some faults is difficult to illustrate at this scale. (**c**) Cross-section showing seismic reflection example from the central northern margin of the Bishri block (seismic profile P-228). Location is shown in Figure 2a. Both extensional and compressional deformation distributed over several faults should be noted.

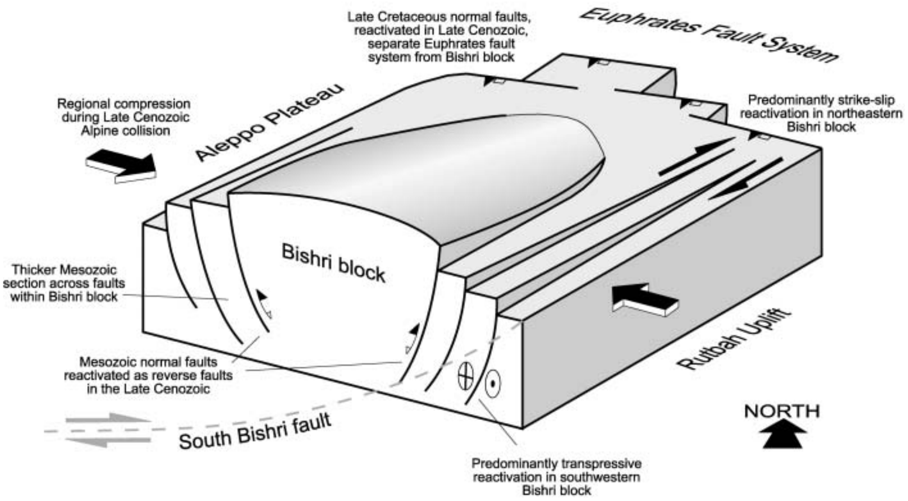

Fig. 4. Highly schematic block diagram illustrating the present structural arrangement of the Bishri block, as viewed from the SW.

ment of these faults with respect to regional compression during the Cenozoic probably caused their largely translational, rather than transpressional, reactivation (Fig. 4). This interpretation is supported by a study of earthquake focal mechanisms from events on or near these faults that confirms the present-day dextral transpressive regime around the Bishri block (Chaimov *et al*. 1990).

Also in the NE of the study area are predominantly NNW–SSE-striking faults (Fig. 2b and c) that again show older normal movement and more recent structural inversion. Of this type, those nearer the Bishri area accommodate sedimentary thickness changes of Cretaceous and Jurassic strata (see thickness changes between Wahab-1 and Bishri wells in Fig. 3b). Near the Bishri block these faults show very clear Cenozoic structural reactivation in a reverse sense (Figs 2c and 3b), thus accommodating much of the present uplift within the Bishri block. Farther east and north, away from the Bishri block, the faults exhibit less Cenozoic deformation (Fig. 3b) and generally show very limited Mesozoic activity except in the latest Cretaceous (Campanian and Maastrichtian). These faults form the boundary between the Bishri and Euphrates areas (Fig. 4).

The remainder of faults in the study area, concentrated in the west, are approximately NNE–SSW-striking Mesozoic normal faults on the NW margin of the Bishri block. Commonly occurring in small groups of several subparallel faults, thickening and reverse movement across individual faults is often small, whereas the cumulative effect is significant (e.g. Fig. 3c around the Kadir 101 well). They exhibit Late Cenozoic structural reactivation leading to net reverse offsets at most stratigraphic levels, with many having a characteristic ‘inverted’ signature, such as coring the anticlines beneath the Kadir wells (Fig. 3c). These faults show many signs of activity in the Triassic and Jurassic, with very significant Jurassic thickening across some faults. This synsedimentary faulting shows that these structures are the rift-bounding faults along the NW margin of the Mesozoic Palmyride trough. Furthermore, as with the eastern faults, Cenozoic structural inversion of these faults has raised the thickened Mesozoic sedimentary section above its depositional base level (e.g. between the Bishri and Wahab-1 wells in Fig. 3b). Hence, the Bishri block (Fig. 4) fits all the criteria for a typical positively inverted structure (Williams *et al*. 1989). This definitive observation of Mesozoic (and possibly Palaeozoic) rift-bounding faults in the NE Palmyrides is very important. Previously, only minor examples of possible rift-bounding faults had been discussed in the literature, and those were in the southern Palmyrides (Chaimov et al. 1990, 1992).

To the south of the main South Bishri fault is a small pre-folding sub-basin of Paleogene and Early Neogene age. This is most clearly seen by the downlapping reflections of Early Miocene age to the NE of the Najeeb well (Fig. 3a and b) suggesting slow subsidence. This overlies a thickened Paleogene section. Miocene progradation from the north reveals the timing of rapid uplifting in the Palmyrides, as discussed below.

Evolution of the Bishri block and regional implications

Geophysical interpretations suggest that the current location of the Palmyride mountain belt lies above a Proterozoic suture and/or shear zone acting as a crustal weak zone for much of the Phanerozoic deformation within Syria (Seber *et al*. 1993). The Palmyride trough formed in the Carboniferous, or possibly even latest Devonian (e.g. Best *et al*. 1993), controlled by the location of this crustal weak zone trending across central and into NE Syria (the Sinjar trough) (Fig. 5a). Over 2000 m of combined Carboniferous and Permian section are found in the Palmyride trough (Sawaf *et al*. 2001). This rapid Palaeozoic thickening into the linear trough, and scattered volcanic rocks (Mouty 2000), led to the interpretation of the Palmyride trough as an aulacogen (e.g. Best *et al*. 1993). This formed in the Late Palaeozoic, with extension continuing into the Early Triassic, under the influence of spreading in the eastern Mediterranean (Fig. 5a). The Bishri area was part of this larger Palmyride rift.

In the Mesozoic section, a Triassic basin, up to 1800 m thick and roughly circular in map view, is centred SW of the present uplifted Bishri block. However, few Triassic synsedimentary faults are observed anywhere in the Palmyrides, suggesting decreased tectonic activity. Sawaf *et al*. (2001) interpreted the Middle and Upper Triassic sequence as post-rift subsidence above Permo-Triassic rift.

A Jurassic basin, more restricted in areal extent, and slightly asymmetric to the north, overlies the Triassic basin. The Jurassic depocentre exhibits relatively rapid thinning to the north and south controlled by rift-bounding faults. The general rifting scenario continued during the Early Cretaceous with the deposition of the Palmyra (Rutba) formation. There is very little variation in the thickness of the Lower Cretaceous sequence in the west of the study area, whereas in the east rapid thickness variations are predominantly fault controlled. Between the

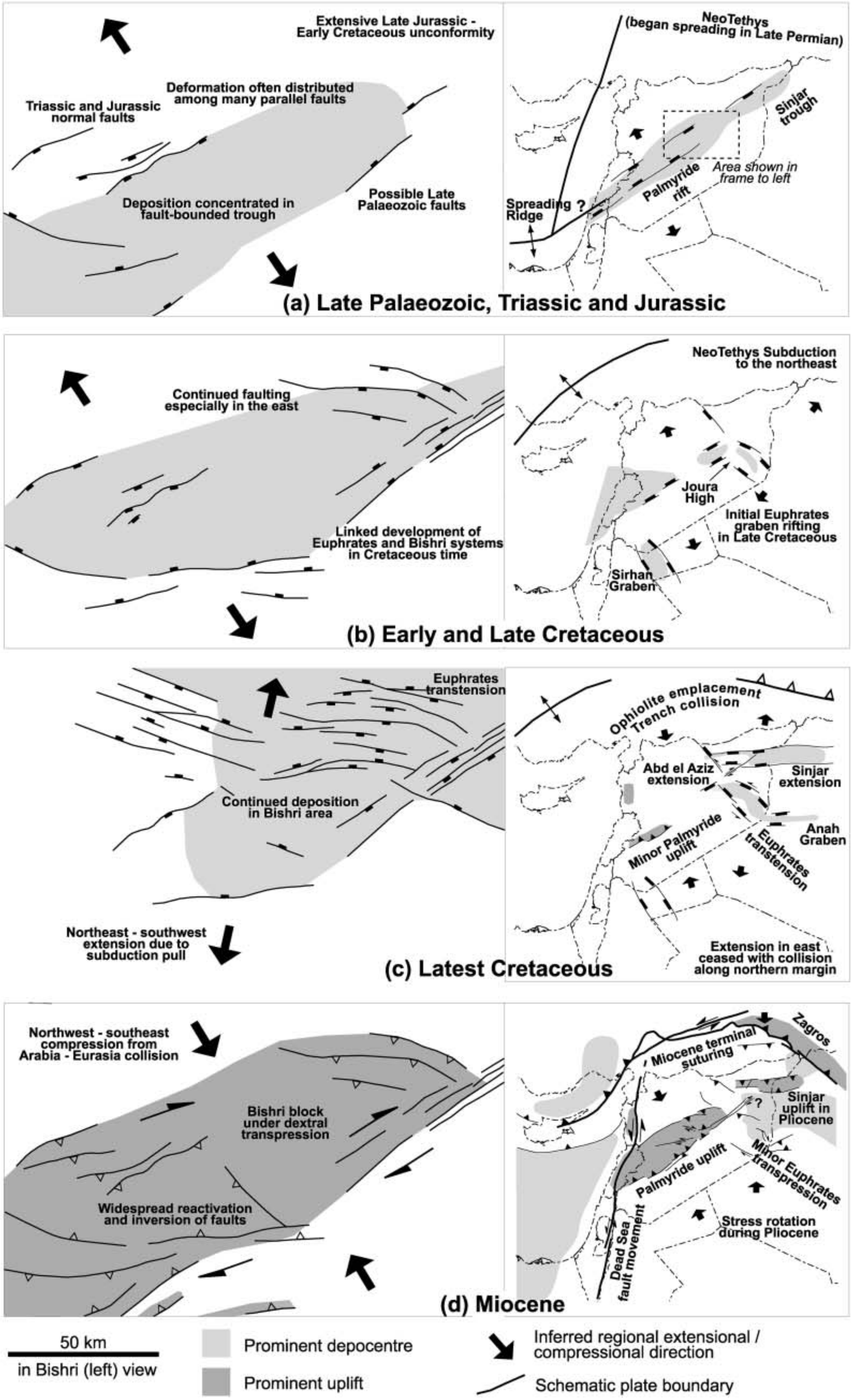

Fig. 5. Maps showing schematic tectonic evolution of the NE Palmyrides (left) area and regional setting (right). Area shown at left for each time step represents the area shown in Figure 2. Location and orientation of faults are schematically illustrated together with areas of most deposition. The maps at the right show a generalized plate tectonic setting of the northern Arabian platform at each time step.

Jurassic and Early Cretaceous the fault activity shows a clear migration to the NE. Furthermore, a shift in the dominant orientation of the major faulting is apparent, suggesting a reorientation in overall extension direction from roughly NW–SE to roughly north–south.

Chaimov *et al*. (1992) showed that the Jurassic and Early Cretaceous were also times of rifting in the southern Palmyrides, with synrift deposits of clastic and volcanic rocks found in the footwalls of these normal faults. The cause of this episode of extension throughout Syria could be related to a renewed period of extension interpreted in the eastern Mediterranean by Robertson & Dixon (1984) (Fig. 5b). An alternative explanation could invoke a mantle plume centred near the Palmyrides interpreted from regional magmatism and uplift (Laws & Wilson 1997). Total Mesozoic thickness change between the Palmyride trough and the adjacent Aleppo and Rutbah highs (Fig. 1) is locally more than 2000 m.

It is well established that the Euphrates fault system began in the Turonian, although the vast majority of its activity was during the Campanian and Maastrichtian (Litak *et al*. 1997) (Fig. 5b and c). Caron *et al*. (2000) showed that throughout most of the Cretaceous, the developing Euphrates fault system was divided into SE and NW portions by the uplifted 'Joura High' (Fig. 5b). Those workers supposed that this high could be a continuation of the well-documented Al-Hamad uplift that separated the Palmyride trough from the Rutbah basin to the south throughout much of the Mesozoic (Mouty 2000). Caron *et al*. (2000) also showed that the SE portion of the Euphrates most resembles a typical fault-bounded rift (the NW–SE-trending Late Cretaceous 'Euphrates graben' of Litak *et al*. 1997), whereas the NW portion was a much more diffuse fault arrangement, and was very strongly affected by the development of what was, at the time, the adjacent Bishri basin. In fact, sedimentary relationships suggest that the NW Euphrates and the Bishri basins were geomorphologically connected throughout much of their development and episodes of significant extension are contemporaneous in the two areas (Sawaf *et al*. 2001).

Notwithstanding this connection, there are distinct differences between the development of the Bishri and the NW Euphrates areas. Alsdorf *et al*. (1995) showed that during the Cretaceous the boundary between these two basins was marked by a series of down-to-the-SW normal faults (Fig. 5b) that controlled sedimentation in the Bishri area. As shown in Figure 3b, the Cenomanian to Campanian section in the Bishri well is many hundreds of metres greater than in the Wahab-1 well in the Euphrates fault system. A similar difference is also apparent in the Campanian–Maastrichtian isopach, whereas in the Euphrates graben Maastrichtian thickness is similar to that in the Bishri area.

These Late Cretaceous extensional events were caused by a shifting regional stress regime that was also responsible for the transtensional formation of the Euphrates fault system, and extension in the Abd el Aziz–Sinjar area of NE Syria. As noted by Brew *et al*. (2001), there is significant evidence for a stress reorientation during the Maastrichtian. Earlier extensional events in eastern Syria indicate a roughly NE–SW extension, whereas younger activity suggests a more north–south orientation (Fig. 5b and c). Hence the NW–SE faults in the Bishri area were opened first, whereas transtension in the latest Cretaceous was the preferred method of accommodation in the Euphrates fault system. Although the exact cause of the stress and its subsequent reorientation is unclear, some workers have attributed it to the pull imposed by the oblique subduction in the NeoTethys ocean NE of Arabia that reoriented with time (Fig. 5c) (e.g. Lovelock 1984).

The first minor uplift in the southern Palmyrides was in the latest Cretaceous (Chaimov *et al*. 1992), and correlates with other compressional activity observed in the Syrian coastal ranges and the Syrian Arc (Fig. 1) (Brew *et al*. 2001). This time corresponds to ophiolite emplacement along the margins of the Arabian plate and cessation of rifting in the Euphrates fault system and NE Syria. Collisions along the northern Arabian margin at the end of Cretaceous time, associated with the closing of the NeoTethys ocean, explain all these observations. A second episode of uplift in the southern Palmyrides started no later than Late Eocene time (Chaimov *et al*. 1992). This correlates with further deformation of the Syrian coastal ranges, and other structures in Lebanon and farther south (Brew *et al*. 2001). The lack of evidence of uplift in the Bishri or Euphrates areas at either of these times suggests that different areas within the Palmyrides may have responded differently to proximal plate boundary events. Late Cretaceous and Eocene collisions in the NW of the northern Arabian margin may have caused uplift in the SW Palmyrides, but not in the east. This is consistent with the observation that the final closure of the NeoTethys ocean along the northern Arabian margin began with collision in the NW corner of the Arabian platform (e.g. Hempton 1987).

Seismic stratigraphy suggests Mid- and Upper Miocene rapid uplift of the Bishri block (Fig. 3a), the only documented period of uplift in the NE Palmyrides. However, the final stage of accelerated uplift in the southern Palmyrides is interpreted slightly earlier in Early Miocene or even Late Oligocene time (Chaimov *et al*. 1992). Although the timing of these events is somewhat imprecise, this difference could suggest a progression of uplift onset in the Palmyrides from SW to NE. Hempton (1987) noted the terminal suturing of Arabia and Eurasian as mid- to late Miocene, after extensive continental margin shortening since the Mid- to Late Eocene. This terminal suturing led to plate-wide contraction; for example, in the Palmyrides, Euphrates fault system, NE Syria and the Zagros zone (Fig. 5d). However, contraction in eastern Syria commenced in the Pliocene, somewhat later than in the west (Brew *et al*. 1999). Palaeostress investigations also show a possible rotation of maximum compression from NW–SE to north–south during the Neogene (Feraud *et al*. 1985). In totality, these observations suggest a 'zipper-like' terminal suturing from west to east along the northern Arabian margin (Hempton 1987), possibly explaining the variation in timing of contraction along strike in the Palmyrides (Fig. 5d).

Continuing oil and gas production and exploration in the Bishri area adds an economic importance to our results, with tectonic history critical to these hydrocarbon plays. Mesozoic rifting led to the deposition of source rocks and sufficient burial for their maturity to develop. The rifting also created fault blocks traps, and Cenozoic compression created the anticlinal traps especially near the crest of the Bishri block (Fig. 4). Transgressive Lower Cretaceous (Rutba) sandstone, Triassic carbonates and Carboniferous sandstones are the most common reservoir, with fault blocks and anticlines as the typical traps. Potential Upper Cretaceous source rocks (Arak marl and Shiranish formations) may not have been sufficiently buried to reach full maturity in the Bishri block, and are positioned structurally higher than the reservoirs (e.g. Fig. 3b). Hence, charge may have come from the adjacent Euphrates graben, or from Permo-Triassic shales in the Bishri area.

Conclusions

Geophysical interpretation of the NE Palmyride mountain belt (the Bishri block) reveals a long-lived and repeatedly reactivated structural zone reflecting regional Phanerozoic plate tectonic evolution. The Bishri area was part of the Palmyride aulacogen from Late Palaeozoic until Paleogene time, accumulating thousands of metres of clastic and carbonate strata. This formed under the influence of Permo-Triassic rifting in the eastern Mediterranean basin, and the locus of deformation was probably guided by zones of crustal weakness dating back to Proterozoic time. We show evidence of rift-bounding faults in the Bishri block, at least during Jurassic and Cretaceous time. Extensive latest Cretaceous extension and deposition in the Bishri basin was linked to the adjacent Euphrates fault system. Thus the centrally located Bishri block shows a changing tectonic affinity; the Mesozoic Bishri basin was part of the Palmyride trough, but the development of the Bishri area was also heavily influenced by the Late Cretaceous Euphrates fault system. Many of the Mesozoic normal faults bounding the Bishri block have been structurally reactivated in the Neogene, hence the Bishri block is a positively inverted structure (Fig. 4). The entire NW Arabian margin is still under right-lateral transpression driven by oblique collision along the northern Arabian margin, principally mid-Miocene terminal suturing of Arabia and Eurasia. Earlier initiation of shortening in the southern Palmyrides suggests that this suturing occurred progressively from west to east. These observations have been combined with previous work to form a consistent plate tectonic evolutionary model of the north Arabian platform (Fig. 5).

This picture of structural inheritance in the Palmyrides demonstrates how the tectonics in an intracontinental area can be dominated by the repeated reactivation of pre-existing zones of weakness subjected to far-field stresses. The orientation of these stresses is critical. For instance, whereas the Late Cretaceous Euphrates fault system (roughly orthogonal to the northern Arabian margin) has remained almost unaffected by collisions along the margin, the same stresses have caused widespread structural inversion in the nearby Mesozoic Palmyrides trough (subparallel to the collision).

Also noteworthy is the current along-strike variability in the Palmyrides. Whereas the Palaeozoic Palmyride trough appears fairly monotonous, this study reveals a fascinating picture of strong along-strike variability in the Mesozoic and particularly the Cenozoic Palmyride mountain belt. In the Bishri area, steep, deeply penetrating Mesozoic faults are evidence for the thick-skinned tectonic style in the NE Palmyrides. Compressional reactivation of these structures thus led to only relatively minor compressional shortening. This is in contrast to the deformation in the southern Palmyrides, where thin-skinned faults and folds are often observed, with significant compressional shortening. This variability is thought to stem from the much greater thickness of Triassic salt in the south, which acted as a detachment layer. Furthermore, we know from our regional analysis that compressive shortening began first in the SW of the Palmyrides by virtue of the geometry of the collision along the northern Arabian margin. Hence total compression in the SW has been greater, and so low-angle thrusting may have been necessary to accommodate this greater shortening. Thus we see that the nature and style of tectonic reactivation is controlled by the orientation and position of the structural weak zones with respect to the nearby plate boundary stresses. Moreover, the relatively rapid along-strike structure variations observed in the Palmyrides point to the potential of similar strong variability in other intracontinental mountain belts over relatively short distances.

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