GeoArabia, 2015, v. 20, no. 3, p. 175-224
Gulf PetroLink, Bahrain

Rethinking post-Hercynian basin development: Eastern Mediterranean Region

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ABSTRACT

The geological community has broadly accepted that the region of NE Africa and NW Arabia deformed under tension during the post-Hercynian disintegration of northern Gondwana. Further, it has also generally accepted that sedimentation occurred within extensional half-grabens that formed along the length of what was then the southern margin of the Neo-Tethys Ocean. Consensus is that Alpine age compression then forced inversion of these half-grabens to form the well-known Syrian Arc structures that stretch from the Western Desert of Egypt to NE Syria. As new data has become available (Enclosures I and II), there are indications that an alternative mechanism, founded in continuous compression rather than extension then compression, better explains the tectonics and sedimentary history of the region since the late Palaeozoic.

Data from Syria, Jordan, the Levant and Egypt demonstrate that distinct post-Hercynian Orogeny, Tethyan and Alpine sequences (basins) lie on a final, deeply eroded and folded Hercynian Unconformity, and that this surface refolded post-Hercynian time to form the confining walls of a single trough extending from NE Syria to the Western Desert of Egypt. Prior to the deposition of the first Tethyan basin in the late Carboniferous, the Hercynian Unconformity surface deformed to establish a plate-scale arch, the Levant Arch, that extended from NE Syria and southern Turkey, over 1,500 km southwest to the three corners region of Egypt, Sudan and Libya. This arch refolded in the late Palaeozoic to form the early Levant Trough composed of the Palmyride Trough, its extension under the Eastern Mediterranean and the Levant, through the Sinai and into western Egypt. Contrary to the now established idea that the southern margin of the Carboniferous–Permian Tethyan Ocean was a "passive margin", the trough and internally constrained basins, slowly narrowed and deepened under continuous compression from the southeast from at least the late Palaeozoic to the Present.

Each internal, distinct basin sequence is well defined by long periods of slow, low-energy, laterally persistent, sedimentation, separated from underlying and overlying basin sequences by almost equally long periods of erosion or non-deposition, coincident with increased regional structuring and volcanism. Each new basin, following a cessation of this regional structural activity, found itself nested within its predecessor, with the older basin lying slightly counter-clockwise to the younger. It is proposed that counter-clockwise, regional (and basin) rotation was facilitated by newly documented NW-oriented cross-shears, with inter-basin periods of erosion or non-deposition due to whole-basin (regional) uplift, forced by trough narrowing.

Tectonic-scale geologic features, such as cross-basin and regional shears, trough margin uplift and northwest migration, laterally extensive, sheet-like sedimentation, sediment feathering onto unfaulted margins, regional erosion related to whole-basin uplift and massive flank gravity sliding with resultant down-slope buckle folding, taken together, attest to compression as the driving agent. Whole-basin and regional, counter-clockwise rotation through time, suggests a constant direction of compression. Understanding the correlation of sedimentary fill to local and regional structural events brings new insight to the deformation of the northern regions of Gondwana during the closure of Tethyan oceans. This model may also apply on a larger scale of whole-plate deformation.

INTRODUCTION

The northeast region of Africa and NW Arabia, from western Egypt, through the Eastern Mediterranean and the Levant, to NE Syria (Enclosure I), is not only geologically complex but also a region of major hydrocarbon deposits and therefore an area of great interest to both academia and the petroleum industry. The variety, orientation and number of troughs and basins containing Palaeozoic through Cenozoic sediments (Alsharhan and Salah, 1996; Keeley and Massoud, 1998; Dolson et al., 2000, 2001; Barakat, 2010; Hussein et al., 2013; Alsharhan, 2014) have been taken to imply that the area developed under local and varying stress conditions, mainly extensional (Litak et al., 1997, 1998; Brew et al., 2001; Hawie et al., 2013) during the breakup of the supercontinent Pangea and the ensuing fragmentation of Gondwana (Veevers, 2004; Robertson and Mountrakis, 2006; Stampfli et al., 2013; Torsvik and Cocks, 2013). This seeming complexity of structuring and a dogmatic belief in a rift origin, has, and continues to frustrate the development of a coherent theory of origin (Engelder, 1994) and therefore our ability to use tectonics as a truly useful tool in understanding local sedimentary and structural trends. This paper will examine the evidence and present a case for a simple tectonic model where deformation and sedimentation are driven by a common, continuous stress that has existed at least since the close of the North African Hercynian Orogeny in the Late Devonian to early Carboniferous.

Stratigraphic columns used throughout the region generally display the following three primary sedimentary and structural periods, each subdivided into component sequences: (1) a lower Palaeozoic, (2) an upper Carboniferous through Lower Cretaceous (the Tethyan sequences), and (3) an Upper Cretaceous through Cenozoic (the Alpine sequences). Of special interest to this paper are the Tethyan sequences, best described by Boote et al. (1998) in their synopsis of petroleum systems of North Africa, but will be shown to describe the sequences (basins) of the Palmyride Trough in Syria and neighbouring countries. The stratigraphic column of the Palmyride Trough (Figure 1) clearly displays these main divisions. For the purposes of this paper, each Tethyan "sequence" will be defined as a basin, a set of depositionally related rock units (formations) (Bally, 1983). Bally viewed a basin as a "realm of subsidence with a thickness of sediments commonly exceeding 1 km that are today, still preserved in a more or less coherent form" and intrinsically have a definable "top and bottom". By this definition, no significant time gaps exist within the sedimentary section of an individual basin. Perrodon (1992, 1995), and Magoon and Valin (1994) preferred to expand the idea of a basin for use in the petroleum industry, to include units of rock connected by an inter-relationship of source rock, reservoir, trap and structure. This definition inherently relates the formation of a basin to regional tectonics. In contrast, a "trough" refers to a linear, structural depression that extends over an aerially larger geographical region, often over many hundreds to thousands of kilometers, and controls the deposition of one or more individual basins or basin sequences. This relationship is described in Figure 2.

This paper will present evidence from more than 5,000 km of 2-D seismic reflection data and various levels of information from over 100 wells plus publically available data (Enclosure II), that show that distinct, post-Hercynian, Tethyan and Alpine regional sequences (basins) were laid down within, and were stratigraphically and structurally controlled by, the underlying development of one massive compressional trough. This "Levant Trough", that extended more than 1,500 km from NE Syria to western Egypt, effectively formed a "Greater Eastern Mediterranean Trough". The case will be derived from this good geological and geophysical data set in Syria's Palmyride Trough then expanded using mainly public domain data, to argue that the trough extended southwestward to at least the Western Desert of Egypt. It will be further proposed that a simple model of constant, NW-oriented, lithospheric-scale compression and folding can account for all superimposed internal structuring and sedimentary patterns of the region.

GEOLOGICAL SETTING

The present-day Eastern Mediterranean Region overlies what was, until the end of the African Hercynian Orogeny in the Late Devonian–early Carboniferous, the slowly disintegrating Pangea land mass. The late Carboniferous–Early Permian period heralded the long process of the

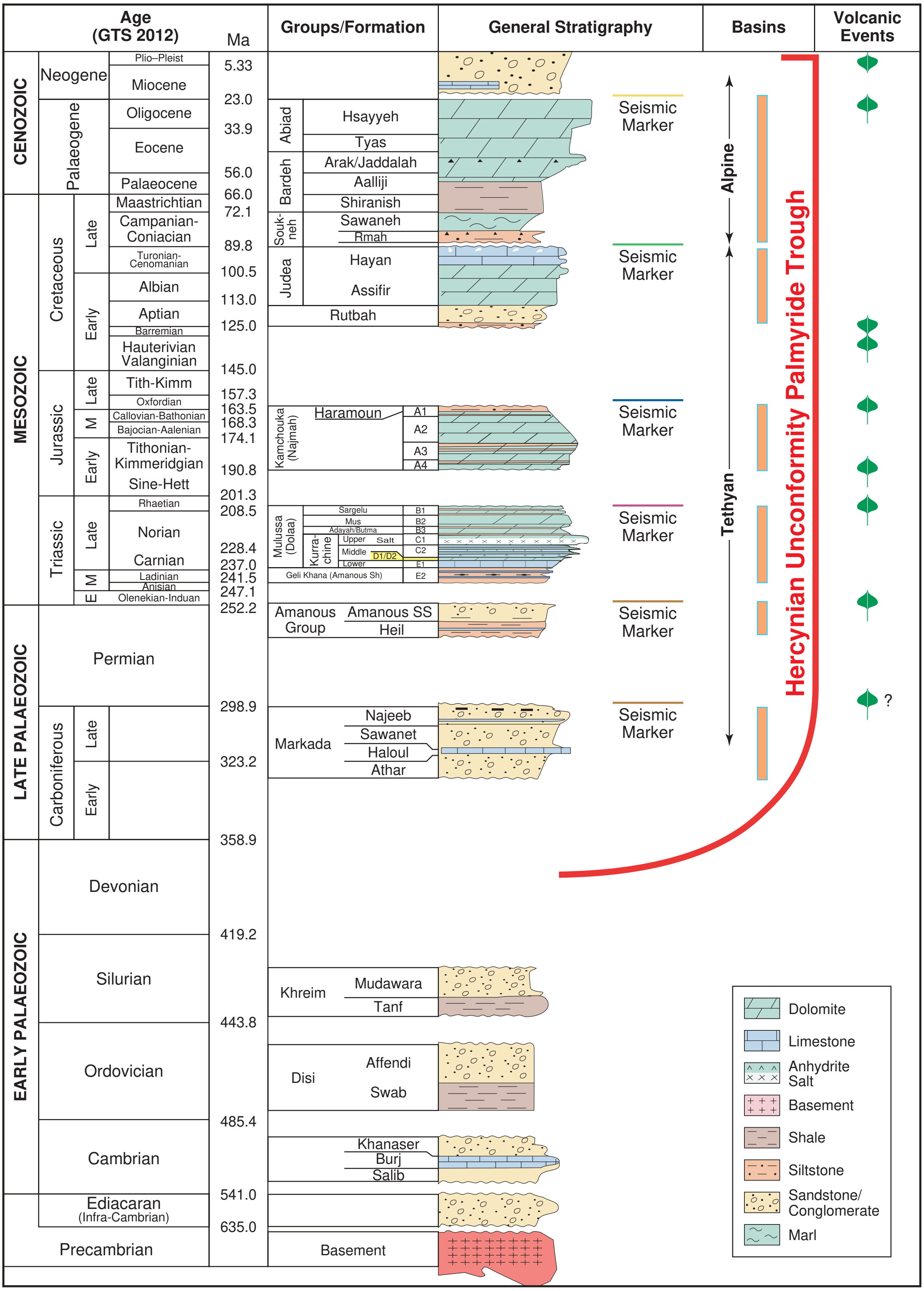


Figure 1: Simplified stratigraphic column of the Palmyride Trough, Syria (after Wood, 2001) with upgraded time scale after Gradstein et al. (2012). Lithologies are representative only but sedimentation purposely covers the maximum time recorded. Time gaps are therefore minimal. The time scale is purposely linear from the Silurian onward, to illustrate the major gaps in the sedimentary record. Seismic marker colours are consistent throughout.

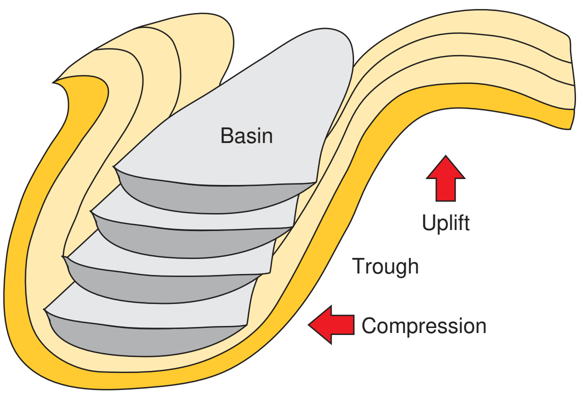


Figure 2. Relationship of a trough to nested basins.

fragmentation and dispersal of the younger Gondwana into ever-smaller continental blocks. This breakup was not random, rather it followed a cyclical scenario where large continental blocks tended to become dismembered from the northeast margins of Gondwana along NW-oriented fracture zones. This is in keeping with Stampfli et al.'s (2001) argument for synchronous rifting from Oman to Libya in the Permian. Freed blocks were then swept northerly away from Gondwana all the while spinning counter-clockwise and acting as great "windscreen wipers" (Sengör, 1979; Sengör and Yilmaz, 1981) sequentially opening then closing successive Tethyan oceans. These blocks were then sequentially welded onto the northerly lying Eurasian Plate (Laurasia), the ultimate backstop from the Carboniferous to present times. While not agreeing with Sengör's very orderly "windscreen wiper" model, Muttoni et al. (2009) agreed that Cimmeride blocks (Sengör et al., 1987) did dismember from Gondwana and rotated counter-clockwise while moving northerly to finally rest against Eurasia (Figure 3) The present-day Arabian Plate may arguably be the latest dismembered mass to begin its northerly journey in the Oligocene, breaking away from Africa along the Red Sea suture, a new continental rift running from the Indian Ocean to the Mediterranean region (Bosworth et al., 2005), closing the then-adjacent Neo-Tethys Ocean and colliding with Eurasia to form the Cypriot/Taurus/Zagros thrust belts (Enclosure I).

Figure 3, a modified Middle Permian map after Muttoni et al. (2009), shows the clear northwest by southeast orientation of the Tethyan oceans, their extensional margins and assumed mid-ocean spreading ridges. The figure also superimposes a not so familiar series of perpendicular, NE-oriented, older arches, the Levant, the Al-Batin and the Hadramat that formed during the final stages of the Hercynian Orogeny in the Devonian to early Carboniferous Period (Faqira et al., 2009). These arches and intervening troughs suggest a crustal-scale fold train of roughly 1,200 km and set the foundation for younger basins such as the Palmyride Trough of central Syria with younger basins forming by refolding through time. Wood (2001, 2011) demonstrated that the Palmyride Trough is a compressional down-warp of the Hercynian surface to form a younger fold train reduced to approximately 250 to 300 km. Ever-younger basins not only demonstrate the formation of shorter and shorter wave trains but also that successor basins narrowed and nested within underlying basins while their depocentres migrated northwestward. These propagating fold trains forced older basins to invert due to sediment crowding with each uplift (inversion) forming adjacent, younger basins. This seemingly complex sequence of events will be re-examined with the inclusion of newly acquired data and shown to be due to lithospheric-scale, simple, constant, horizontal compression.

The Palmyride Trough, an Overview

The Palmyride Trough of central Syria (Enclosure Ia and Figure 4) occupies a cone-shaped depression that deepens and opens to the southwest until it becomes involved in the complexity of the young Levant mountain chain in Lebanon (see isopach maps of Figures 19 and 20). The thickest Jurassic section documented to date, the 2,500 m sequence exposed on Mount Herman (Mouty, 1997), exemplifies this southwest expansion of the trough. The trough's northwestern flank is controlled by the Aleppo Uplift, while its southeastern margin is limited by the Rutbah High. Surface geology (Ponikarov, 1964) shows the present trough subdivides laterally into two NE-oriented depressions (Addaw and Homs) separated by the Central Uplift. A series of *en-echelon* structures (the Southern Mountains) overlie and define the southern margin while a sequence of Cretaceous carbonates exposed on the surface northeast and southwest of Hama, appear to mark the crest of the Aleppo High. Vertically the trough contains the stacked basins of the Tethyan and

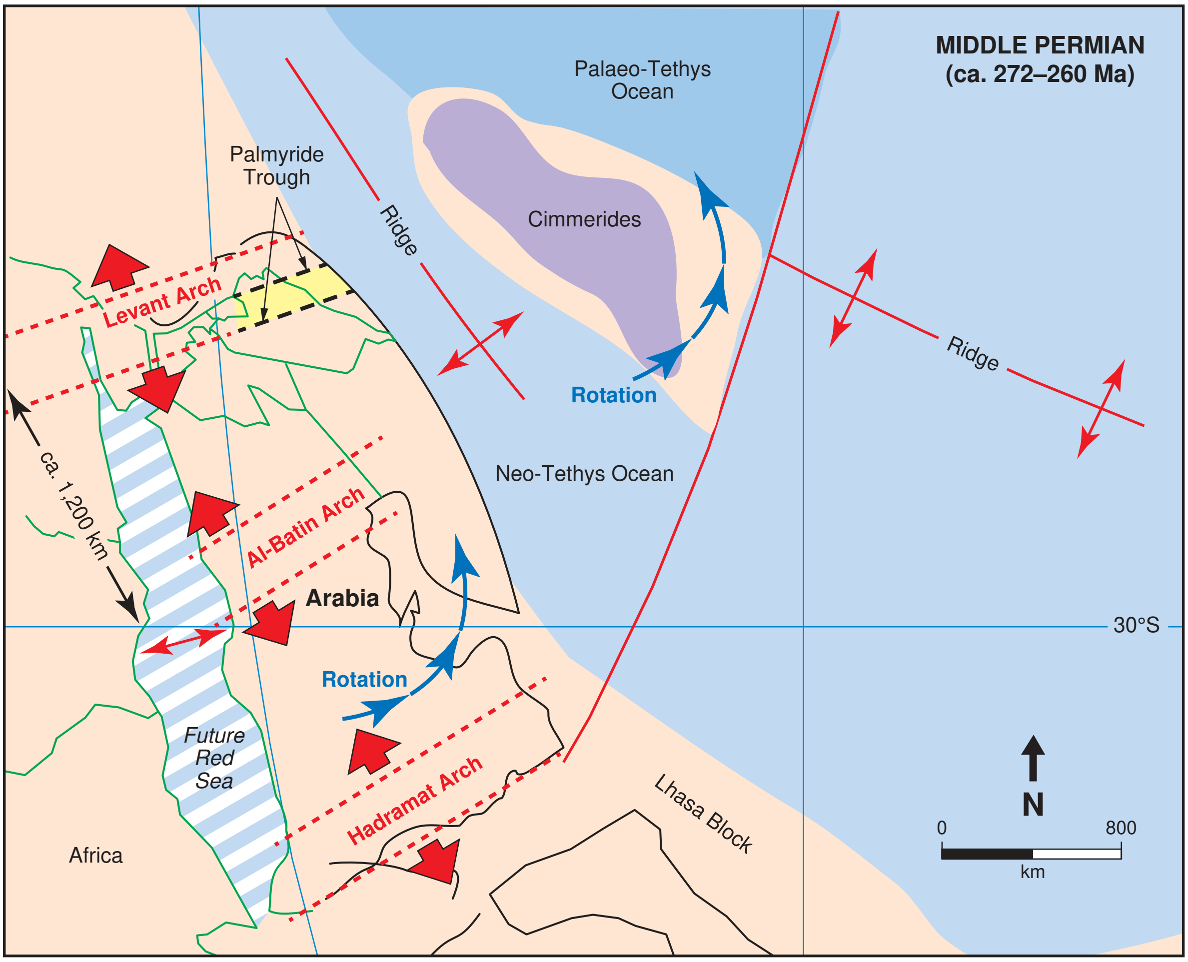


Figure 3: Orientation of Africa, Arabia and the Cimmerides in the Middle Permian (adapted from Muttoni et al., 2009). Green lines show present-day country boundaries for reference. The dashed red lines delineate the pre-existing Hercynian arches (after Faqira et al., 2009), while the cross-hatched blue and white area designates the position of the future Red Sea. The heavy black dashed lines indicate the position of the early Palmyride Trough of late Palaeozoic age. This time period was coincident with the preliminary collision of Gondwana against Laurasia (Veevers, 2004).

Alpine mega-sequences (Figures 1 and 4). All contained basins thicken to the southwest and thin steadily onto the northwest and southeast flanks of the trough with no significant NE-oriented marginal faulting (Figures 5 and 9). Upper Palaeozoic fine-grained clastics gave way to sequences dominated by muddy carbonates, sometimes evaporitic, toward the basin's depocentre (Figure 1). Sediment types suggest low-energy deposits that were laid down in quiet environments such as deep water or platform sabkha conditions where blanket-like sedimentation is the common denominator.

Substratum and Basement

The pre-Tethyan substratum of Syria consists of Infra-Cambrian through to lower Silurian sediments lying on the igneous and metamorphic basement of the Arabian Shield. Knowledge of the basement is restricted to one well penetration, Busra-1, in the southwest near the Jordanian border. This well penetrated granite, probably Precambrian, directly below an attenuated Triassic, the entire Palaeozoic being missing (personal communications). Our regional understanding of the basement under Syria and northern Jordan is therefore restricted to geophysical investigations (Alsinawi and Al-Banna, 1992; Nasir, 1992; Litak et al., 1997; Seber et al., 1992, 1993; Brew et al., 1997).

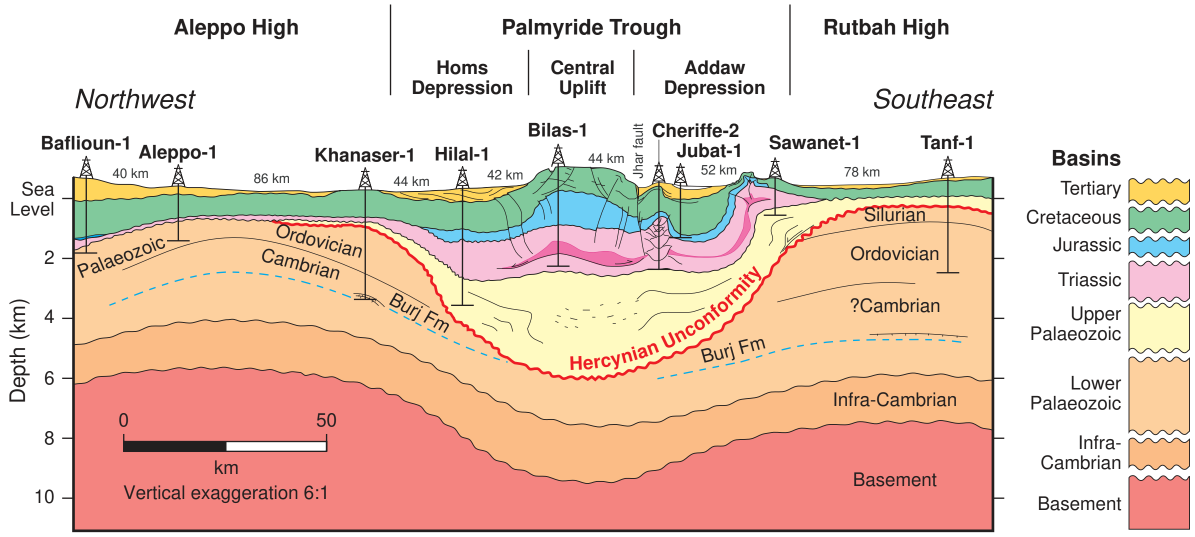


Figure 4: Cross section of the Palmyride Trough. The shallow section (down to ca. 4 km) is based on well and seismic data while the lower trough configuration is based on refraction and gravity information taken from Seber et al. (1993). Of special note is the thinning of the lower Palaeozoic under the Hercynian Unconformity directly beneath the trough reflecting the position of the pre-existing Levant Arch (Faqira et al., 2009, Figure 7). Also note the "crowding" of basin sequences within the trough. See Figure 6 for line position.

Estimates of the thickness of the crust range from 27 km to almost 40 km across the northern Arabian Plate from Lebanon to Iran. Rapid thickness changes are restricted to the Levant coast where, from a uniform 35–38 km east of the Levant Fracture under Syria and Jordan, the crust thins to less than 27 km adjacent to the fracture (El-Isa et al., 1987; Nasir, 1992; Best et al., 1993; Khair et al., 1993). Within the interior of the plate, specifically under the Euphrates Graben and its extension into Iraq, the Anah Graben, crustal thinning is remarkably minimal, from 37 km adjacent to the rift to 35 km beneath it inferring only minor extension across the graben (Sawaf et al., 1993). This lack of thinning was also noted under the parallel, Cretaceous-age, Sirhan-Azraq Graben of Jordan (El-Isa et al., 1987) again suggesting minor extension (rifting) during its development. Lining up as they do with other regional lineaments such as the Abba Fault Zone (Brew et al., 1999) and the Al Furat FZ (Krasheninnikov, 2005) in NE Syria, the Anah-Abu Jir Fault Zone of Iraq (Fouad, 2007) and the Northwest Arab Graben System of northern Saudi Arabia (USGS-TR-98-3, IR-948), these features (Enclosure I) probably initiated along deep-seated crustal fractures, opening or closing differentially along their length to form negative or positive flower structures in areas of transtensional or transpressional movement respectively. The presence and significance of many deep, NW-oriented, fractures dissecting the subsurface of the Palmyride Trough is a topic of this paper and will be discussed below.

The metamorphic basement surface, estimated to range from 5,500–6,000 m depth under the Aleppo Uplift and from 7,000–8,000 m under the Rutbah High, lies at approximately 9,000 m under the Palmyride Trough (Barazangi et al., 1993; Seber et al., 1993) suggesting a syncline at the basement level under the trough with about 1,000–2,000 m of relief (Figure 4). Above this depression lies the Palmyride Trough containing upper Palaeozoic, Mesozoic and Cenozoic sediments, ranging in total thickness from 5,000–6,000 m in central Syria to 8,000–9,000 m near the Lebanese border. Unfortunately, seismic reflection lines do not image a basement horizon and therefore detailed shape determination of the basement surface itself remains elusive. However, there is one deep and continuous reflector visible on conventional seismic reflection profiles across Syria and into northern Jordan originating from the middle Cambrian Burj Limestone (McBride et al., 1990; Best et al., 1993) and this reflector helps to control deep subsurface mapping. Below the Burj reflector, Barazangi et al. (1993) recognised, from refraction data, a 1.5 km thick, uniform, sedimentary unit that may have been partially penetrated at the Khanaser-1 Well (SPC final well report). They correlated this basal clastic unit to the lower Cambrian and Infra-Cambrian.

The Lower Palaeozoic Succession of the Northern Arabian Plate

The lower Palaeozoic is known from wells and outcrops in the Amanous Mountains of the Iskenderun region and the Mardin High and Hakkari area of southeast Turkey (Ala and Moss, 1979; Lovelock, 1984; Ozcan et al., 1988; Hosgör et al., 2014) and Jordan (Basha, 1982; Beydoun, 1988; Al-Zoubi and Batayneh, 1999), outcrops and wells in northern Saudi Arabia (Basha, 1982; Gvirtzman and Weissbrod, 1984; Beydoun, 1988) and finally, well penetrations and seismic data throughout Syria (Sawaf, et al., 1993; Litak et al., 1997). While Beydoun (1988) asserted that no Palaeozoic or older rocks occur in outcrop in Syria, a small outcrop of Carboniferous was later mapped in the core of Jabal Abd el Aziz in NE Syria. However, as it was entrained in a section of Late Cretaceous rocks, it may represent a block caught up in the core of a late structure (Al-Youssef and Ayed, 1992). Where drilled in Syria, the upper Silurian, the Devonian and lower Carboniferous are missing and therefore the lower Palaeozoic section, attenuated directly under the Palmyride Trough (Al-Youssef and Ayed, 1992; Barazangi et al., 1993), attains a thickness in excess of 5,000 m under the Aleppo Uplift and 8,000 m under the Rutbah High (Lovelock, 1984; Al-Youssef and Ayed, 1992; Barazangi et al., 1993). Post-Hercynian uplift (inversion) of these former lower Palaeozoic depocentres resulted in the thin upper Palaeozoic and Mesozoic section common to these and other Palaeozoic-cored blocks (Lovelock, 1984; McBride et al., 1990; Figure 4).

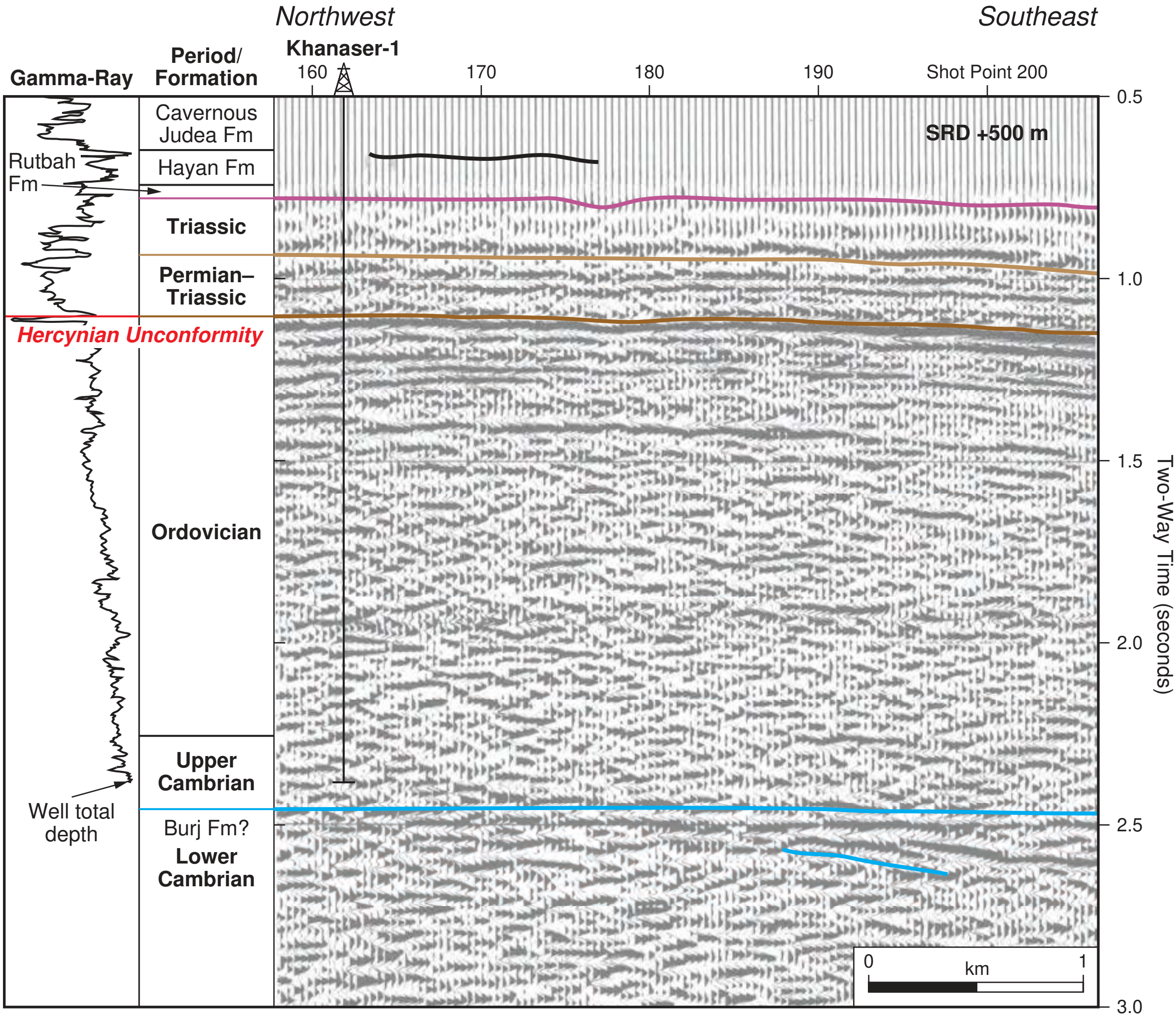


Figure 5: Seismic line HR-80-60 passing through the Khanaser-1 Well, represented by its gamma-ray log. Here the Jurassic section has been entirely eroded and a thin middle Cretaceous Rutbah clastic section lies directly on Lower Triassic carbonates. Undifferentiated Permian–Triassic clastics then lie on Ordovician clastics. The well terminated within a shaley carbonate sequence just above the middle Cambrian Burj Formation. Line of section is shown on Enclosure Ia.

Seismic reflection line HR-80-60, lying over the northwest flank of the Palmyride Trough and passing through the Khanaser-1 Well (Figure 5), illustrates the thick lower Palaeozoic substratum and the attenuation of the Palmyride Trough fill along the trough's northwest margin. Missing the Jurassic entirely, a thin middle Cretaceous, Rutbah Formation lies directly on an attenuated lower Triassic carbonate section while, below, a thin section of undifferentiated Permian–Triassic clastics lie directly on the Hercynian Unconformity. Below the unconformity there is a very thick section of Ordovician clastics with the entire Silurian and Devonian sections missing. The well terminated within a very shaley carbonate sequence thought to be the Cambrian Burj Formation (Barazangi et al., 1993); however a strong reflector just below the bottom of the well probably originates off the true top of the formation and the angular unconformity clearly seen to the southeast of the well below 2.5 seconds TWT, supports this interpretation.

THE HERCYNIAN LEVANT ARCH

Portions of the continental-scale Levant Arch (Figure 6; Faqira et al., 2009), such as the Mardin High (Litak et al., 1997; Alsharhan and Salah, 1997), the Geanticline of Helez (Gvirtzman and Weissbrod, 1983, 1984) and the Awaynat-Bahariah Arch of central Egypt (Klitzsch, 1971; Keeley, 1989; Keeley and Massoud, 1998) are well known individually, however their places and relationships in the whole of the Middle East, from a tectonic perspective, have only been specifically addressed by Wood (2001, 2011) and Faqira et al. (2009). Gvirtzman and Weissbrod (1983, 1984) did attribute the uplifts to the Hercynian Orogeny, however preferred to consider the "Geanticline of Helez", as one of a series of domal-shaped uplifts, including the Mardin High of southeast Turkey and the Awaynat-Bahariyah Arch, as probably the result of local, underlying plume activity.

Wood (2001), with a good data set from Syria, noted the well-organised, systematic nature of the Hercynian subcrop map (Figure 6) from Syria into the southern Levant and the persistent development of the Palmyride Trough above the Hercynian surface, structurally and sedimentologically. In Egypt, the arch was first described by Klitzsch (1971) as an uplift that extended from the Sinai, southwest across Egypt into Libya and the Sudan. Keeley (1989) and Keeley and Moussoud (1998) expanded on the theme that the arch represented a massive NE-oriented arch across Egypt (the Awaynat-Bahariyah Arch). From this early work of others and his own observation, Wood (2001, 2011) suggested the various uplifts represented a single continuous regional arch and that such an organised and extensive feature could not be related to an *ad hoc* plume-driven system.

On an even larger scale, Faqira et al. (2009) presented an argument for the development of three such regional, NE-oriented, arches, the Hadramat Arch lying along the coast of Oman and Yemen, the Al-Batin Arch across the interior of Arabia and the Levant Arch stretching across Syria and the Levant into the Sinai. Not wanting to introduce yet another name for the arch, Wood (2001) just called the northern arch, the Hercynian Geanticline of Helez (Modified) however, this author now prefers to go with Faqira et al. (2009) and use the more general term "Levant Arch" for the northern geanticline. Wood (2001, 2011) went on to suggest that the very development of such a massive regional arch, reaching from NE Syria to SW Egypt, plus other parallel arches like it in central Arabia and Oman, occurred as a result of a common, lithospheric-scale, horizontal, far-field force.

Figure 6 is an updated subcrop map of the Hercynian Unconformity across Syria, the Levant and Egypt incorporating more data than was previously available. The truly regional extent and continuity of the Levant Arch is, the author believes, now without question. The regularity of the subcrop pattern across the region is striking with the crest of the arch lying under the Khanaser-1 Well in central Syria, effectively the same position as the present Aleppo Uplift. Without accounting for the offset along the Dead Sea Fault (minimal with respect to the scale of the arch), the crest trends from the Khanaser area, south-southwest through SW Syria where the basement subcrops the Mesozoic section at the Busra-1 Well (Enclosure I and Figure 6, under the Golan Heights and the Northern Highlands of Jordan, through the Levant, across the Sinai into central and SW Egypt where its presence is also indicated by the erosional limits of lower Palaeozoic units (Lüning et al., 2005). Interesting NW-oriented offsets controlling the northeast margin of the Dakhla Trough

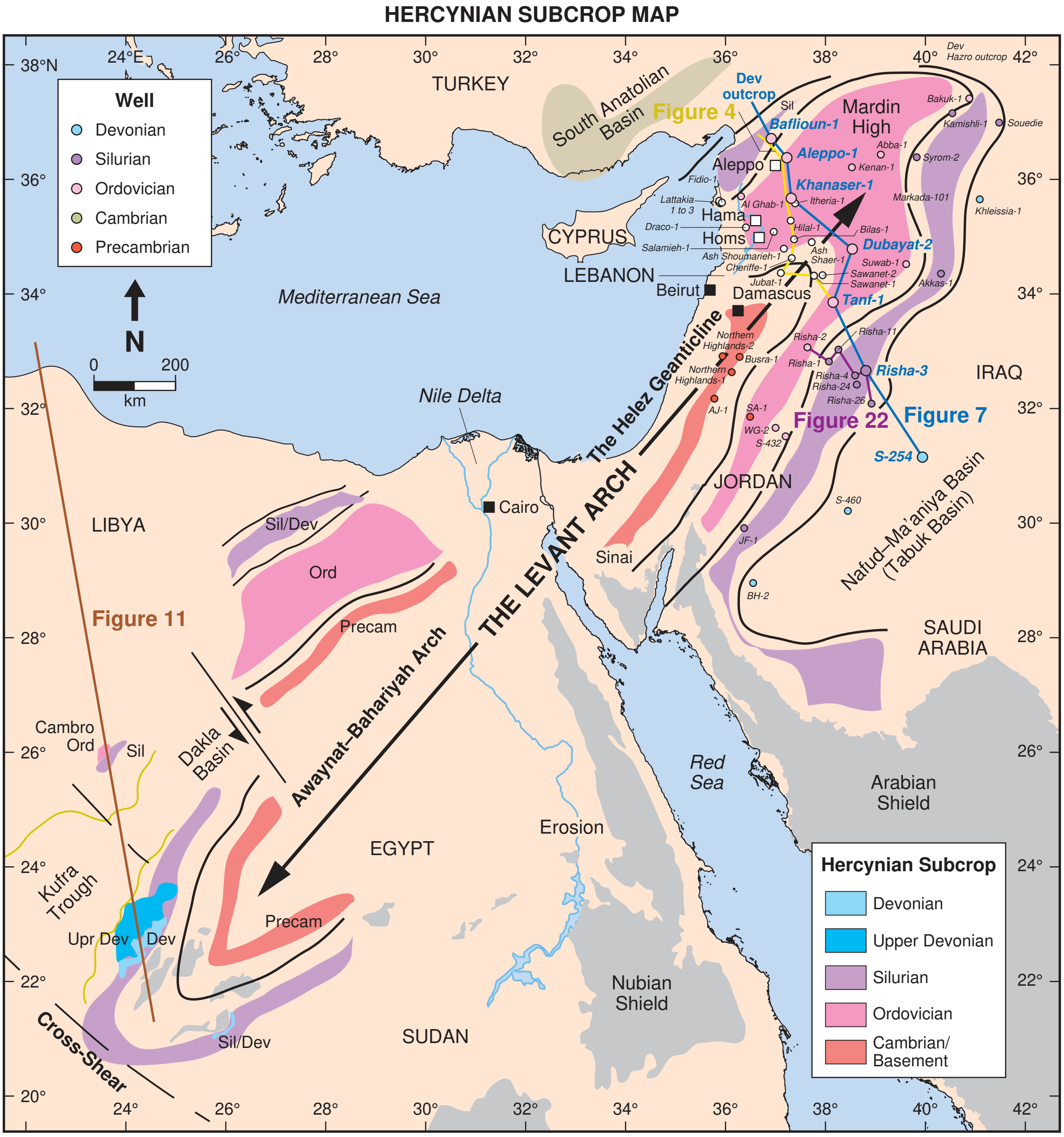


Figure 6: This Hercynian Unconformity subcrop map highlights the extent and orientation of the upper lower Palaeozoic to early Carboniferous (Hercynian) Levant Arch. Extending from NE Syria to SW Egypt, this massive, elongate tectonic feature questions a simple plume-related origin; rather it suggests crustal-scale (lithospheric?) folding. Superimposed on the arch, late Palaeozoic sediments began to fill the early Palmyride Trough in Syria, a depression that initiated as a re-fold of the Hercynian Unconformity surface (see Figure 10 and text for additional explanation). Equivalent in time to the early Palmyride Trough, the Kufra Trough in SE Libya also originated as a re-fold of the Hercynian surface so the picture at the southwest end of the Levant Arch as depicted here is a bit later in time, probably the end of the Permian (see Figure 11 and text for more detail). Sparse data prevents seeing a good picture of the southwestern extension of the arch at the end of the Hercynian Orogeny.

and offsetting the Kufra Trough (adapted after Lüning et al., 2010), appear to split the southwest extension of the Levant Arch, however this is deceptive as the surface geology is recording the arch after sediments of the Kufra and Dakhla troughs have already occupied a late Palaeozoic re-fold of the arch. This will be dealt with below when discussing the formation of the contemporaneous early Palmyride Trough.

Figure 7 is a south to north cross-section, based on well and surface data, flattened on the Hercynian Unconformity to expose the Levant Arch. It was purposely constructed to the east of the Levant Fracture to avoid interference with this younger feature. At the Dubayat-2 and Tanf-1 wells in central Syria, the oldest sediments of the Palmyride Trough, the Carboniferous Markada sandstones, lie on the unconformity surface and indicate where the new depocentre of the Palmyride Trough would eventually form. To the north at Khanaser-1 (Figure 5) the Permian–Triassic Amanous sandstones lie on the Ordovician, while further north, at the Aleppo-1 and Baflioun-1 wells, thin, younger Middle Triassic Kurrachine carbonates lie directly on Ordovician sediments. While directly under the line of section, the oldest rocks under the unconformity are Ordovician, to the southwest at Busra-1 in SW Syria, basement granites were tagged below Triassic Amanous Shales at 2,640 m (personal communications) indicating the arch rises toward the southwest from central Syria. From the crest of the anticline, toward the northwest and the southeast, ever-younger lower Palaeozoic sediments subcrop the unconformity, with Ordovician and lower Silurian rocks subcropping most of the region of Syria. As already mentioned, no surface outcrops or subsurface sections of Devonian or Late Silurian age have been identified in Syria (Beydoun, 1988; Sawaf et al., 1993).

Independent evidence of the timing of uplift of the Levant Arch comes from zircon fission-track dating by Kohn and Eyal (1981), Kohn et al. (1992, 1993) and Bojar et al. (2002). Kohn et al.'s data recorded reset ages for the Proterozoic basement granites of the Sinai and southern Levant of 373–328 Ma (Late Devonian to early Carboniferous) followed by rapid cooling. Only in the northern Levant was a weak Mesozoic thermal signal recognised, not unexpectedly with the volumes of Mesozoic volcanics present. Even with high geothermal gradient estimates (> 50°C/km), at least 3–5 km of sediment was removed over the crest of the Levant Arch. Bojar et al.'s (2002) fission track data from the Eastern Desert of Egypt also sets uplift between the Late Devonian and the Early Cretaceous with a much younger cooling event in the Oligocene coincident with dyke intrusions

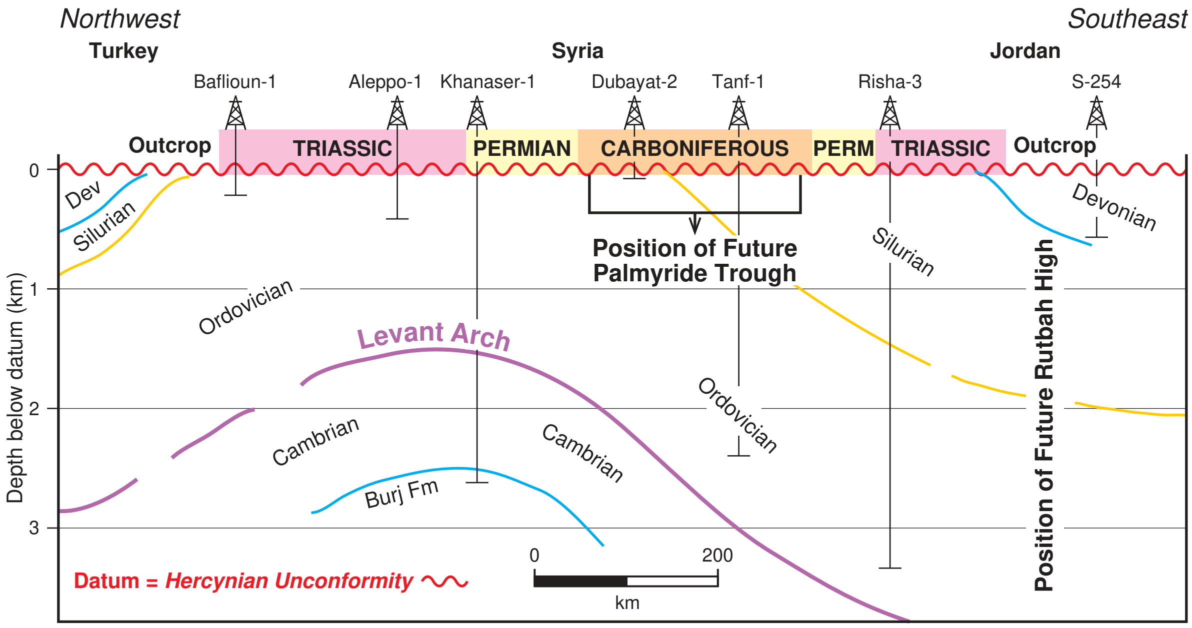


Figure 7: By flattening on the Hercynian Unconformity, the massive Levant Arch (Wood, 2001; Faqira et al., 2009) is unveiled. See Figure 6 for location of this line and where the full extent of the arch is shown. Uplift has been verified by fission track work by Kohn and Eyal (1981) and Kohn et al. (1992, 1993) in the area of the southern Levant and northern Sinai and by Bojar et al. (2002) in the Eastern Desert of Egypt, both authors relating the uplift to a Late Devonian–Early Carboniferous event. In Syria this uplift stripped off the entire Devonian and upper Silurian section. The deposition of Carboniferous clastics above the Hercynian Unconformity at Tanf-1 and Dubayat-2 wells indicates the site of the future Palmyride Trough. See Enclosure IV where the development of the trough is demonstrated to have formed, not by extensional collapse, but by horizontal compression and the resulting refolding of the Hercynian surface.

occurring across the entire northeast of Egypt culminating in the opening of the Red Sea and Gulf of Suez.

The arch is a massive, doubly plunging anticline. To the north-northeast toward the Mardin High of SE Turkey (Figure 6) it is defined by a fringe of Silurian and Devonian rocks. The dominantly clastic lower Palaeozoic gives way here to carbonates in the Devonian only along the northwest flank of the arch (Sengör et al., 1987) where they are metamorphosed by multiple younger orogenic events (Ozcan et al., 1988; Varol, 1994). To the southeast of the arch in Iraq, the presence of Devonian clastics rather than carbonates (Basha, 1982; Gvirtzman and Weissbrod, 1984; Beydoun, 1988), reflects an intra-cratonic “Nubia-like”, clastic-rich environment. The northeastern extent of the Levant Arch appears to have formed a major barrier in the Devonian with very contrasting sedimentary packages on either flank.

To the north and northwest, the lower Palaeozoic section thickens under the Taurus fold-and-thrust belt where its pre-Alpine history is obscure. To the southeast, the lower Palaeozoic section thickens under an area roughly corresponding to the present surface expression of the NNE-trending Rutbah Arch (May, 1991; Al-Youssef and Ayed, 1992). This thick section of sediment experienced regional uplift (inversion) during the late Palaeozoic (Al-Laboun, 1986; Beydoun, 1988) with crestal erosion during inversion providing sediments southeastward into a much-reduced Central Arabian Trough (the Nafud-Ma’aniya Basin of Faqira et al., 2009), the Tabuk Basin of Al-Laboun (1986) and a basin, the proto-Palmyride Trough, to the northwest in central Syria. The Hercynian surface was in fact refolding to form a series of parallel but laterally reduced troughs.

A comparable pattern of structuring and resultant flank sedimentation occurred in Egypt and Libya (Bellini and Massa, 1980; May, 1991; Keeley, 1994; Keeley and Massoud, 1998; Boote et al., 1998) and Algeria (Macgregor, 1996). A series of regional, parallel, NNE-trending lower Palaeozoic basins lay on the central North African craton. They formed during the same Devonian–Carboniferous, Hercynian, events as in Syria with latest early Palaeozoic deposition (Devonian) restricted to the flanks of arches time-equivalent to the Levant Arch. Earliest late Palaeozoic orogenic activity then not only seriously back-stripped the sedimentary section over inverting lower Palaeozoic troughs (Gvirtzman and Weissbrod, 1983), but more importantly, reset the distribution and configuration of each upper Palaeozoic successor basin.

With respect to scale, it is clear that the Levant Arch was both linear and very extensive, covering an area from at least NE Syria, some 1,500 km southwest to the corner area of Libya, Egypt, Chad and Sudan. In conjunction with the formation of parallel structures across the Afro/Arabian Plate at the same time, an *ad hoc* origin can be precluded. Plume activity with an expected dome signature cannot account for the arches and should be abandoned as a driving force behind the pre- and post-Hercynian structural activity throughout northern Afro-Arabia.

POST-HERCYNIAN DEFORMATION: PERCEPTIONS AND DILEMMAS

That the history of the Palmyride Trough spanned the late Palaeozoic to Neogene, post-Hercynian period (Laws and Wilson, 1997; Brew et al., 2001; Ziegler, 2001; Hawie et al., 2013), is the one area upon which there is a consensus based on sound geological evidence. Post-Hercynian trough formation began in the late Palaeozoic with the deposition of late Carboniferous sands and shales confined to an area high on the southeast flank of the underlying Levant Arch (Figure 7) On a continental scale, initiation of the trough coincided with the initial deformation of the Pangea Supercontinent, persisted throughout the following fragmentation of Gondwana during the Mesozoic Tethyan period, or “Cimmerian Orogeny” of Sengör (1979), and the development of the multiple Tethyan cycles and finally the Alpine Orogeny of Late Cretaceous (Senonian) to Neogene age. The initiation of the trough also coincided with the noted inversion of older, lower Palaeozoic, depocentres to form uplifts such as the Rutbah High, originally the site of a lower Palaeozoic trough. Unfortunately, this is where consensus ends and perception driven by dogma and/or more speculative ideas begins. There is effectively no direct evidence that the region deformed as a passive margin under tensional forces.

That the Palmyride Trough, and its extension to the northeast, the Sinjar Trough, lay within a migrating and disintegrating plate complex is without controversy (Best et al., 1993). Overlying the northwest margin of the Arabian Plate in Syria, the predominantly marine carbonate and evaporitic sediments of the Triassic, Jurassic and Lower Cretaceous indicate it was periodically open to the Neo-Tethys Ocean. Published stratigraphic sections and isopach maps of the trough document thick, persistent, NE-trending upper Palaeozoic and Mesozoic depocentres (Lovelock, 1984; May, 1991; Beydoun and Habib, 1995; Laws and Wilson, 1997; Garfunkel, 1998). These maps, however, constrained by a limited database, consistently are depicted as relatively simple rift basins running northeast across Syria from Lebanon.

It is not without interest that Ponikarov (1964) and Ponikarov et al. (1966, 1967), the first to conduct an exhaustive geological evaluation of Syria, were working at a time when Plate Tectonics was morphing from Continental Drift. It was therefore reasonable for them to theorise that the Mediterranean Basin was of oceanic origin complete with a mid-ocean ridge. Moreover, its position, basically perpendicular to the Levant coastline, resulted in their description of the Palmyride Trough as an "Impachtogen" or "Aulacogen type" depression. Later authors, with little evidence to the contrary, simply have referred to the trough as an intracratonic rift or just a "rift" (Sengör and Yilmaz, 1981; Al-Saad et al., 1992; Barazangi et al., 1993; Beydoun and Habib, 1995; Laws and Wilson, 1997; Brew et al., 2001; Hawie et al., 2013) and have all assumed (accepted) early Tethyan rifting, then compression and inversion during the Late Cretaceous to Cenozoic Alpine Orogeny, to account for compressional features mapped on the surface, such as the Southern Palmyride Mountains. Further, compressive and/or transpressive actions between the confining Aleppo and Rutbah "basement blocks" have been deemed to be the driving force. While the "why" these confining blocks closed on the trough is a major question; perhaps the salient point to be addressed is why the trough sediments overlie and are laterally confined by lower Palaeozoic sediments not "inferred" basement blocks. This is never mentioned let alone discussed.

Not helping, is that the present dogma regarding the most likely and/or dominant mechanism driving plate movements in general is slab-pull (gravitational forces) or dissipation of the Earth's heat (plume activity) (Wortel and Spakman, 2000; Conrad and Lithgow-Bertelloni, 2004). With respect to the area under scrutiny in this paper, Ben-Avraham et al. (2006) stated that the "rifting of continental fragments away from Africa, while the African Plate was moving northward relative to the Eurasian Plate, means that subduction along the Calabrian, Hellenic and Cyprian arcs had to be faster than the convergence of the two plates." Clearly this conclusion is only necessary if a rift origin of the Palmyride Trough is true and that "slab-pull" as a mechanism is fact, both ideas not necessarily warranted by the data or lack thereof. Unfortunately, so often has early Tethyan rifting and Late Alpine inversion been cited as the mechanism for the formation of not only the Palmyride but also most Syrian Arc related structures as far west as the Western Desert of Egypt, it is now rarely challenged. It is therefore essential to return to basics and review both rifting and inversion processes with respect to expected structures and sedimentary fill and consider a new model based on a top-down approach, that is, starting with basic surface geology, subsurface well data and seismic reflection interpretations.

Rifting and Rift Inversion

The mechanics of rifting and rift inversion generally follow a prescribed structural sequence that has been documented in many regions of the world (Eubank and Makki, 1981; Bally, 1983; McClay, 1989; Roberts, 1989). Rift inversion necessarily involves a change in the local stress regime causing a former rift basin, inherently a negative topographic feature bounded on one or both sides by normal, that is, extensional, faults, to "invert" or, in effect, turn itself inside out as basin volume is reduced by compression. Inversion along strike-slip systems, with excellent subsurface, seismically controlled examples, was first documented along the Sumatra Fracture of Indonesia (Eubank and Makki, 1981). Local examples of structural features dominated by early extension, such as the Gulf of Suez in Egypt (Khalil, 1998; Khalil and McClay, 2009) and the Mount Carmel Fault system of the Levant (Rotstein et al., 1993), have been extensively examined. These predominantly extensional, NW-oriented features were all exposed to a late, short, burst of oblique compression, resulting in mild strike-slip and inversion of the rift sedimentary sequences.

Understanding the depositional environment within extensionally controlled depressions and the interplay of structure and stratigraphy is critical. The East African Rift has been studied and described since the early to mid-1980s (Rosendhal et al., 1986; Rosendhal, 1987; Daly et al., 1989; Cohen, 1989) and has become a "classic" example of intra-cratonic rifting and structural control on sedimentation. These rifts are composed of a series of individual depocentres, generally having a half-graben cross-sectional shape, strung along an interwoven and/or branching, active, fault network. The basic half-graben shape of the basins resulted from dip-slip on single bounding faults. The stratigraphic fill of these one-sided, subsiding basins consists of groups of individual facies (vertically and laterally) and collectively are referred to as "syn-rift" deposits.

In parallel, the application of sequence stratigraphy has been instrumental in our understanding of sedimentation with respect to sea-level fluctuations (Vail et al., 1977; Neal et al., 1993) and is integral to this review of the stratigraphy along the northern margin of Africa and Arabia. Two end-member environmental conditions control sedimentation within a rift basin, complete flooding and complete aridity. Rift systems are inherently tectonically active and fault activity could quickly create barriers with individual basins trapping large volumes of water and sediments entering the system. With a rift flooded with either marine or fresh water, deltas of coarse to fine sediment build out over the dip-slope of the rift. Against the opposing, steep fault scarp, coarse, often conglomeratic, alluvial fans merged into submarine fans. Laterally away from clastic input, fringing carbonate sedimentation may have occurred depending on climatic conditions. Alternatively, a former barrier holding back a perched sea or lake could be breached, leading to complete aridity. These periods are generally represented by by-pass river systems and if no ponding occurred within the rift, thick sandstone deposition will occur. With ponding and the right climatic conditions, evaporitic conditions could result in the deposition in playa lakes of salts and/or anhydrites depending on water source, volume and evaporation rates, with sediment input via axial rivers and ephemeral marginal streams. Alternating periods of deposition will therefore result in a complex pattern of sedimentation where rapid facies changes, vertically and laterally, will be the norm.

Problems with a Rift Model for the Palmyride Trough

Against this picture of rift (extensional) related faulting and rapidly changing facies, two major obstacles arise when examining the Palmyride Trough, first a sedimentological problem and second, a structural one. With respect to the first, Figure 8 is but one example. Here, a single sedimentary cycle within the Triassic, Middle Kurrachine Formation, itself a sequence of low-energy carbonates, shows, by way of a detailed wire-line log correlation, a 30–40 m-thick unit (the D1) easily recognised in wells as far apart as 50–80 km. In fact, this unit can be recognised across most of the Triassic basin. Figures 10 and 12 will later show other Mesozoic units that correlate at a basin scale and the trough-wide extent of the Cambrian Burj Formation has already been mentioned as a good regional, deep seismic marker. Palmyride Trough sedimentation, therefore, is a prime example of "layer-cake geology". From from a seismic correlation vantage point, simple stratigraphic correlation generally equates to easy seismic correlations and this is exemplified in Figures 9, 15 and 17 where "tram-line" reflectors are the norm.

Seismic line PM-01 (Figure 9, see Enclosure Ia for location) over the southern margin of the trough demonstrates several aspects of the trough fill and structure. First, the continuity of the seismic reflectors supports blanket-like bedding, second the entire section thins by feathering or top-down erosion toward the basin margin, features most obvious at the Jurassic/Triassic and the Triassic/Permian boundaries, and third, the disconformity surfaces at the inter-basin gaps are exceptional in light of the long time periods represented. Fourth, there is no basin margin faulting. A small salt pillow under the Qum Qum structure is the toe of a buckle fold formed in response to slippage on an evaporite-bearing glide plane and this form of deformation will be illustrated below. A vertical, chimney-like feature, coincident with a change in seismic quality and reflector dip angle at about shot point 230, suggests a disturbance by vertical NW-oriented fracturing. Better examples of vertical shearing will be shown below, however it has been raised here as it is the only form of internal faulting and emphasises the fact that the trough margin is effectively an undisturbed ramp.

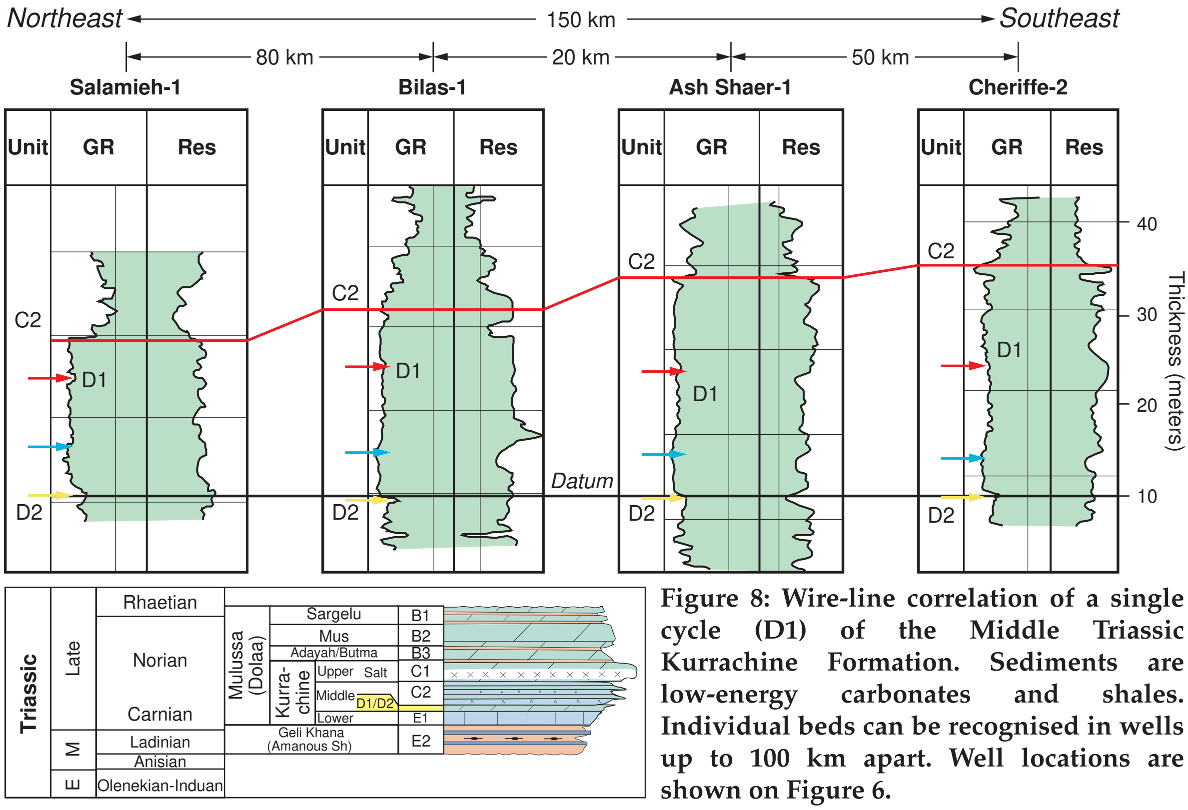


Figure 8: Wire-line correlation of a single cycle (D1) of the Middle Triassic Kurrachine Formation. Sediments are low-energy carbonates and shales. Individual beds can be recognised in wells up to 100 km apart. Well locations are shown on Figure 6.

While a rift origin of the Palmyride Trough is not often challenged, it has been hinted at. Lovelock (1984), working with Shell Oil in Syria, noted that the flanks of the Palmyride Trough were not fault controlled. However, in spite of his excellent description of the Euphrates Graben with its classical rift architecture and sedimentary fill, he chose to accept an extensional model for both the Euphrates Graben and the cross-trending Sinjar/Palmyride troughs in spite of his access to seismic data indicating the contrary. He preferred to defer to tectonic ideas of the day stating, "These basins (Palmyride and Sinjar) were not obviously fault controlled, but were areas of broad down-warping with gently dipping flanks. This down-warping should be seen against a wider background of penecontemporaneous rifting in the Tethyan region during Ladinian–Norian times (Sengör and Yilmaz, 1981)."

To this author's knowledge, no one other than Lovelock (1984), with his access to seismic, has questioned a rift origin of the Palmyride Trough in spite of evidence to the contrary. Therefore, bearing in mind the stratigraphic and structural characteristics of the basin as already suggested by the data, that is, basin-wide low-energy deposition is the norm and there is effectively no marginal faulting, an integrated structural/stratigraphic review of the trough is long overdue.

TETHYAN BASINS OF THE PALMYRIDE TROUGH: AN ALTERNATIVE MODEL

Accepting the possibility of an alternative model, Figure 10 shows a stratigraphic cross section of the early Palmyride Trough flattened on the top of the lower Permian. With the upper Permian missing across Syria, this is effectively a geological section at the end of the Palaeozoic. The stratigraphy of the late Palaeozoic section of the Palmyrides has been documented by Al-Youssef and Ayed (1992), their work based on Syrian Petroleum Company data from upper Palaeozoic gas fields northeast of Palmyra in central Syria. Building on this work, and controlled by seismic and well data, the cross section displays the absolute absence of marginal faulting and clear sets of continuous, easily correlated, individual basin sequences.

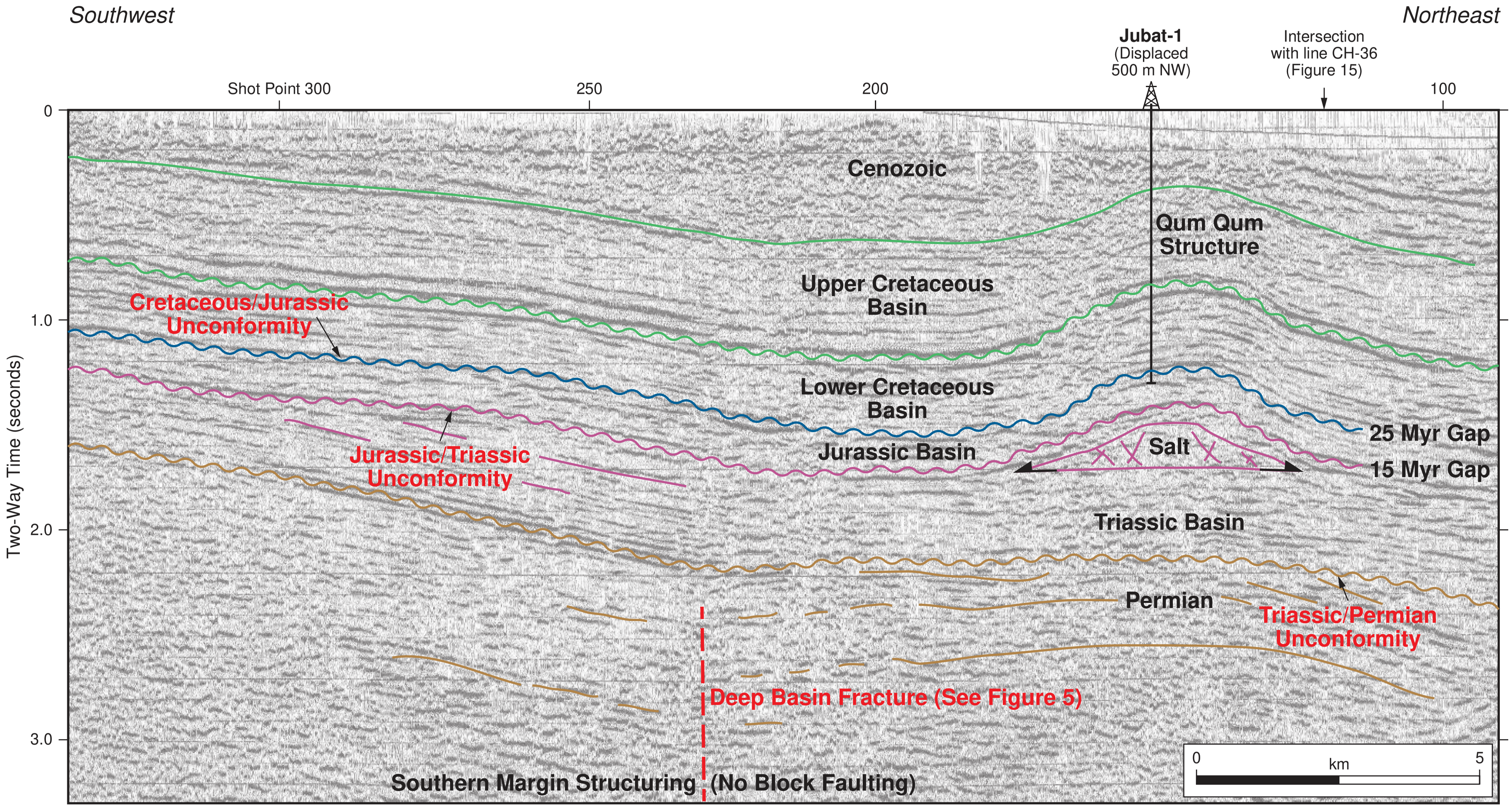


Figure 9: Seismic line PM-01 over the southeast margin of the Palmyride Trough (see Enclosure Ia for location) showing the mildly angular unconformity between the Triassic and Jurassic and the Triassic and Permian in spite of the extensive time gaps. The Jubat-1 Well was drilled just southeast of shot point 150 and penetrated a normal Cretaceous and Upper Jurassic section. The Qaryatein-1 Well was drilled ca. 1 km off the southwest end of the line and encountered Jurassic Haramoun carbonates resting on Triassic Adayah dolomites confirming the major unconformity. Note the continuity of the reflectors within each basinal cycle indicating lateral continuity of facies. The structure on the right is a southeast protrusion of the Qum Qum buckle fold (Figure 15). No block faulting is indicated, however the change in slope and loss of continuity of reflectors under about shot point 230 occurs at the position of a deep-seated fracture. Parallel fractures are imaged better on Figures 17 and 18.

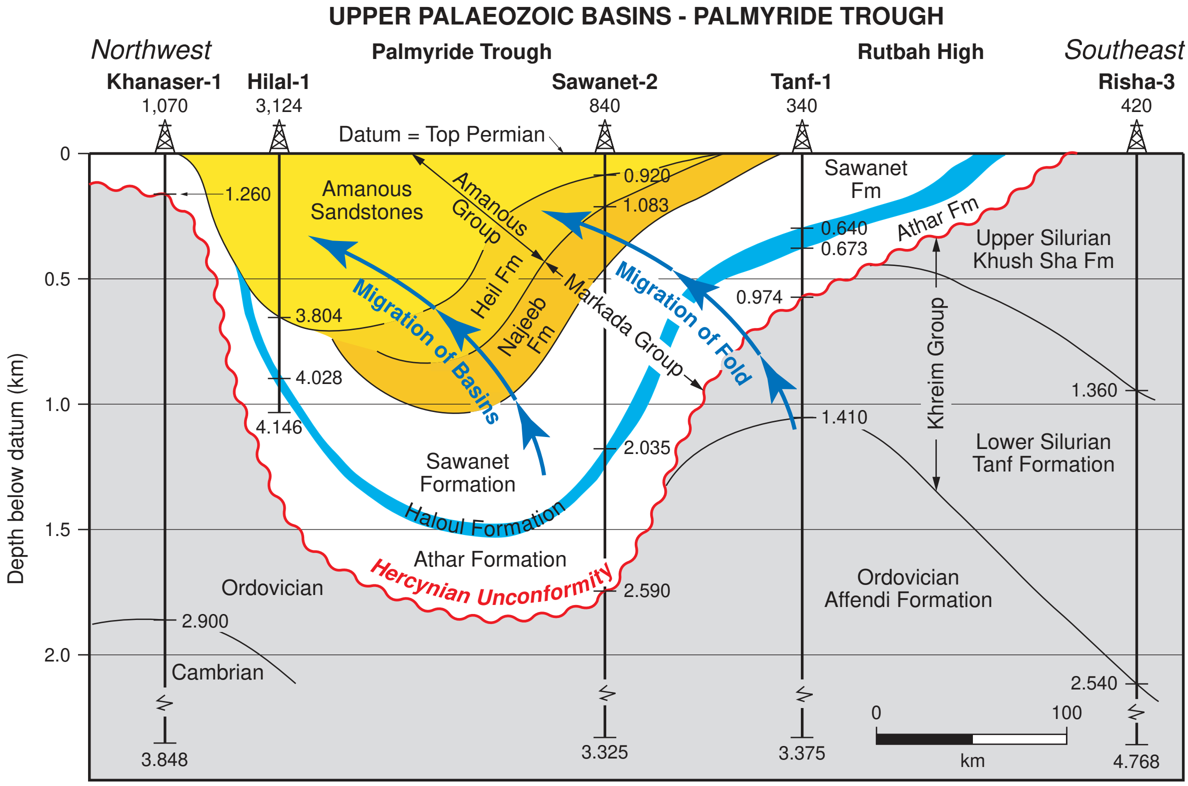


Figure 10: Cross section of upper Palaeozoic basins (Carboniferous and Permian) hung on top Lower Permian unconformity (see Figure 6 for position of section). Younger units nest within predecessor basins. Angularity of the upper/lower Palaeozoic interface is demonstrated on Figure 9. The carbonate-bearing Haloul Formation provides an excellent marker unit across the entire trough for both stratigraphic and seismic correlation. Note the northwest migration of successor basin depocentres and the asymmetry of the trough suggesting a wave-like, northwest migration of a refolded Hercynian surface.

The early trough saw an influx of fine-grained, shallow-marine, sandstones of the Carboniferous Markada Group deposited on its margins with silts and shales filling the deeper areas. Within this clastic sequence the trough-wide Haloul carbonates not only make a good seismic and stratigraphic marker, but along with the silty and shaley nature of the bulk of the section, attest to a generally low-energy system with trough flanks structurally subdued. Successor sequences built a series of vertically nested basins, however beginning in the Permian, basins began to migrate toward the northwest in unison with the migration of the southeastern flank (the Rutbah High) with the trough contracting in width. By the end of the Palaeozoic, the basin had a width of 400–500 km, much reduced from the 1,200 km peak to peak distance of the earlier end-Hercynian Orogeny anticlines.

The late Carboniferous to Middle Permian trough was perched high on the flank of the Hercynian Levant Arch with its southeastern margin formed by the northwest flank of a rising (inverting) Rutba High. As the new, younger trough and its set of internal basins, migrated toward the northwest together, there is clear linkage between sedimentation and tectonics. The termination of sedimentation within this new Palmyride Trough coincided with regional uplift, indicated by the fact that the upper Permian is missing across Syria. This is also time coincident with the emplacement of ophiolites in northern Iran along the Alborz orogenic belt (297 Ma and 268 Ma, Early to Middle Permian) during closure of the Palaeo-Tethys Ocean (Hassanipak et al., 2002) while in southeast Europe, Palaeo-Tethys was also closing (Stampfli, 2000).

At the far SW end of the Levant Arch in SE Libya, albeit schematic, Figure 11a shows a geological section after Guiraud and Bosworth (1999) that runs from the south across the Kufra Basin, north to the Cyrenaica region of NE Libya. The Kufra Basin (properly the Kufra Trough) appears

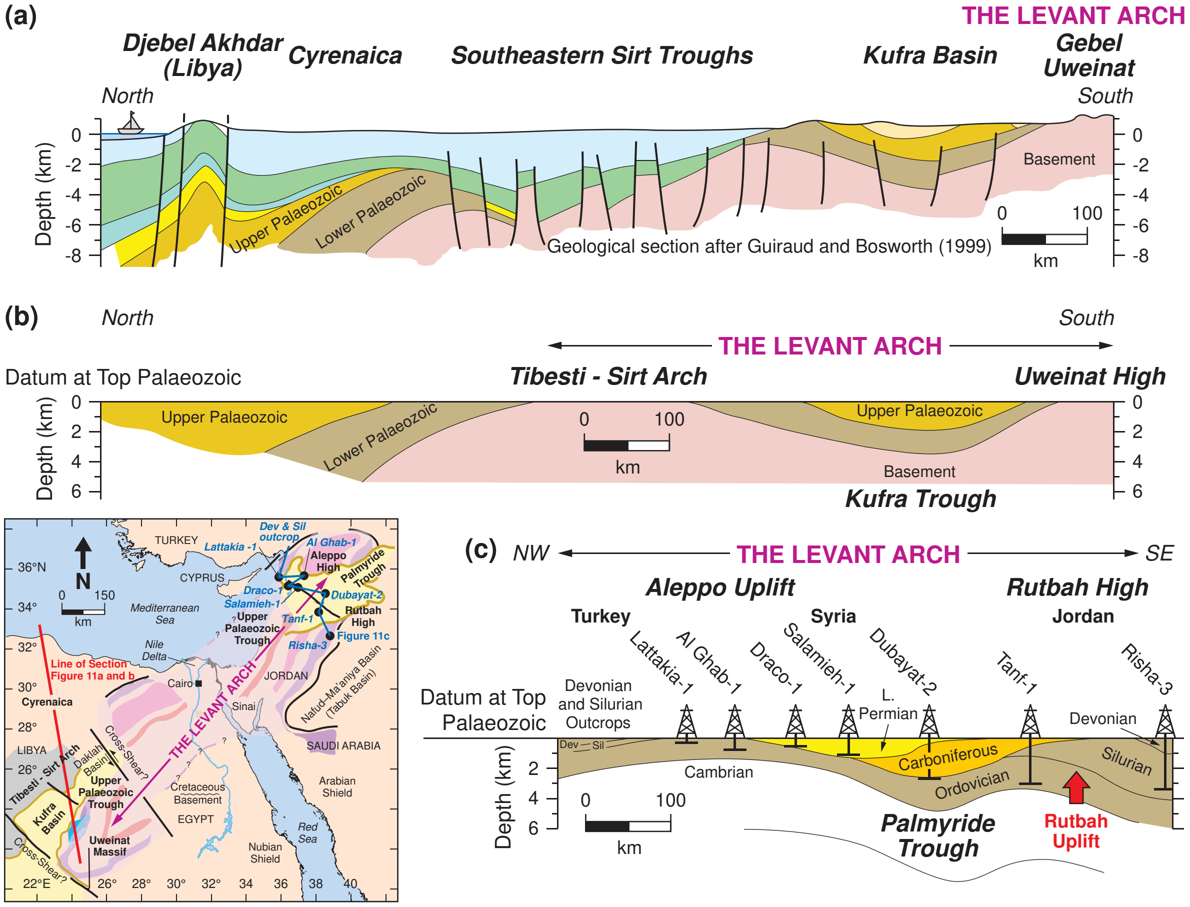


Figure 11: (a) Geological cross section from Gebel Uweinat in southern Egypt, to Djebel Akhdar in northern Libya (inset map) (modified after Guiraud and Bosworth, 1999), flattened on the Top Palaeozoic in (b). The inset map shows the Levant Arch extending from the Aleppo Uplift in Syria (c) to the Uweinat High in southern Egypt. Superimposed on the arch in Syria, late Palaeozoic sediments began to fill the early Palmyride Trough, a depression that appears to have initiated as a re-fold of the Hercynian Unconformity surface. The Kufra Basin, or properly the Kufra Trough, is a late Palaeozoic depression of the same magnitude and structural position on the Levant Arch (as noted in the inset map) as the Palmyride Trough of Syria suggesting a common stratigraphic and structural history.

as a perched depression with lower and upper Palaeozoic sediments resting on basement. Flattening on the top of the upper Palaeozoic Permian strata reveals the trough lying between the Tibesti-Sirt Arch and the Uweinat Massif (Figure 11b) within a down-warp strikingly similar to the early Palmyride Trough to the point it is equivalent both in vertical and horizontal scale (Figure 11c). Trough fill consists of upper Palaeozoic, Carboniferous and Permian, shallow-marine clastics (Lüning et al., 2010). Above the top Permian Unconformity surface there are outcropping Lower Triassic (Scythian) to Carnian, continental sandstones. The Kufra Trough extends to the northeast into Egypt where Jurassic then Cretaceous rocks progressively outcrop, suggesting the trough plunges gently to the northeast (USGS, Geological map of Africa, 2000). Several offsetting, NW-oriented fractures dissect the Kufra Trough itself and separate the Kufra from the Dakhla Basin to the northeast (Figure 11 inset).

Figure 12 shows cross sections of the overlying Triassic, Jurassic and Cretaceous basins of the Palmyride Trough, each hung on its unconformable top surface. Palaeontological work has been incorporated to not only help in identifying and correlating chronostratigraphic units but also to demonstrate the enormous time gaps, as long as 25 million years (Myr), between individual basins.

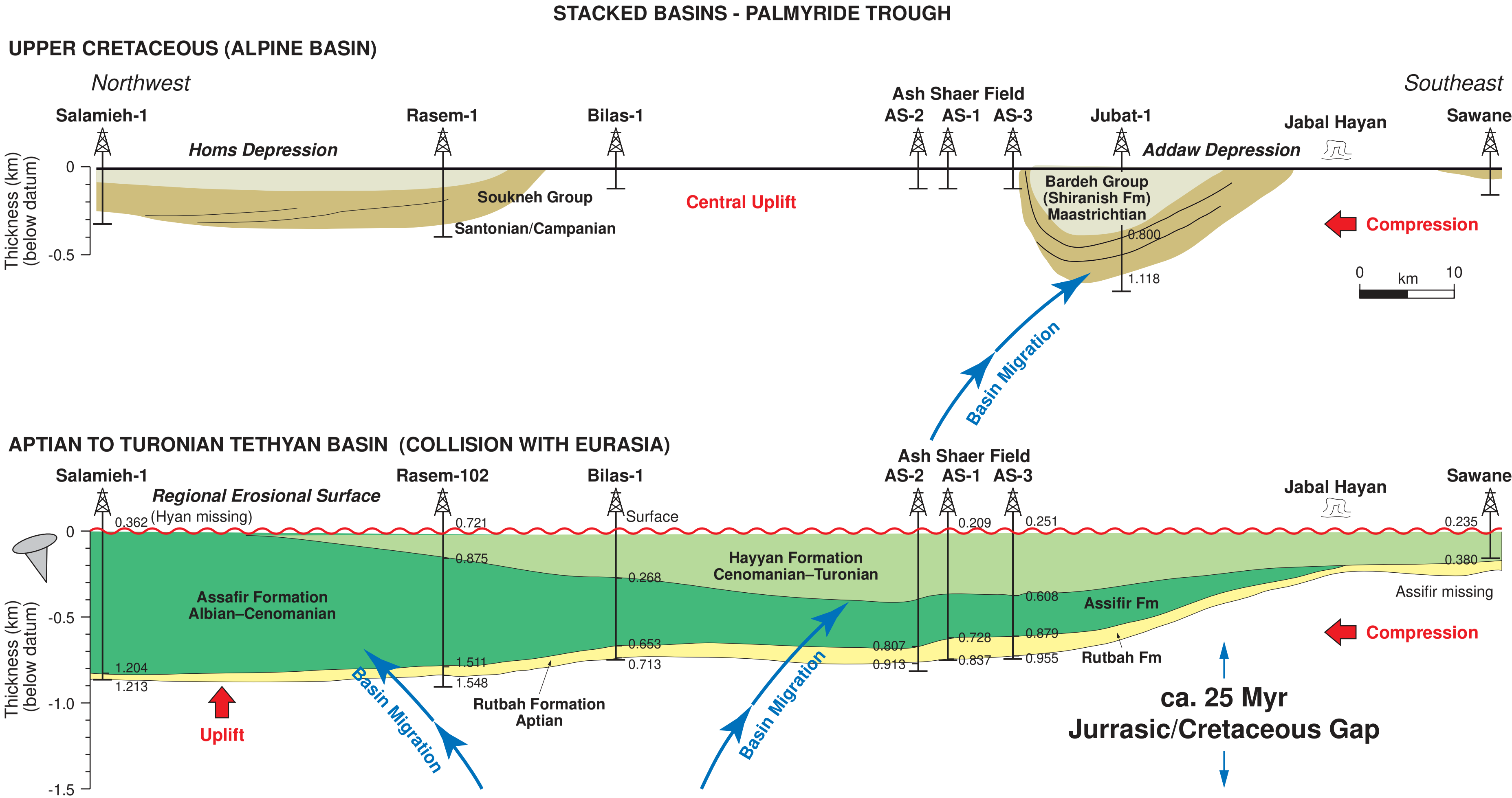


Figure 12: Stacked Basins – Palmyride Trough. Following ca. 25 Myr of non-deposition, the clastic Rutbah Formation begins to fill a Lower Cretaceous trough, the depocentre of which has migrated further toward the northwest. During the Turonian the trough migrated southeastward indicating collision with Eurasia and subsequent uplift of northern Syria. Deformation by narrowing of the trough continued into the Late Cretaceous with uplift of the Central Uplift and the formation of the two adjacent depocentres, the Addaw and the Homs depressions.

See facing page for continuation.

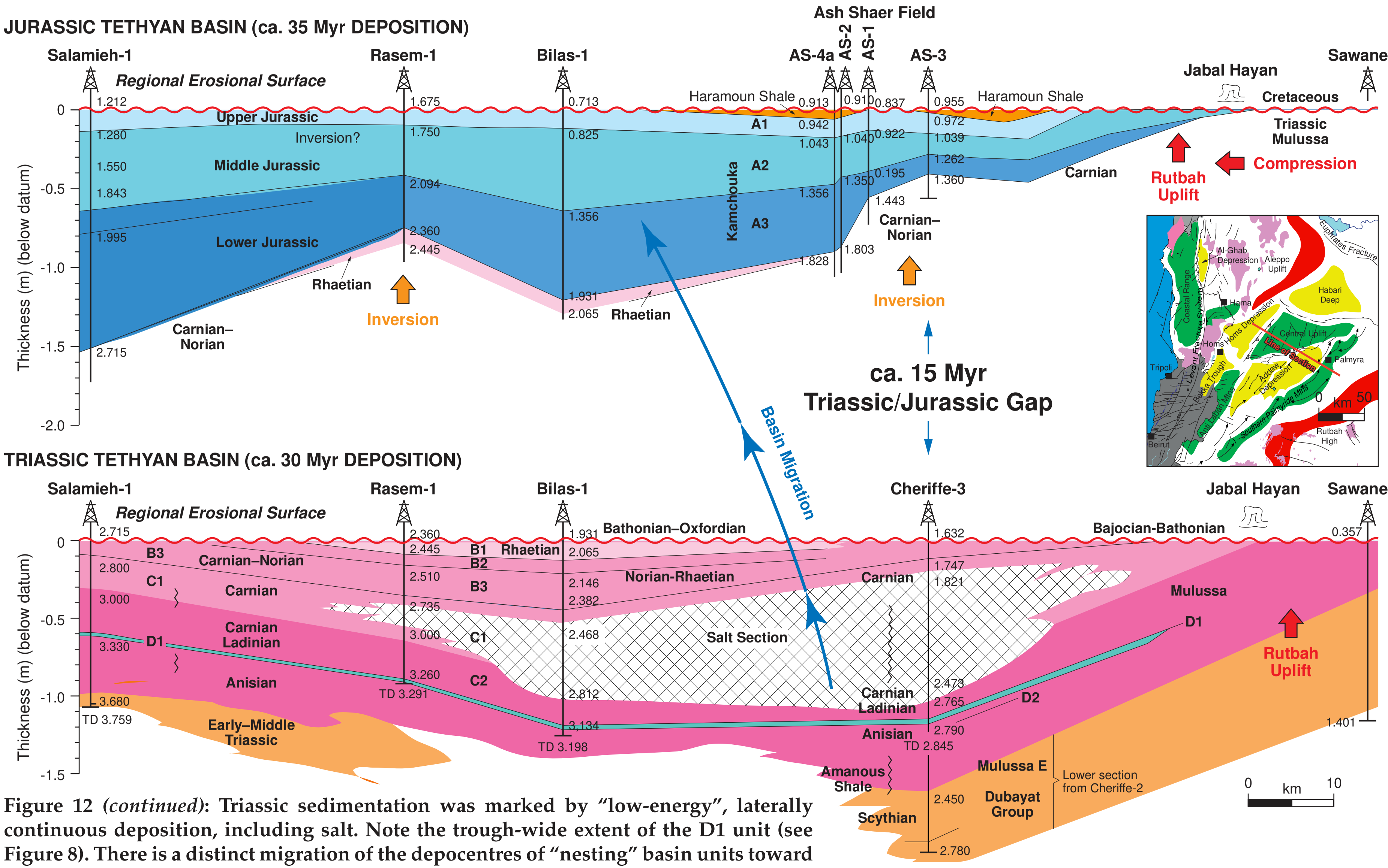


Figure 12 (*continued*): Triassic sedimentation was marked by "low-energy", laterally continuous deposition, including salt. Note the trough-wide extent of the D1 unit (see Figure 8). There is a distinct migration of the depocentres of "nesting" basin units toward the northwest and even after a ca. 15 Myr gap in sedimentation, there is a continuation of this depocentre migration during the Jurassic. The Jurassic basin, however, shows the result of trough narrowing by refolding, forcing a mid-basin inversion. At the end of the Jurassic, deposition clearly shifts to the southeast indicating uplift of the northwest margin of the trough probably related to collision with Eurasia. This also marked the end of a ca. 35 Myr of deposition across the region for another ca. 25 Myr.

The Triassic Basin has a simple bowed shape with evaporites (where present) filling the centre of the depression. Individual units (note the D1 unit) show remarkable lateral continuity plus, as within the underlying upper Palaeozoic basin, a slow, continuous migration of internal depocentres toward the northwest with a final Upper Triassic (Rhaetian age) sub-basin lying under the Rasem and Bilas areas. Migration of the basin depocentres suggests a continuously, gently rising, Rutbah High (inversion) in the south drove the system.

After ca. 30 Myr of quiet, low-energy, basin-wide deposition, suddenly sedimentation ceased for some 15 Myr with Lower to Middle Jurassic, Bajocian sediments, the oldest Jurassic sediments in the new Jurassic Basin, resting on an enduring yet unimposing disconformity. While the Jurassic cross section shows a continuation of low-energy, easily correlatable basin fill, it also shows the southeast margin shifting northwest with respect to the Triassic basin with coincident folding of the basin fill into three sub-basins separated by two inversions, one creating the Ash Shaer structure, the other forming the Rasem uplift. During the final stages of the Jurassic, during the Callovian–Oxfordian periods, the basin shrank dramatically with its centre migrating southeast suggesting uplift of the Aleppo High possibly caused by a resistance to prevailing northwest migration by a backstop positioned somewhere to the northwest, possibly the Eurasian continent.

If, as suggested here, there was a general resistance to northwest movement of the Palmyride system throughout the Jurassic Period culminating in even stronger resistance causing the Callovian–Oxfordian regional uplift, then the regions to the northwest probably also existed throughout this period under a regime of constant compression. Certainly, coincident with the uplift and termination of Jurassic sedimentation in the Palmyride Trough, to the northeast in Iran, the Khoy ophiolites of Oxfordian–Kimmeridgian age (ca. 159–155 Ma) were emplaced (Hassanipak et al., 2002) confirming the final destruction of the Palaeo-Tethys Ocean. After ca. 35 Myr of sedimentation, the Palmyride region again spent ca. 25 Myr above any depositional base level before being flooded with clastics of the Barremian to Aptian age, Rutbah sandstones and shales.

Following deposition of the Rutbah sandstones, carbonates of the lower Judea Formation show a continuation of the migration and thickening of the Lower Cretaceous Basin toward the northwest. By Turonian times, however, the younger, upper Judea Formation consisted of carbonates in a much reduced and southeast shifted basin centred under the Ash Shear area. This shift in the depocentre coincided with uplift in the northwest and emplacement of extensive ophiolites in the Eastern Mediterranean (Robertson and Mountrakis, 2006) such as the Baer Bassit north of Lattakia in NW Syria. Regional northwest compression however did not cease, and further refolding and the development of narrow Late Cretaceous and Cenozoic aged troughs and inter-trough inversions completed the final structural deformation of the area.

Magmatic Activity

Magmatic activity in the Levant region has been reasonably well documented (Barberi et al., 1980; Sharkov et al., 1989; Meneisy, 1990; Mouty et al., 1992; Baer et al., 1995; Guiraud, 1998; Wilson et al., 1998; Segev, 1998; Ilani et al., 2001). Figure 13 shows the results of Wilson et al.'s (1998) regional work and Segev's (1998) more specific Levant effort, both set against the stratigraphic column of the Palmyride Trough. Wilson et al. (1998) rightly point out that many age dates have been derived by the whole rock K-Ar method and may be unreliable thus accounting for the large background scatter of ages. This problem is slowly being corrected as more ^{40}Ar-^{39}Ar work is completed. Nevertheless, against a background of seemingly continuous sporadic volcanism, Figure 13 shows a very interesting pattern when matched against the individual basins of the Palmyride Trough. Wilson et al. (1998) show a very clear rise in volcanic activity during the gap between Jurassic and Cretaceous sedimentation, and a burst of activity during the end of Triassic deposition and on into the gap period.

Segev (1998), with data more specific to the Levant area, shows a very good correlation with the start and end of basin deposition. He shows that regional peaks of activity occurred at about 240 Ma near the Permian/Triassic boundary then again at approximately 208–209 Ma (ca. Norian, J1) at the end of the Triassic. There is then a burst of activity at the base of the Jurassic Basin during the

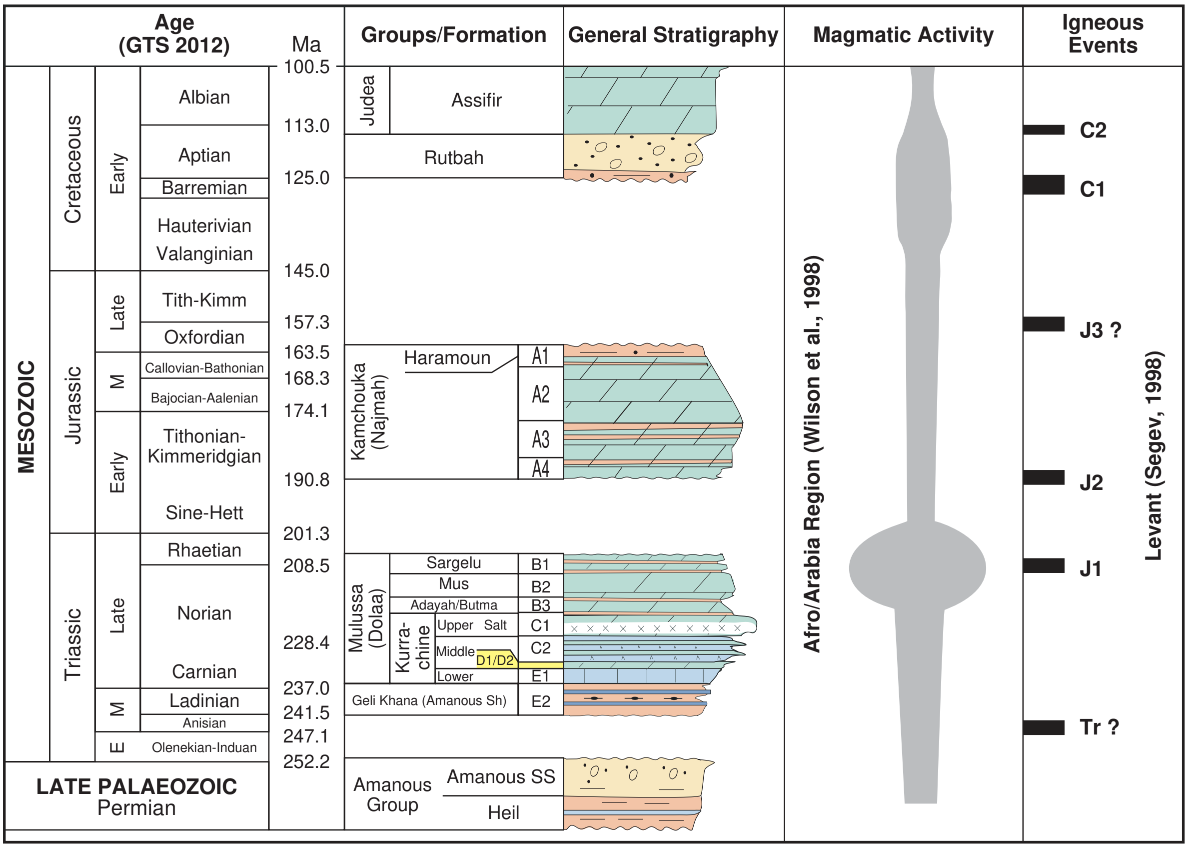


Figure 13: Plot of ^{40}Ar-^{39}Ar ages of igneous events in the Levant (Segev, 1998) and magmatic activity in the Afro/Arabian Region (Wilson et al., 1998) with respect to stratigraphic cycles in the Palmyride Trough. The time scale is linear. Periods of magmatic activity at the Permian/Triassic, the Triassic/Jurassic and late Jurassic/Cretaceous boundaries correlate well with the initiation and termination of periods of non-deposition in the Palmyride Trough.

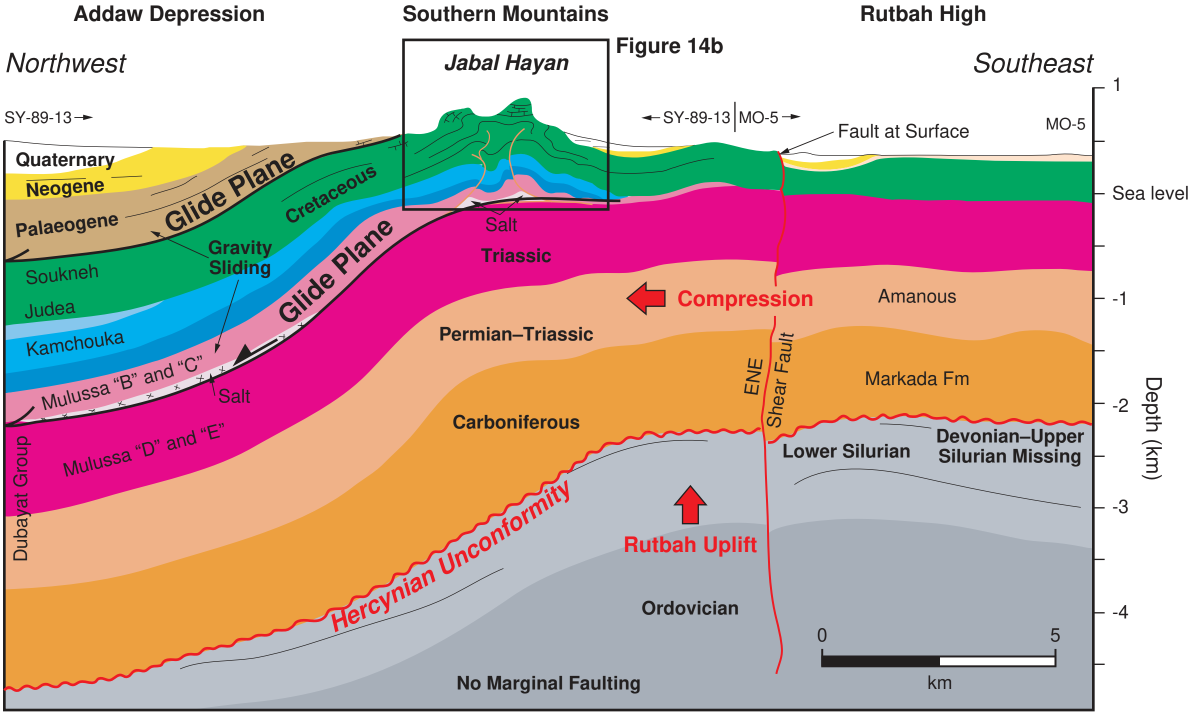
middle Liassic (Early Jurassic) and again at the top of the Upper Jurassic coincident with deposition of the clastic units of the Haramoun Formation. Two further bursts of activity occurred during the Early Cretaceous just prior to and following deposition of the Cretaceous Rutbah Formation.

Deformation of the Palmyride Trough

Turning attention to trough deformation, the absence of marginal normal faulting involving the basement precludes a rift origin (Figure 14). Figure 14, constructed with seismic, well data and surface information, shows a section running across Jabal Hayan, one culmination of the Southern Palmyride Mountains near Palmyra. These mountains have variably been mapped as thrust folds with Salel and Séguret (1994) stating that the Southern Palmyride Mountains structure "resulted from thin-skinned tectonics and includes duplexes, anticlinal stacks and imbricate thrusts". Others have suggested the mountains formed as inverted fault blocks along a rifted margin (Sengör and Yilmaz, 1981; Al-Saad et al., 1992; Barazangi et al., 1993; Beydoun and Habib, 1995; Laws and Wilson, 1997). Serious issues arise from the fact that there is no development of even a minor foreland basin, no obvious normal faulting on the surface or on seismic and no erratic "syn-rift" sedimentation to suggest the presence of a bounding fault. Instead, the Triassic, Jurassic and Cretaceous sections simply feather out to the southeast with the Jurassic thin under Jabal Hayan and absent in wells further southeast. Bedding is again tram-line monotonous with thin beds often being walkable across the entire mountain.

Searle (1994) conducted a complete field study of two structures southwest of Palmyra (jabals Hayan and Al Mazar) and clearly demonstrated that trough margin structures are in fact a series of box

(a) GEO-SEISMIC SECTION ACROSS SE MARGIN OF THE PALMYRIDE TROUGH



(b) Jabal Hayan Box Fold

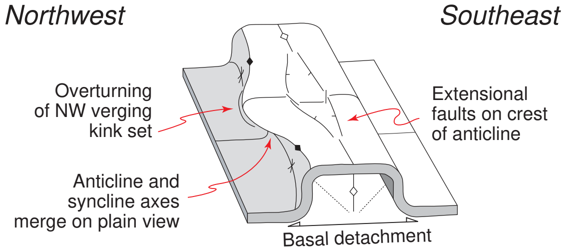


Figure 14: (a) Geo-seismic section showing a total lack of normal (extensional) faulting, no initiation of a foreland basin plus late-stage gravity sliding. Compression from the southeast forced the Rutbah High to rise triggering the thin-skinned structuring (Wood, 2001). (b) Jabal Hayan fold model after Searle (1994). See Enclosure Ia for line position.

folds lying on Middle Triassic evaporites (Figure 14b). These formed during the Cenozoic along an over-steepened trough margin coincident with uplift of the Rutbah High during the Alpine Orogeny. Down-slope rafting with resultant box folding was facilitated by evaporitic or shaley units acting as glide planes. Two glide plane surfaces were noted, the first and most significant, a Middle Triassic one and a second, within the shaley Eocene section. While the work of Searle (1994) was confined to surface exposures, a geo-seismic section across Jabal Hayan (Figure 14a) adds seismic to the interpretation and clearly backs his effort. Albeit the seismic image directly under the jabal is poor, there is sufficient lateral data to confirm the surface work plus the absence of margin faulting, no foreland basin and no thrust-related duplexing indicating neither horizontal thrusting nor extensional tectonics played any role in the formation of the Southern Mountain chain. One vertical shear fault is present, one that has been mapped on the surface (Ponikarov, 1964) and of probable Alpine age. It is one of many ENE-trending, right-lateral, strike-slip faults, such as the Jhar Fault forming the southern margin of the Central Uplift. They are probably faults that are conjugate to the major left-lateral Levant Fracture running through Lebanon (Searle, 1994) and helped accommodate the overall shortening across the trough during Alpine structuring.

To see the entire system at work, Enclosure III shows a series of surface geology, well and seismic based geo-seismic depth sections, the first running from the Southern Palmyride Mountains, across the northeastern and narrow section of the Addaw Depression to the Central Uplift, then across the Homs Depression to the Salamieh Arch often deemed to be the northwestern flank of the Palmyride Trough (Enclosure IIIa). It will be shown later that this arch is internal to the Palmyride Trough, the true Aleppo Uplift offset and lying further northwest. Jabal Hayan can be seen perched on the northwest migrating margin of the Rutbah High. Under the Central Uplift this northwest migration of basin depocentres is clear with a second set of basins under the present Homs Depression and Salamieh Arch, reflecting the trough division starting in the Jurassic (Figure 12), also showing this migration toward the northwest. The entire trough fill has been constantly on the move, shifting northwest through time. The Salamieh Arch becomes active during the Late Cretaceous to Cenozoic period (Alpine) as indicated by the filling of the Homs Depression from the northwest. A rising, broadly asymmetric, Central Uplift is tilted to the southeast with high-angle thrust faults controlling its northwest margin, the southeast margin controlled by the vertical Jhar Fault. While salt movement is clear, it does not appear to be a driving force, rather it acts as a glide plane and a passive fill of gaps formed between pre- and post-Middle Triassic structuring. Note again the continuity of the stratigraphy allowing for accurate correlations.

The Addaw Depression opens and deepens to the southwest toward Lebanon and Enclosure IIIb shows the active structuring within it forming the down-flank Southwest Fold Belt. Down-slope rafting of the post-Middle Triassic section resulted in a series of buckle folds formed by sediment collapse into a crowded trough along a sharp, bedding-parallel glide plane at the level of the Carnian–Norian evaporites. Each structure shows distinctive sediment on-lap onto its southeast flank indicating both structural and sedimentary migration towards the northwest. While the on-lap has been noted in the past and therefore the timing of formation (Chaimov et al., 1992), the sense of migration of the structures has not. In addition, the core of the Abu Rabah structure contains Permian–Triassic mobile shales suggesting that a deeper glide plane may exist within the underlying section, however seismic definition is extremely poor at this level making both correlations and depth conversion suspect at this lower level.

Figure 15 is an enlargement of one structure (Qum Qum) within the Addaw Depression. The section is in two-way-time (TWT) so there is structural distortion at depth, particularly under the fold where the glide plane is not flat due to velocity pull-up. The box-fold shape is distinctive with bedding continuity very clear up to at least the Upper Cretaceous level. On-lap of sediments on the southeast flank of the structure began at least in the Palaeogene, however other structures show the on-lap began in the Late Cretaceous (Chaimov et al., 1992) coincident with the initiation of the Alpine Orogeny. With the Rutbah High active at this same time, as indicated by the Late Cretaceous formation of the Wadi Sirhan Graben in Jordan, and the outpouring of volcanics in the Late Cenozoic in southern Syria and northern Jordan, it is reasonable to assume that uplift of the Rutbah High caused over-steepening of the southeast flank of the Palmyride Tough triggering down-slope mass transport. With the Central Uplift also actively rising (inverting) at this time as the trough narrowed, it probably acted as a backstop, with the flank sediments therefore collapsing into a crowded trough.

2-D MODEL OF TROUGH DEVELOPMENT

Based on the evidence above, a sequence of events can be presented that describe the two-dimensional development of the Palmyride Trough through time. Enclosure IV is a series of flattened sections controlled by well data and seismic demonstrating very clearly, initiation of the Palmyride Trough through compression-driven refolding of the Levant Arch. From that time forward, the trough narrowed and refolded several times, driven continuously by a slowly rising, itself inverting, Rutbah High forming the southern flank of the trough with the resultant narrowing and crowding of sediments within the trough between the Rutbah and Aleppo uplifts. Internal basins migrated northwest in wave-like fashion, the fold train shortening with time as the trough narrowed. The end of each cycle (basin) coincided with trough-wide gentle inversion (eustatic uplift) with complete retreat of marine waters from the region and the onset of regional volcanism and ophiolite emplacement.

It is interesting that the Aleppo Uplift remained almost static, acting mainly as a very slowly rising backstop to the relentless push by the Rutbah High. As noted earlier, this infers that the Aleppo High was continuously feeling resistance to northwest movement, a situation suggesting the regions north of the Aleppo High were also under constant compression between Afro-Arabia

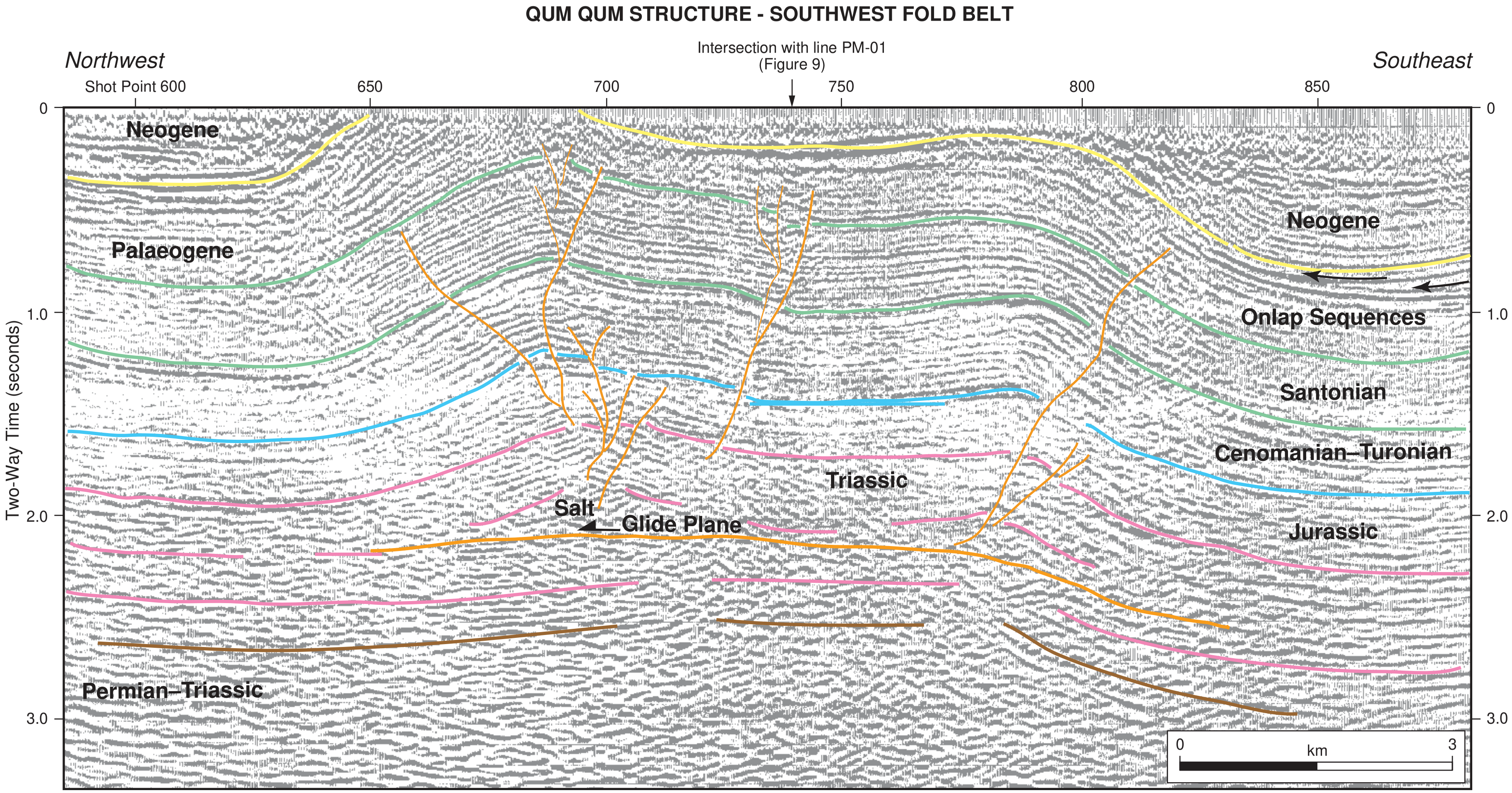


Figure 15: Seismic line CH-36 (see Enclosure Ia for location) across the Qum Qum structure within the heart of the Palmyride Trough showing the structure is a symmetrical box fold parallel to the axis of the trough. The detachment surface is the Middle Triassic evaporites. Thick, onlapping Palaeogene sediments to the right of shot point 800 and left of shot point 650 show timing of movement is Alpine age as Middle Triassic to Cretaceous units and the Lower Triassic and Upper Permian–Triassic are effectively parallel. While it is not obvious on this line, Chaimov et al. (1992) suggested the uplift started in the Late Cretaceous. Note that, as this is a time section, there is considerable pull-up on the glide plane. In depth this surface will be almost flat.

and Laurasia, the ultimate backstop. It is also interesting that low-energy, *in situ*, sedimentation remained the norm throughout the Mesozoic and the early Cenozoic with almost no lateral input suggesting extremely low relief over the rising Aleppo and Rutbah highs. Strong structural movements, as during the main development of the Euphrates Graben, down-slope rafting in the Addaw Depression, the initiation of the Levant Fracture and the resultant uplift of the Levant Mountain chain, all coincided with the termination of the Tethyan era and essentially concealed the pre-history of the region.

CROSS-TROUGH FRACTURING

To complete an examination of structural features that have contributed to at least the young deformation of the Palmyride Trough, one has only to look to the Oligocene to Recent Druze Plateau basalts south of Damascus (Figure 16) that cover a large area of SW Syria and extend into Jordan, their outline elongated northwest by southeast. Young cinder cones line up on the top of these basalts in a distinct northwesterly direction defining sharp lineaments, probably reflecting basement fractures. The inference is that NW-oriented, deep fracturing has provided an opening in the crust for magma extrusion.

Figure 17 is seismic line CH-81-44, a trough-parallel line in the heart of the Addaw Depression where seismic quality is not affected by fold structures and therefore deep imaging is good to excellent. The line clearly shows two deep-seated, vertical shears that compartmentalise the lower

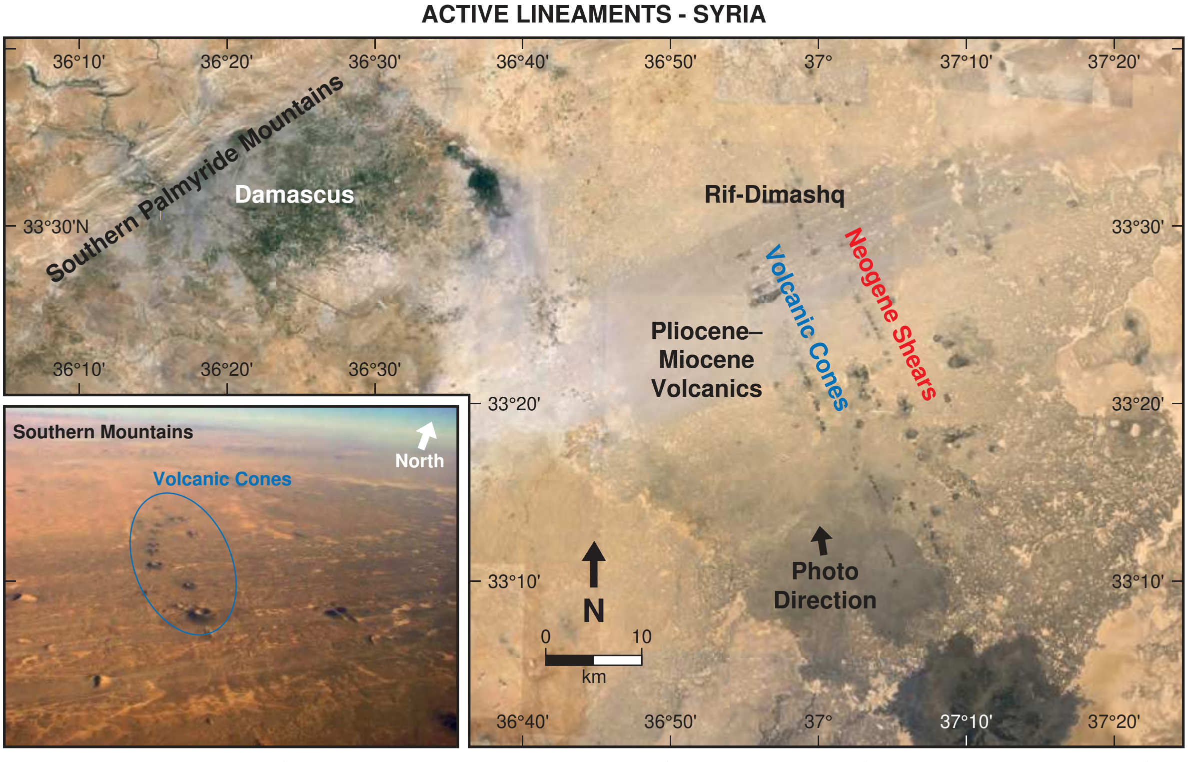


Figure 16: Southeast of Damascus, the Druze Plateau (northern part of the Harrat Ash Shaam) is composed of Cenozoic age basalts (25 Ma to Recent). Extrusion happened coincident with the initiation and development of the Levant Fracture, now running from the Gulf of Aqaba to northern Syria, so the two events are probably structurally related. While the entire plateau, including the Jordanian region, generally trends northwesterly (see Enclosure I), cinder cones line up in a distinct NNW orientation marking several distinct lineaments from which lava has emanated over time. The relationship of the two lineaments (the Levant Fracture and the Cenozoic lineaments) is best explained as structuring related to NNW-directed compression with the cinder cones marking the traces of compression-parallel tension fractures and the Levant lineament a related left-lateral conjugate fault.

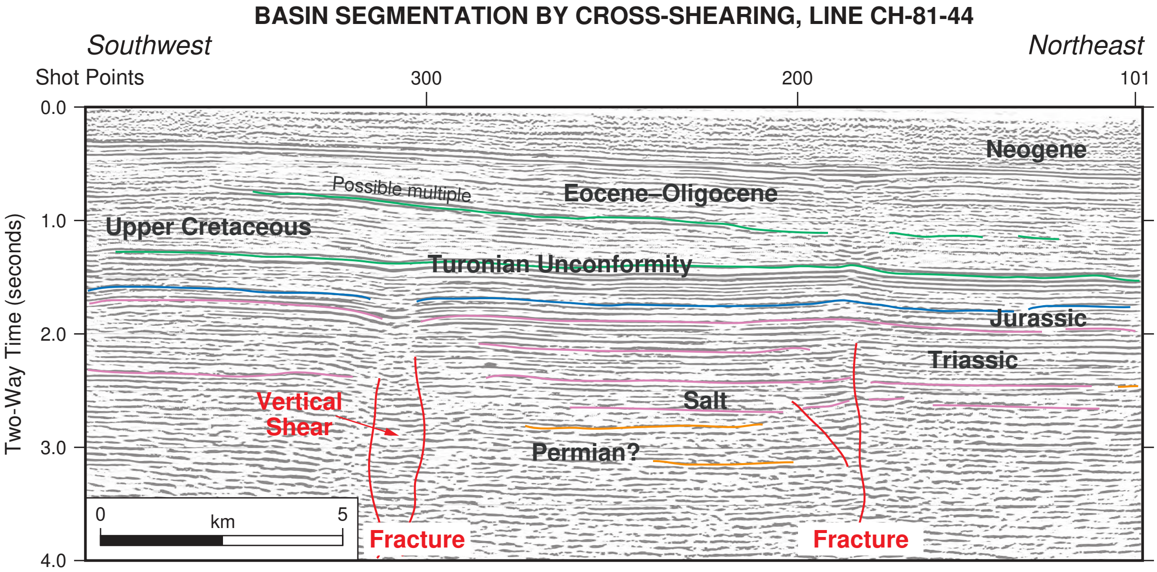


Figure 17: Seismic time section showing NW-oriented cross-shears within the Addaw Depression, Palmyride Trough. See Enclosure Ia and Figure 19 for line position. Two vertical shear fractures come from depth and appear to penetrate only up to the Turonian unconformity. As demonstrated on Figure 15, onlap of sediments onto the rising box-folds occurred at about this same time. Below this horizon, the monotonous flat bedding of the section again suggests the low-energy environment of deposition of the Tethyan basins. Also, here in the heart of the trough, unconformable surfaces are not angular. The Triassic salt section is bedded, and while offering a glide plane for down-slope rafting (Figure 19), clearly it is not diapiric in nature.

part of the imaged section into three blocks. The fractures originate at depth, dying out and splaying upwards to about the top Lower Cretaceous horizons. At that point, the Upper Cretaceous and Cenozoic sediments can be seen to prograde onto the Turonian Unconformity coincident with the onset of regional Alpine orogenesis while pre-Turonian sediments only reflect the now familiar tram-line-like bedding including the bedded salt of the Middle Triassic. No salt movement is visible, the salt beds being too thin to act independently or as diapirs. The position of the fractures is shown on Figure 19. While they often do not reach the surface, and therefore must represent older periods of fracturing, one small, undated (but believed to be Cenozoic) volcanic outcrop has been mapped within the Addaw Depression (Ponikarov et al., 1966) indicating some fractures broke through to the surface.

Across the trough on its northwest flank, Figure 18 shows that the same cross-basin shears exist. Seismic line HR-80-11 images a less apparent, yet very significant, cross-trough fracture zone, the Habari Shear. Good stratigraphic and age control from adjacent wells (SPC Internal Reports) backs the interpretation. Of special note is the very large vertical offset to the southwest across the shear zone where a full Jurassic and Triassic section has been deposited. To the northeast, the entire Jurassic is missing and the Triassic is severely attenuated. As in the Addaw Depression, faulting appears to die out at or near the top Turonian Unconformity where again younger sediments on-lap the unconformity surface.

To the author's knowledge, neither the presence nor the significance of cross-trough shears have ever been addressed except by Wood (2001, 2011). Certainly their impact on trough sedimentation and deformation has been ignored. It will be shown here that they not only played a significant role in trough segmentation and rotation but line up with more regional NW-oriented fracture patterns suggesting a tectonic level relevance.

THE PALMYRIDE TROUGH THROUGH TIME

To recap, the origin of the Palmyride Trough dates back to the Carboniferous Period, not as an extensional collapse structure but as a result of compressional folding, down-warping and cross-

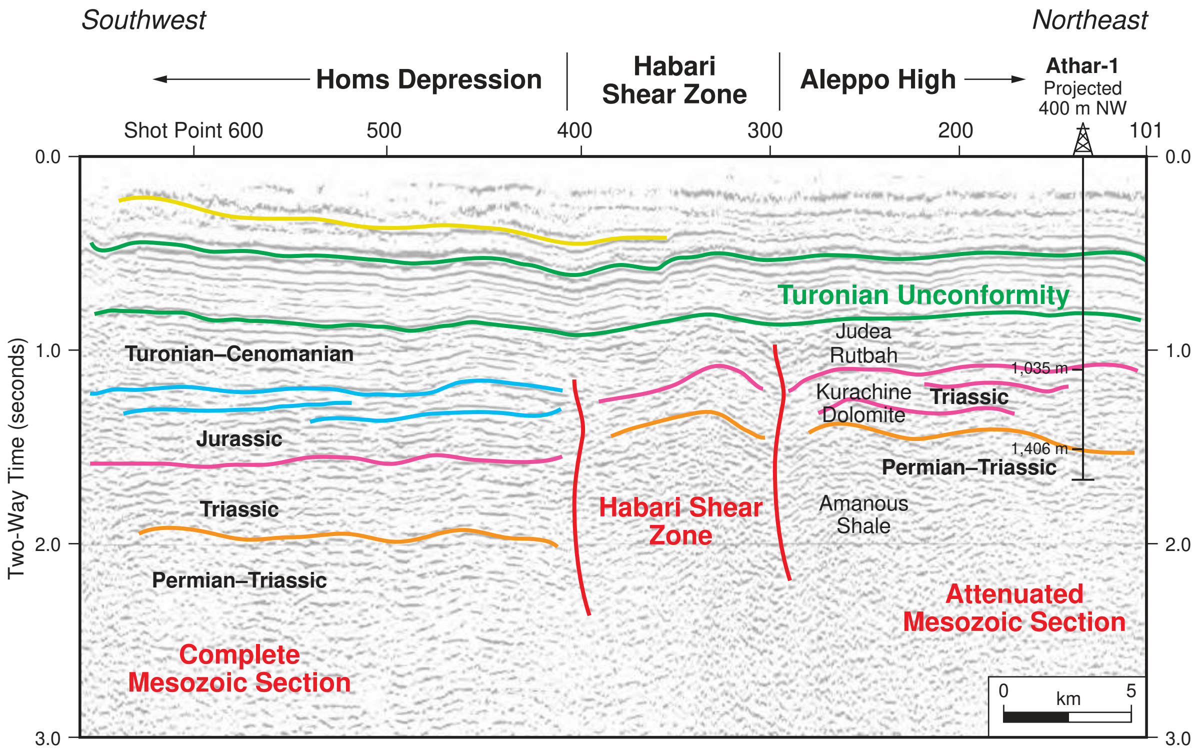


Figure 18: Line HR-80-11 across the Habari Shear Zone. This fault zone offsets the northwest margin of the Homs Depression and although data quality is poor across the fault zone, correlations are tightly controlled by reliable adjacent well data on either side. The Athar-1 Well, lying just off the northeast end of the line, encountered a section similar to Khanaser-1 with the entire Jurassic and the Upper Triassic missing. The well bottomed in Permian–Triassic shales. To the southwest of the fracture, a full Jurassic and Triassic section is encountered in wells. Line and well positions can be seen on Enclosure Ia and Figure 19.

shearing of the underlying, more extensive regional geanticline, the Levant Arch (Figure 6). This reset a regional, NW-propagating, fold train to one with a crest-to-crest distance of 250 to 400 km. To the southeast the new Rutbah High formed the southeastern wall of the new trough and as it continued to rise and migrate northwest, it acted as the local driving force. The new trough filled in stages, each stage (basin sequence) separated by a subtle disconformity, each deceptively representing long periods of exposure. It is proposed that the persistent uplift and northwest migration of the trough's southeast margin (the rising Rutbah High) forced basin crowding resulting in end-of-basin, gentle regional inversion and the retreat of basinal seas. These inter-basin periods were marked by peripheral and regional magmatic and structural activity. Continued uplift and northwest migration of the trough's southeast margin finally resulted in over-steepening of the southeast flank of the trough in the latest Cretaceous and Cenozoic (Alpine time) triggering down-slope rafting of the entire post-Middle Triassic section. This in turn exaggerated internal basin crowding resulting in the strong inversion of the Central High we see today.

The northwest, wave-like propagation of internal folds and the northwest migration of successive basins, speaks to the domination of the southeast flank of the trough in this deformation, driven by the uplift (inversion) of the Rutbah High to the south. On a larger scale, the trough was feeling Gondwana's steady northward approach to Eurasia. This regional overriding compression, the near total absence of margin parallel normal faults within the trough, the total absence of internal block faulting plus laterally persistent, low-energy sedimentation eliminates a rift origin for the trough.

With NW-trending, cross-trough shears having significant effects on basin compartmentalisation through time, just two forms of deformation, folding at various scales and cross-basin shearing, dominate the architecture of the Palmyride Trough and regional, horizontal compression from the southeast appears to offer a simple, elegant answer to what has been the driving force. The recognition of an alternative origin of the Palmyride Trough mandates a new look at basin deformation through time by a review and update of basin isopachs compiled by a number of authors (Beydoun and Habib, 1995; Laws and Wilson, 1997; Brew et al., 2001; Wood, 2001, 2011).

New Isopachs of the Palmyride Basins

Figure 19 is an isopach of the Triassic Basin based mainly on Wood (2001, 2011) but inclusive of new information and additional published data (Brew et al., 2001; Nader and Swennen, 2004; Basha, 2008). For example, the Draco-1 Well drilled in 2010 and the Itheria-1 Well drilled in 2011 offer confirming evidence. The contour interval is 500 m. In general, drill and seismic data acquired over the last 10 years has modified but not challenged the original isopach. The broad opening and deepening of the basin to the southwest under Lebanon is clear with no indication of termination in that direction. The sedimentary limits of the basin are directly controlled by marginal highs and the cross-basin shears discussed above.

The Draco and Itheria wells are significant in that they were both drilled over what was considered to be the Aleppo Uplift. Both were drilled on outcropping Cenomanian carbonates, the Draco-1 Well on the Hama Anticline, an uplift running southwest from Hama, the Itheria-1 Well on an isolated window of Cretaceous carbonates just south of the Khanaser-1 Well. The Hama Anticline is defined on the geological map of Syria (Ponikarov et al., 1966) as "an expansive window of Cenomanian carbonates that stands out against a background of flanking Palaeogene carbonates and Neogene clastics and volcanics". This uplifted area has been assumed to be the southwest extension of the Aleppo High where the Mesozoic section has been universally deemed to be severely attenuated as under the Khanaser-1 Well drilled in 1975. For this reason, no seismic had been shot and no wells drilled on the Hama Anticline before the Draco survey and well were proposed.

The two wells were drilled on opposite sides of the Habari Fracture (Figure 18), a feature not mapped by earlier workers and Figure 19 demonstrates the tremendous effect of this particular cross-trough shear. Itheria-1, as expected, hit the Ordovician Affendi sandstones at a depth of 1,470 m (Kulczyk Oil Ventures Inc., press release, March 29, 2012) after drilling a very attenuated Mesozoic section. This confirmed its position on the Aleppo High. To the southwest however, the Draco-1 Well bottomed at 3,990 m in Permian Amanous sandstones after penetrating 1,825 m of Triassic sediments including a full section of the evaporitic Kurrachine dolomites (personal communications). This single well proved a massive offset of the Palmyride Trough across the Habari Fault and expansion of the Palmyride Trough to the northwest to include the Hama Uplift and probably the Latakia area on the Syrian coast where both the Latakia-1 and Fidio-1 wells bottomed in Triassic sediments (Bowman, 2011).

If the Hama Anticline is not an extension to the Aleppo High, then it must represent an independent, second fold within an expanded trough, parallel to and coincident in time to the Central Uplift. These two folds therefore define a new fold train, crest-to-crest being from 65 to 75 km. Wood (2001) recognised further refolding of the Hama Anticline itself, to a wavelength of approximately 15 km. If true, then a series of ever younger refolding events have set up overprinting fold trends, reducing successive and younger wavelengths from over 1,200 km at the end of the Hercynian Orogeny in the Late Devonian to early Carboniferous time to just 15 km in the Cenozoic.

In SW Syria, it has been shown that the well-known Neogene Druze volcanics are associated with linear sets of volcanic cones and on Figure 19, a map of the new Triassic basin, a piece of the geological map of Syria (Ponikarov, 1964, Ponikarov et al., 1966) has been inset to indicate the orientation of these surface lineaments. The Triassic cross-basin shears clearly line up about 20 degrees counter-clockwise to the younger set suggesting either the stress field has rotated through time or that the whole Afro-Arabian tectonic plate rotated. While beyond the scope of this paper, it has been established that regional rotation of the Afro-Arabian plate occurred during the fragmentation of Gondwana (Visser and Praekelt, 1998; Veevers, 2004), so the notion of rotation

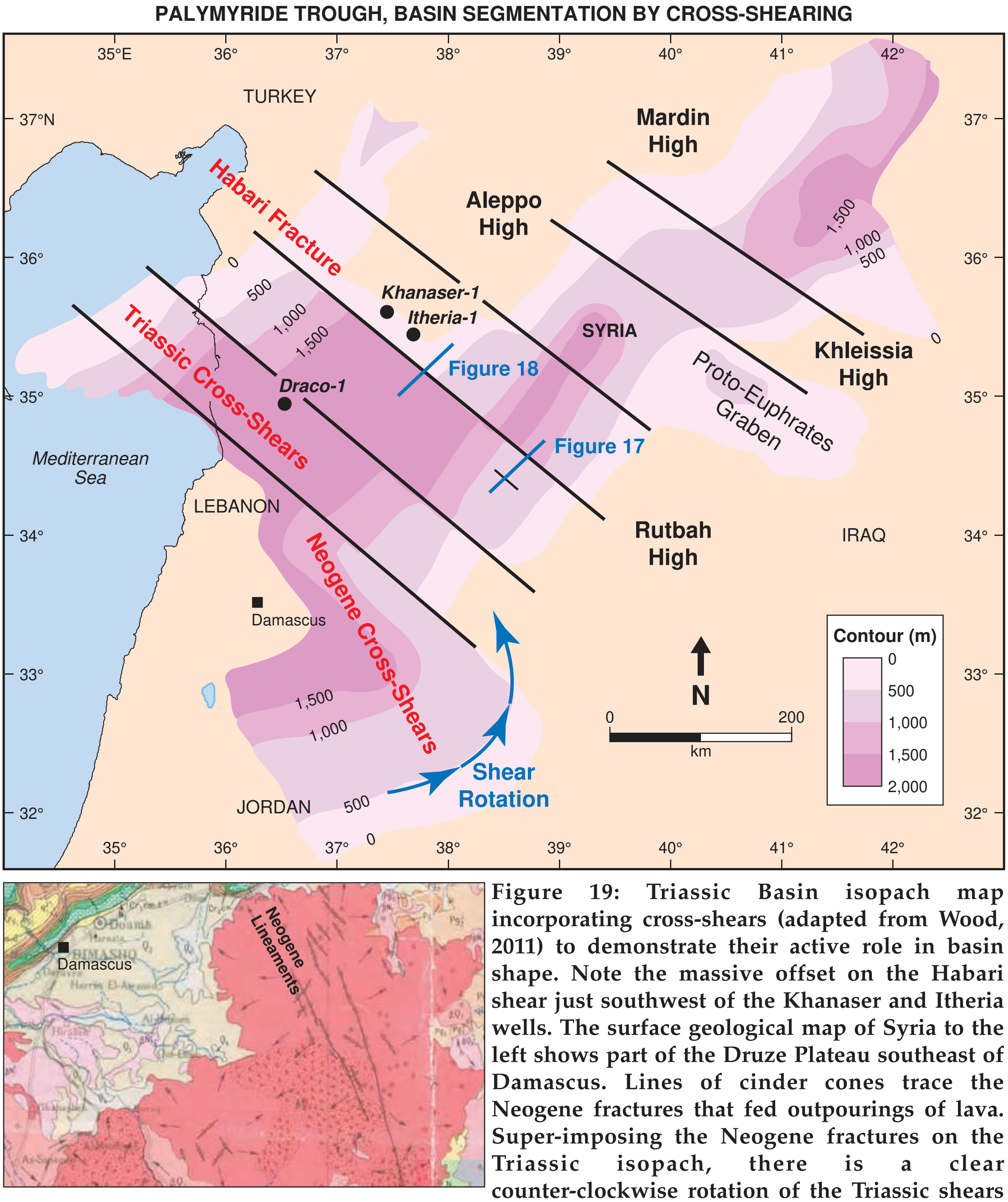


Figure 19: Triassic Basin isopach map incorporating cross-shears (adapted from Wood, 2011) to demonstrate their active role in basin shape. Note the massive offset on the Habari shear just southwest of the Khanaser and Itheria wells. The surface geological map of Syria to the left shows part of the Druze Plateau southeast of Damascus. Lines of cinder cones trace the Neogene fractures that fed outpourings of lava. Super-imposing the Neogene fractures on the Triassic isopach, there is a clear counter-clockwise rotation of the Triassic shears *versus* the younger fractures.

derived from this study's isopach work of the Triassic basin relative to the present should be correct. Further, as the cross-basin shears clearly controled sedimentation, they were also probably instrumental in basin genesis and rotation.

In separate efforts, Dewey (1987) and Dewey et al. (1989) demonstrated counter-clockwise rotation of Afro-Arabia relative to a fixed Europe by linkage through Atlantic magnetic striping. Wood (2001) with only detailed isopachs to work with, demonstrated that up to 19.5° of counter-clockwise rotation of the Palmyride region may have taken place between the Miocene and Triassic periods. While he was unable to determine the true error in his rotation calculations, it was clear, first, that regional and local counter-clockwise rotation did occur through time and second, that the amount of rotation was in the order of 20°. Wood (2001) went on to use his calculated rotations for several basins to demonstrate that if each basin were rotated back to its original orientation, then the regional stress direction remained effectively constant from the southeast. He therefore concluded that the regions of NE Afro-Arabia deformed through time under a single, constant, far-field stress system.

Figure 20 is a comparison of the Jurassic basin orientation *versus* the Triassic to show the counter-clockwise rotation of the older basin relative to the younger. The clear narrowing of the Jurassic basin relative to the Triassic basin adds to evidence of compressional folding and cross-basin shortening driven by a NW-oriented force. Accepting that cross-basin shearing controlled sediment distribution, some movement on the shears has clearly occurred throughout the life of any one basin. However, with sedimentation dominated by low-energy deposits, any activity along these shears during the life of each basin must have been minor. It is therefore reasonable to expect that the majority of the shearing and therefore rotation, occurred during inter-basin times, coincident with periods of high local and regional volcanic and structural activity. If this is true, then it would also be reasonable to look for a linkage between the cross-shears and volcanism. With respect to this idea, minor volcanic activity is indicated by volcanoclastic debris recorded in the lowest section of the Anisian age Kurrachine Formation of the Mulussa Group, where the unit is described only as "green in colour with calcite filled vugs".

At the Khanaser-1 Well there is a 141 m unit of "undated" Triassic containing a 5 m sill of basalt described as "green to black and granular, consisting of laths of plagioclase and glassy pyroxenes". At Mount Herman on the Syrian–Lebanese border, the Jurassic is represented by more than 2,500 m of alternating massive and thin-bedded limestones ranging from Lias (Early Jurassic) to Oxfordian in age. Volcanics near the base of the section have been deemed to be Bajocian in age based on their stratigraphic position below a dated Bathonian section (Mouty et al., 1992) although these are probably Liassic based on ^{40}Ar-^{39}Ar geochronology data (Segev, 1998). At Hilal-1 Well in the Homs Depression, the Lower Cretaceous contains interbedded clay and volcanic detritus below a sandy section. Basalt has been reported at the base of this unit in the Euphrates Graben and a basal volcanoclastic unit has been logged in the Coastal Mountains. Unfortunately, these reference points are scattered and it is hard to relate any volcanics with the cross-shears. The Khanaser-1 Well might be a candidate as it lies adjacent to the Habari Fault Zone.

Figure 21 is a block model showing the forms of data-supported deformation and how these all relate to a single horizontal stress system. Under a hypothesised, constant, NW-directed, far-field force, the entire NE African and Arabian region reacted by fragmenting along NW-oriented, vertical, deep-seated tension fractures into linear, NW-elongated, crustal strips. Individual strips then independently folded, sediments accumulating in the down-warped areas with later inversion of sediments contained/confined in the down-warps. Northeast to southwest general expansion occurred and regional rotation was accommodated by shear movement on the original tension fractures. Depending on transpression or transtension occurring at probable bends in the factures, localised flowering or rifting would occur, some shears seeding none to minor rifting such as the Wadi Sirhan Graben of Jordan, others initiating sites of major rifting such as the Euphrates Graben. Finally, N-directed conjugate shearing, exemplified by the Levant Fracture (Dead Sea Fault), crosscut the region adding complications to an already complex structural system. Figure 21 presents a simple but elegant model that connects the various forms of deformation documented within and around the Palmyride Trough.

REGIONAL EVIDENCE FOR A GREATER EAST MEDITERRANEAN TROUGH

Simultaneous geological events across the North African and Arabian area have been carefully recorded by a number of authors (Guiraud, 1998; Stampfli and Borel, 2004; Guiraud et al., 2005; Frizon de Lamotte et al., 2011) and while they confirm the synchronicity of regional events (and therefore indirectly suggest a common driving force), their work unfortunately suffers from

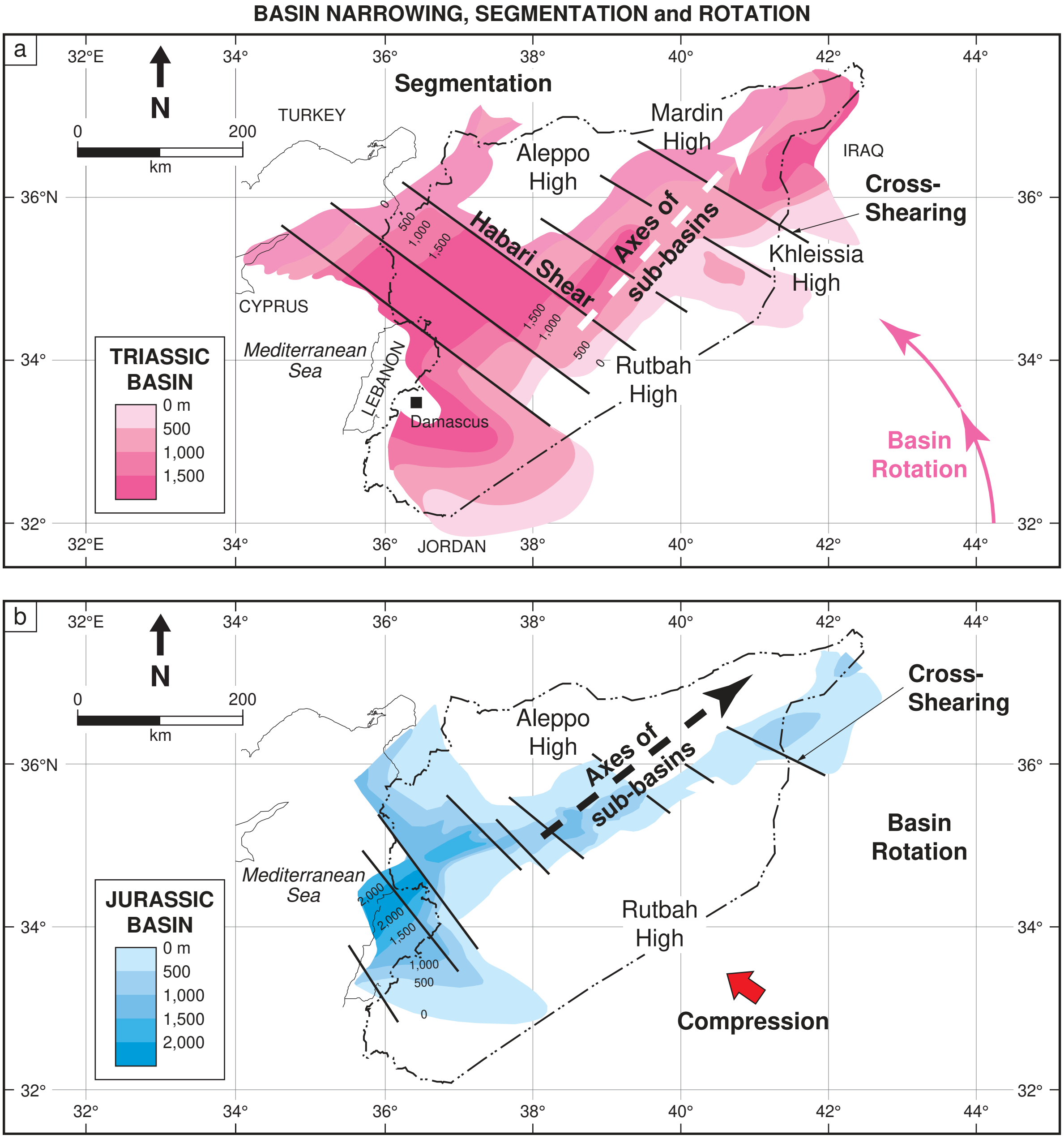


Figure 20: Trough narrowing and rotation by compression and cross-shearing. (a) Basin cross-shears, developed from tension fractures, break individual basins into independent sub-basins with individual fold axes effectively perpendicular to the shears. During inter-basin periods, each basin appears to have rotated counter-clockwise in step with the entire Afro-Arabian plate. (b) The axes of each new successor basin's sub-basins, under constant, unidirectional compression from the southeast, therefore developed at an angle to the underlying older basin. In addition, younger basins would be progressively narrower.

neither having nor suggesting a convincing mechanism of deformation. Further, as arguments for-and-against what tectonic force(s) drove the overall northwest progression and spinning motion (counter-clockwise) of Afro-Arabia focus on ridge push, slab pull, and/or plume activity, the quest for an answer is seemingly far from over. Now with a Palmyride Trough model, backed by data to establish, certainly offer, a form of deformation anchored in constant, NW-oriented, compression the question arises as to the feasibility of adopting such a model on a more regional scale.

Models, to be useful, need to be predictive and to be accepted they need to be tested and the Palmyride Trough model presented to this point was partially tested by two significant wells. The new data proved the expansion of the trough was facilitated by cross-shearing and that the enlarged trough suggests that it expands even more to the southwest under the western mountains of Syria, all of Lebanon and at least south to the highlands of western Jordan. While far from practical in this paper to show sufficient data to prove it is correct, a few figures from Jordan, the Sinai and the Western Desert of Egypt will show some common sedimentary and structural features that suggest there may have been a connected and continuous trough, the Levant Trough of upper Palaeozoic to Present age, extending from the Palmyrides of Syria as far southwest as the Western Desert of Egypt. In the case of the northern Sinai Peninsula, the new model indicates a serious rethink of the now almost traditional formation of the well-known "Syrian Arc" structures is in order.

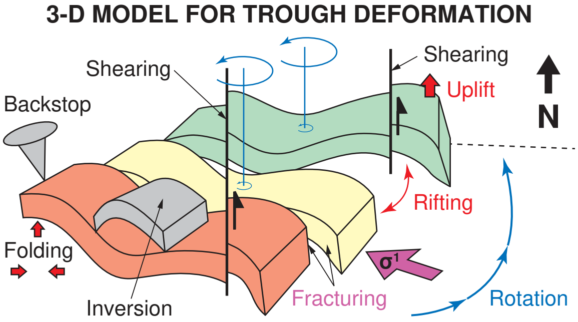


Figure 21: Proposed model for a tectonic-scale deformation under a constant, far-field, horizontal stress (σ^1). Fracturing parallel to σ^1 segments the originally contiguous continental block into NW-oriented strips that then fold creating troughs within which sediments accumulate. Continuous folding forces internal crowding and the sedimentary section to invert. Finally, the entire complex is sheared and rotated with inter-block rifting taking place.

Jordan

Jordan overlies the present crest of the Rutbah High (Enclosure I), a documented regional uplift active at least during the late Palaeozoic (Al-Laboun, 1986, 1988; Beydoun, 1988). Sedimentation and structural patterns discussed above, however, suggests the uplift has been continuously active with cross-cutting NW-oriented fractures such as the Middle Cretaceous, NW-trending, Wadi Sirhan rift and the Pliocene–Pleistocene Druze volcanics and associated cinder cones, attesting to this activity as recent as the Late Cenozoic. The Wadi Sirhan rift formed coincident in time, and parallel to, the Euphrates Graben of central Syria and far to the west, the Sirt Basin of Libya, arguing for a common driving force. The rift lies slightly counter-clockwise to the younger Neogene Druze Plateau with its lines of cinder cones indicating it predates the outpouring of volcanics making up the plataeu.

Figures 22 and 23 show the general stratigraphy of Jordan adapted from Naylor et al. (2013) and Sharland et al. (2001) respectively. The well correlation of Figure 22 shows the stratigraphic section expanding smoothly and regularly off the northwest flank of the Rutbah High into the heart of the Palmyride Trough across the border in Syria. Individual units (basins) expand in thickness, with the Jurassic basin nesting within the underlying Triassic. While this is a pure stratigraphic section with no structure inferred, to the author's knowledge, no margin-parallel, extensional faulting has been documented and the lateral continuity of the stratigraphic section from Syria argues that no rifting or fault-related activity has taken place. The NW-dipping, angular, Hercynian Unconformity surface clearly marks the base of the Palmyride Tough in Jordan with underlying older Palaeozoic formations progressively subcropping the trough toward the northwest as in Figure 10. Figure 23, a stratigraphic column of Jordan after Sharland et al. (2001), very clearly confirms the distinctive, long duration, regional hiatuses between the various basins and their low-energy contents. With respect to the lateral continuity of facies just mentioned above, the presence of the evaporitic Middle Triassic sediments here, and specifically the Norian–Carnian units, some 200 km south of the same drilled and logged, evaporitic deposits of Syria, attest to not only the lateral extent of these sedimentary packages but more to the extensive, low-relief nature of the trough and the very low-energy environment within it.

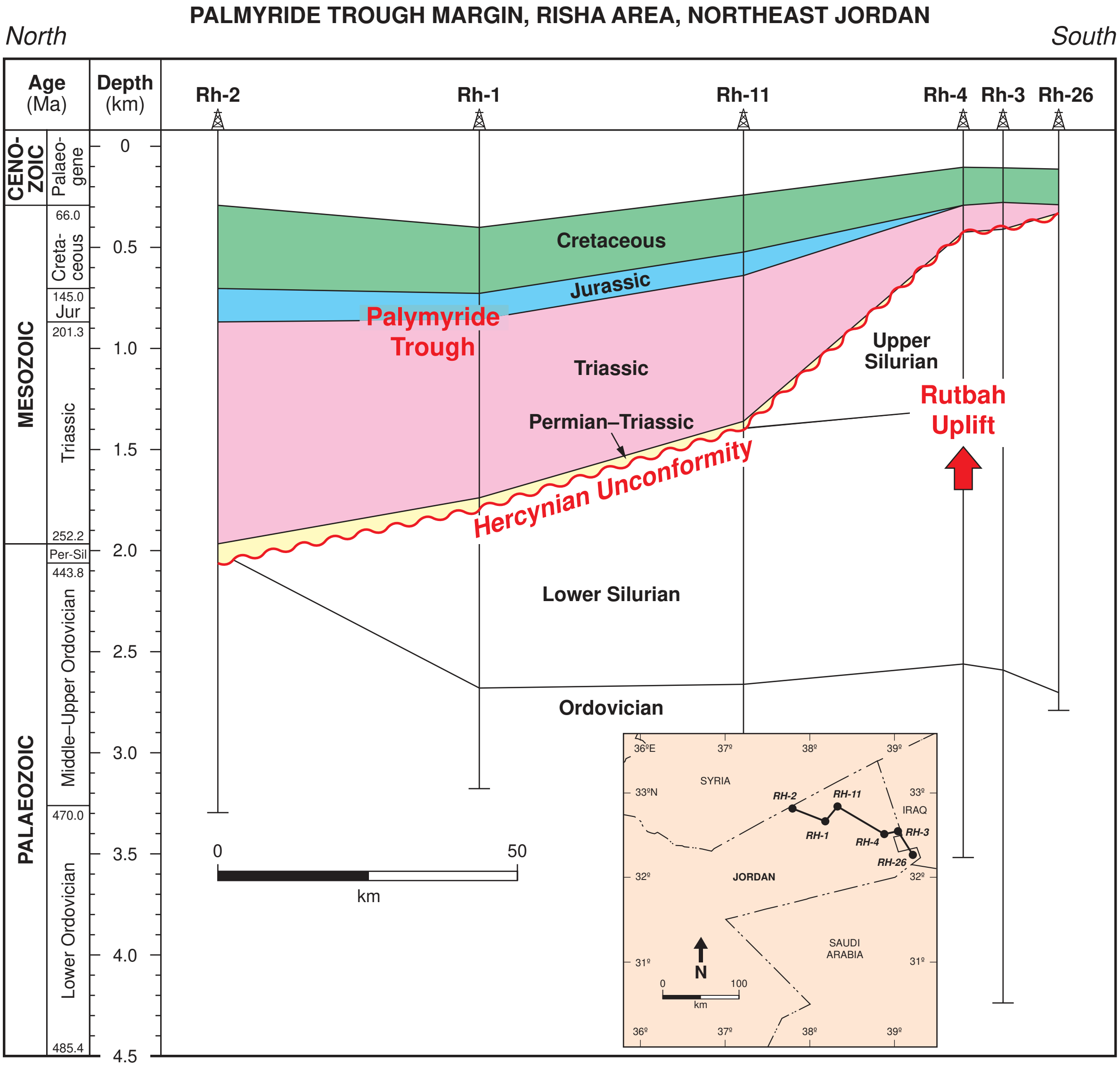


Figure 22: Palmyride Trough Margin, Risha area, Jordan (modified after Naylor et al., 2013). This well correlation shows individual units (basins) expanding toward the northwest into the heart of Palmyride Trough across the border in Syria. The Jurassic basin nests within the underlying Triassic. To the author's knowledge, no marginal faulting has been documented. The basal Permian–Triassic beds lie on the angular Hercynian Unconformity clearly making the base of the Palmyride Trough. Underlying older Palaeozoic formations progressively subcrop the trough toward the northwest demonstrating the trough formed over the pre-existing Levant Arch (see inset and Enclosure Ia for position of section). A rising (inverting) Rutbah High now forms the southeast wall of the trough.

Syrian Arc

Moving further southwest across the Levant, structures exposed on the northern Sinai were first documented by Krenkel (1925) and considered to be part of a more regional trend of uplifts that formed the "Syrian Arc", stretching from at least the Nile Delta and the Sinai to central Syria (Enclosure I). Interpretations of the structural architecture of this region have generally relied on surface and well examinations (Ponikarov, 1964; Ponikarov et al. 1966, 1967; BEICIP, 1974; Gvirtzman and Weissbrod, 1983; Keeley, 1989; Keeley and Massoud, 1998; McBride et al., 1990; Chaimov et al., 1992, 1993; Best et al., 1993) although subsurface data was incorporated as it became available (Gardosh et al., 2008; Gvirtzman, 2010; Yousef et al., 2010; Moustafa, 2010, 2013, 2014). However, when it came to determining a tectonic model for the region, most authors have turned or returned to the scenario of late Palaeozoic–Triassic through Early Cretaceous (Tethyan) rifting followed by Late Cretaceous to Cenozoic (Alpine) compression (Aal and Lelek, 1995; El-Motaal and Kusky, 2003; Moustafa, 2010, 2014). Further west in the areas of the Nile Delta and the Western Desert (Enclosure I), field mapping in the early 1980s, spearheaded by Conoco Oil Company, and continuous drilling by a great number of companies, has produced a vast data base, however the notion of the two-phased history of the region, tension then compression, remains strong (Wescott et al., 2011).

It is, however, accepted that this entire region, including the Palmyride Trough, lay along the southern margin of the various Tethys oceans. Therefore, if the Palmyride Trough formed under continuous compression and gentle down-warping as demonstrated above, and if it extended openly to the southwest as far as northwest Egypt, then stratigraphy and structuring along the length of this margin should reflect the same low-energy sediment content and exhibit similar structural characteristics.

Gebel Maghara, Egypt

Figure 24 is a geological map of the Gebel Maghara, a well-studied folded and thrusted anticline onshore north Sinai (Kuss and Boukhary, 2008; Moustafa, 2013, 2014). In outcrop, the gebel exposes a thick Jurassic section of more than 1,800 m of Late Pliensbachian to Mid-Oxfordian age (Keeley et al., 1990, Keeley and Wallis, 1991) overlain by more than another 1,500 m of Cretaceous to Recent sediments. The boundary between the Jurassic and the overlying Cretaceous is unconformable and coincident with tectonic-level activity characterised by regional tilting, uplift, erosion, and folding (Ibrahim et al., 2001). The base of the Jurassic is not exposed at Gebel Maghara, but it is to the east in the Halal-1

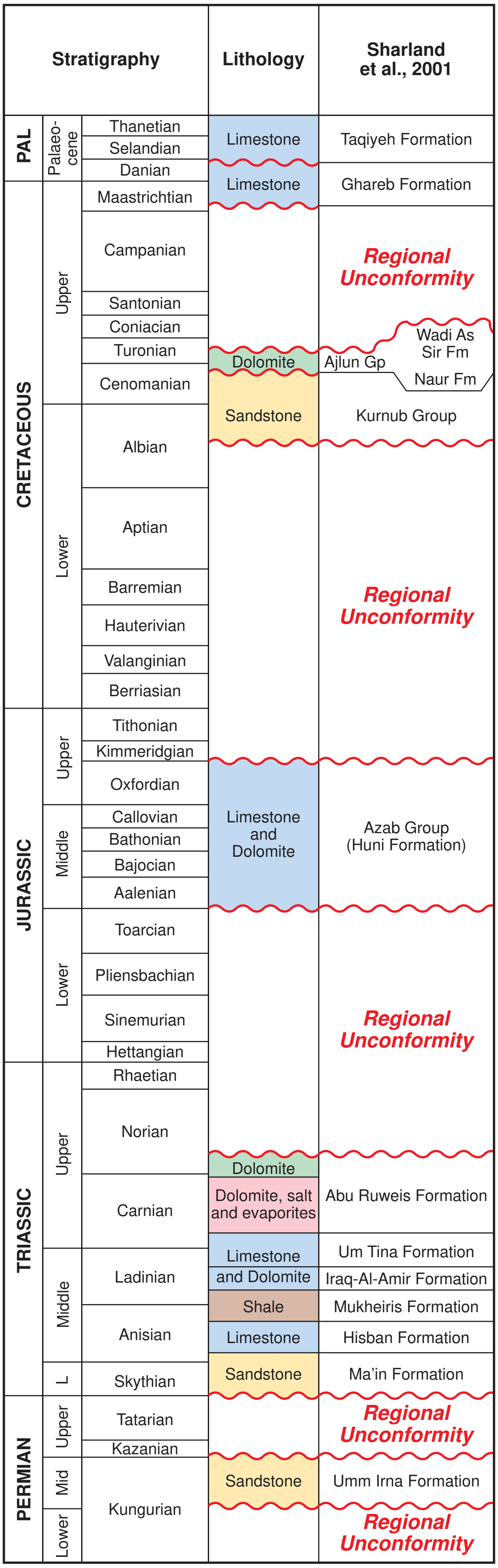


Figure 23: Permian to Cenozoic basins of Jordan. Stratigraphy, nomenclature and generalised lithologies are based on Sharland et al. (2001). This Tethyan and Alpine section confirms that the same long periods of non-deposition or erosion affected both Syria and Jordan.

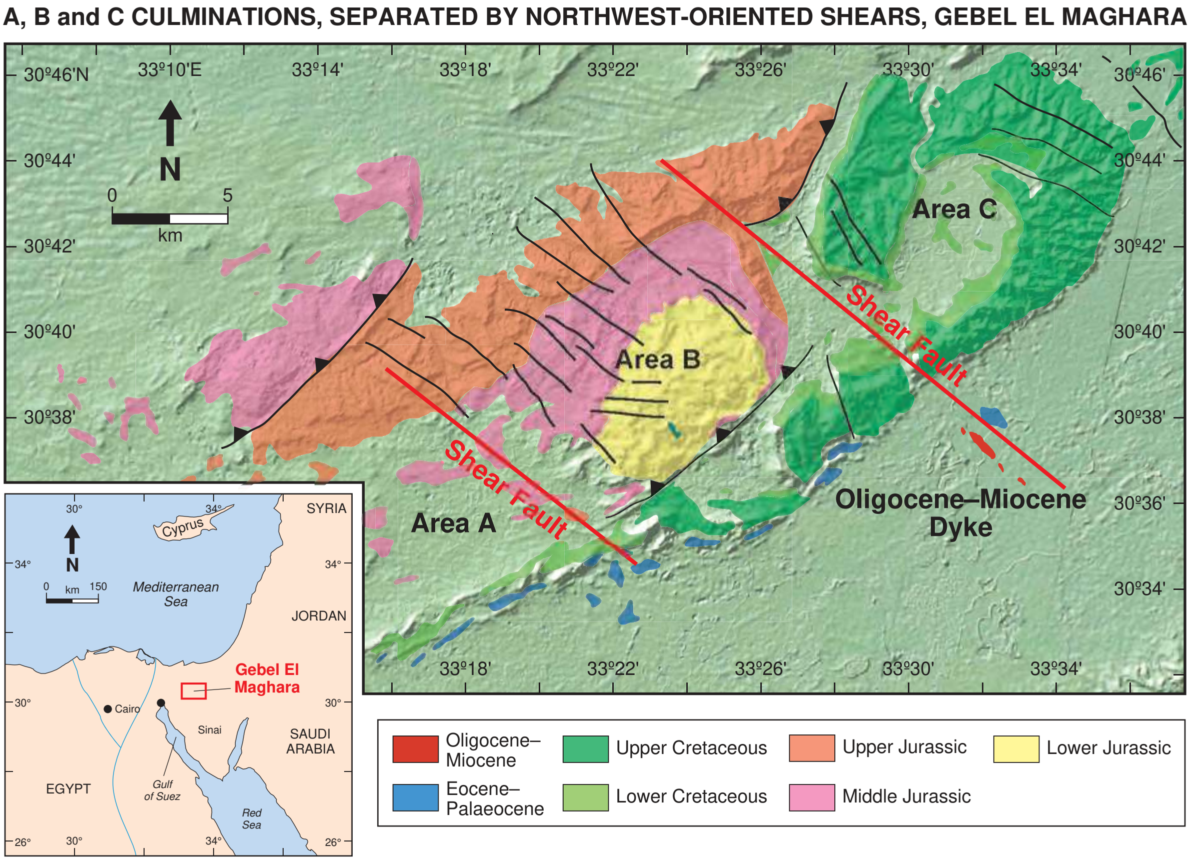


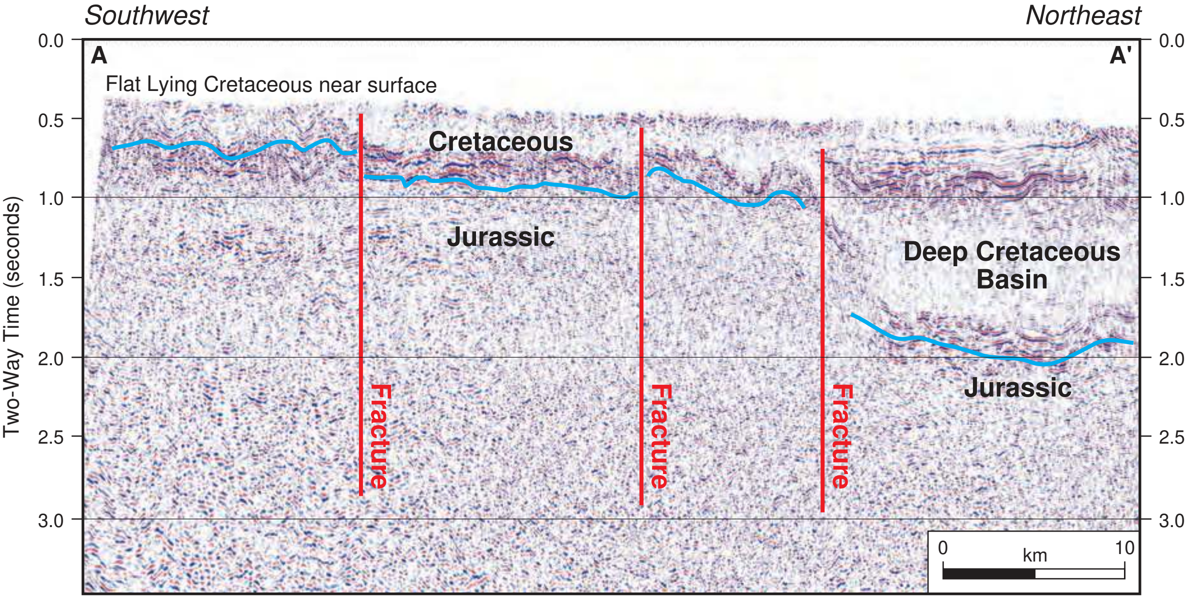
Figure 24: Gebel El Maghara surface geology showing widespread jointing/shearing of the structure (base map from Moustafa, 2014; Kuss and Boukhary, 2008; annotations this author). The two main shears proposed by this author are based on overall structural and stratigraphic offsets, terminations of mapped thrust faults and the presence of the uppermost Oligocene or the lowermost Miocene dyke (Elsayed, 2012) suggesting a deep connection to a magma chamber.

Well where over 3,200 m of Jurassic was penetrated overlying another 200 m of Triassic sediments (Moustafa, 2010). The base of the Triassic was not reached.

Deformation by small-scale, NW-oriented fractures is clear and a feature common to all the Sinai gebels (mountains) such as Yelleg (Moustafa and Fouda, 2014) and Halal. Mustafa (2010) noted that Mesozoic and Cenozoic rocks generally show a gradual northward increase in thickness, while abrupt changes in thickness are also commonplace. Traditionally, the abrupt thickness changes have been taken to indicate syn-depositional, NE-oriented, normal (extensional) faulting during Mesozoic rifting, while the northern thickening simply reflects the position of the gebels on the margin of the Tethyan oceans lying to the north. Few have countered this concept except El-Gawad and Ibraheem (2005), who, based on an interpretation of gravity data covering the northern Sinai, suggested that "The analysis and interpretation of the gravity data concluded that at shallow depths, the predominant structural trend is NE-SW whereas at deep levels, the structural trends are NW-SE. This indicates that the deep structural trends are different from the shallower trends, which suggests a lateral compressive origin for the north Sinai folds rather than vertical uplift, that is, the origin of the structures in the area under investigation based on gravity analysis is genetically related to thin skinned deformation." Here was a first indication outside of Syria that rifting may not be the responsible mechanism for the "Syrian Arc" structures.

While Gebel Maghara outcrop geology shows widespread NW-oriented jointing and shearing of the structure, the presence of two main shears is suggested by lining up offsets of mapped thrust fault terminations and other geological offsets. These two proposed shears also divide the gebel naturally into three structural culminations or compartments (named in Figure 24 Areas A, B and C), each slightly offset by the two master shears. What cannot be immediately recognised however, is the lateral scale or depth of these offset shears. The first indication that these shears are not superficial is provided by the presence of an outcropping, Upper Oligocene to Lower Miocene, NW-oriented, volcanic dyke to the south of the gebel (Elsayed, 2012) that coincides with the more northerly shear. It is one of many dykes and flows associated with pervasive, NE extension that occurred across NE Egypt, including the Sinai, culminating in the opening of the Red Sea and the Gulf of Suez rifts (Steinitz et al., 1981; Bosworth et al., 2005; Perrin et al., 2009; Moustafa, 2010). This dyke suggests that the associated shear acted as a deep, open conduit for magma to reach the surface. It further suggests, at least Alpine age, slightly extensional, shear movement.

Without sufficient seismic over the gebel, certainly seismic of good quality, to verify the subsurface configuration of the mountains and their structural makeup, plus a dogmatic adherence to an inverted rift origin, the Sinai structures continue to be considered fault-related anticlines with local jointing and/or minor shears forming during inversion (Moustafa, 2013, 2014). Figure 25 is a seismic line of fair quality, not over Gebel Maghara but to the north and parallel to it (see inset map). This line clearly images several deep-seated, vertical, NW-oriented fractures on trend with the fractures mapped at Gebel Maghara and on-line with the well-documented Temsah-Bardawil trend of fractures (Aal et al., 2001; Khaled et al., 2014) that extend to the northwest into the offshore (Enclosure I). The fractures show minor to massive offsets across them and these offsets clearly could account for any observed abrupt changes in thickness of Mesozoic rocks noted in well penetrations and generally taken as thickness changes over rift scarps. It is not possible to determine the exact timing of the shears with present data, however the thick Cretaceous section under the northeast segment of the line indicates movement from at least Early to Mid-Cretaceous time (Late Tethyan to Early Alpine), coincident with uplift and transtensional shearing of the Rutbah High in Jordan and resultant rafting of sediments in the Palmyride Trough. No NE-oriented



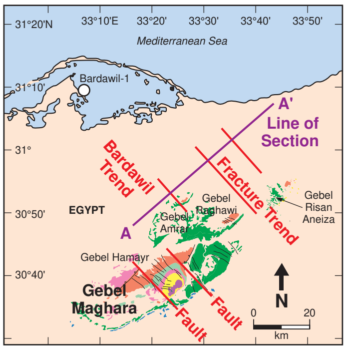


Figure 25: Seismic time section across the north Sinai showing compartmentalisation by NW-oriented fracturing and shearing. Data below the top Jurassic reflectors are unfortunately poor so Triassic and older horizons cannot be picked with any confidence. However, these fractures clearly line up with the Maghara fractures and the Bardawil trend that extends into the offshore as the Temsah trend. These fractures are more likely to be responsible for the abrupt changes in sediment thickness often noted in the area (Moustafa, 2010) rather than proposed NE-trending normal faults. See Figure 24 for legend.

faults have been noted in spite of a good suite of seismic reflection lines. Instead, a pattern of local and regional, NW-oriented shearing is emerging (Enclosure I) that not only has affected the Sinai but also involves the entire region including the Palmyride Trough of Syria (this paper), the eastern offshore Mediterranean (Tari et al., 2012; Longacre et al., 2007), and the Western Desert of Egypt (Wescott et al., 2011). Their regional presence must be factored in with respect to any discussion of the tectonic deformation of NE Africa and NW Arabia.

Triassic Stratigraphic Correlation of Syria, Jordan and Egypt

The Tethyan stratigraphic story of Egypt continues that of Jordan and the Syrian Palmyride Trough in terms of the presence of common basins and similarity and continuity of sedimentation through time including erosional events (Ibrahim et al., 2001; Khalifa, 2007) and the Triassic sequence illustrates this well. The presence of Triassic sediments from the Western Desert to the Galala Plateau east of Cairo, across the North Sinai and the southern Levant has been recognised for some time (Peterson and Wilson, 1987; Kuss, 1988; Kerdany and Cherif, 1990; Alsharhan and Salah, 1996; Keeley and Massoud, 1998; El-Azabi and El-Araby, 2005; Khalifa, 2007; Gvirtzman, 2010). In the northern Sinai, the basal Triassic has not been penetrated in wells and is not exposed in outcrop,

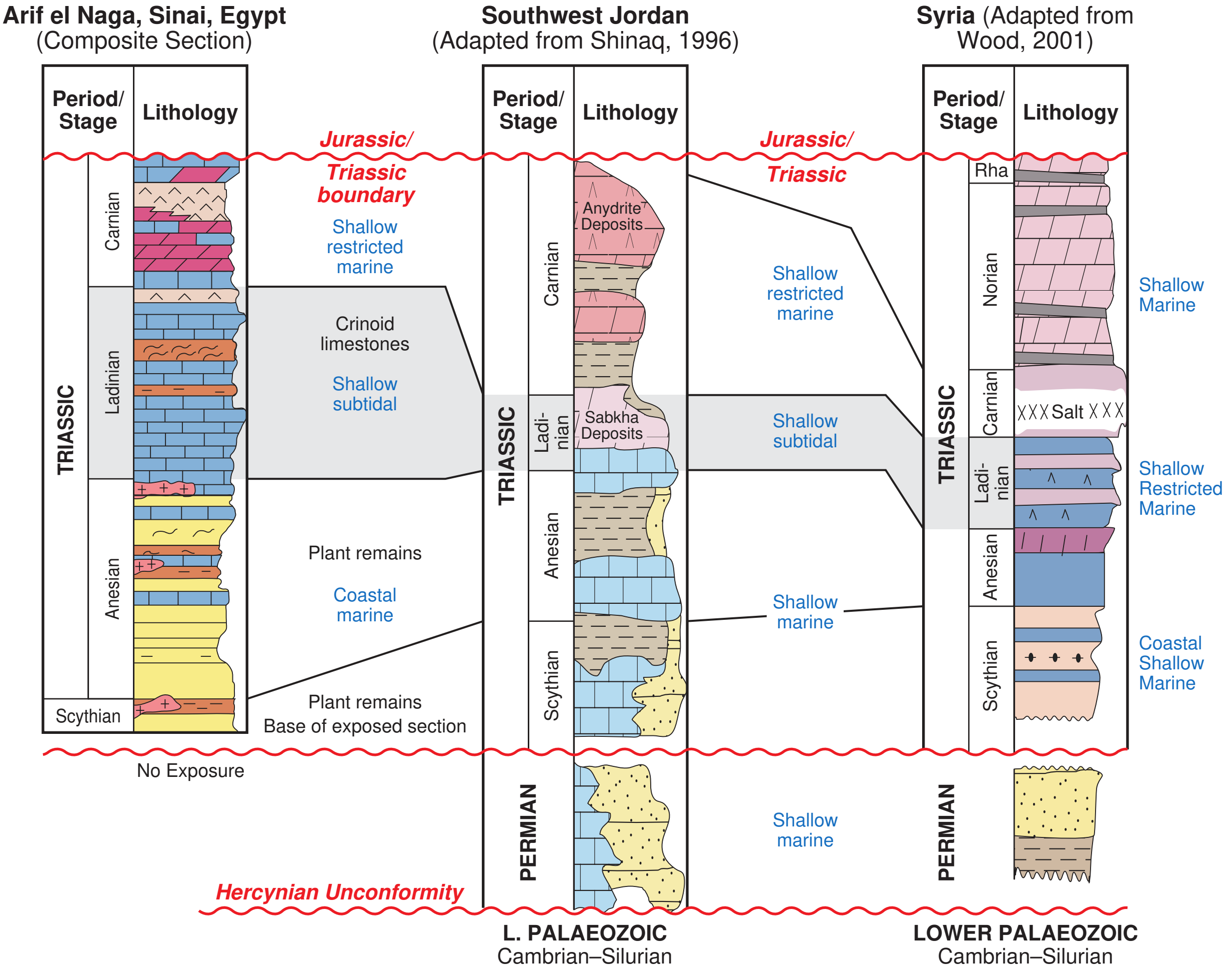


Figure 26: Cross section showing continuity of Triassic sedimentation from Syria to Sinai, Egypt. Throughout the Lower Triassic, the southern margin of the Tethys Ocean in the study area was the site of coastal to shallow-marine sedimentation, becoming, in the Ladinian period, a more restricted to subtidal shelf. Restriction became more severe with time with salt deposition in the Carnian in the Central Palmyride Trough and thick evaporitic sediments elsewhere. The total absence of rapid facies changes across such a large area challenges the concept that sediments were laid down in multiple "rift" basins scattered along the southern Tethyan margin during the Triassic.

however, to the south and west into the northern Gulf of Suez area and west of the Suez Canal, the Triassic rests unconformably on upper Palaeozoic with the upper Permian always missing (Alsharhan and Salah, 1996, 1997; Khalifa, 2007). Across the Sinai, the Upper Triassic is missing (El-Azabi and El-Araby, 2005), while in the Levant to the northeast, a major sedimentary gap occurs between the Triassic and Jurassic coincident with arguably the largest mass extinction of all time (Gvirtzman, 2003) and the eruption of the Asher volcanics (Segev and Rybakov, 2011) leaving the Triassic bracketed by common inter-basin unconformities from the Sinai through the Levant and Jordan and into the Palmyride Trough of Syria.

Figure 26 compares the general Triassic stratigraphy of Syria, Jordan and the Sinai in Egypt. In all three areas, the Triassic sequence changes upward from basal continental to near-shore, coastal marine sediments, in the Sinai containing plant fragments, to shallow subtidal and shallow restricted, then back to more open, yet still shallow marine. The upper units of Ladinian to Carnian age show a return to evaporites, with bedded salt deposits in Syria. No high-energy clastics, such as delta and delta channel sands or alluvial deposits, have been recorded. The low-energy, omnipresent facies are truly laterally regional, being present along a margin over 1,000 km in length. The apparent absence of high-energy or mixed environment sediments indicates the sediments were not laid down in separate "rift" basins but were deposited on a broad, gently northerly dipping, margin of the Neo-Tethys Ocean.

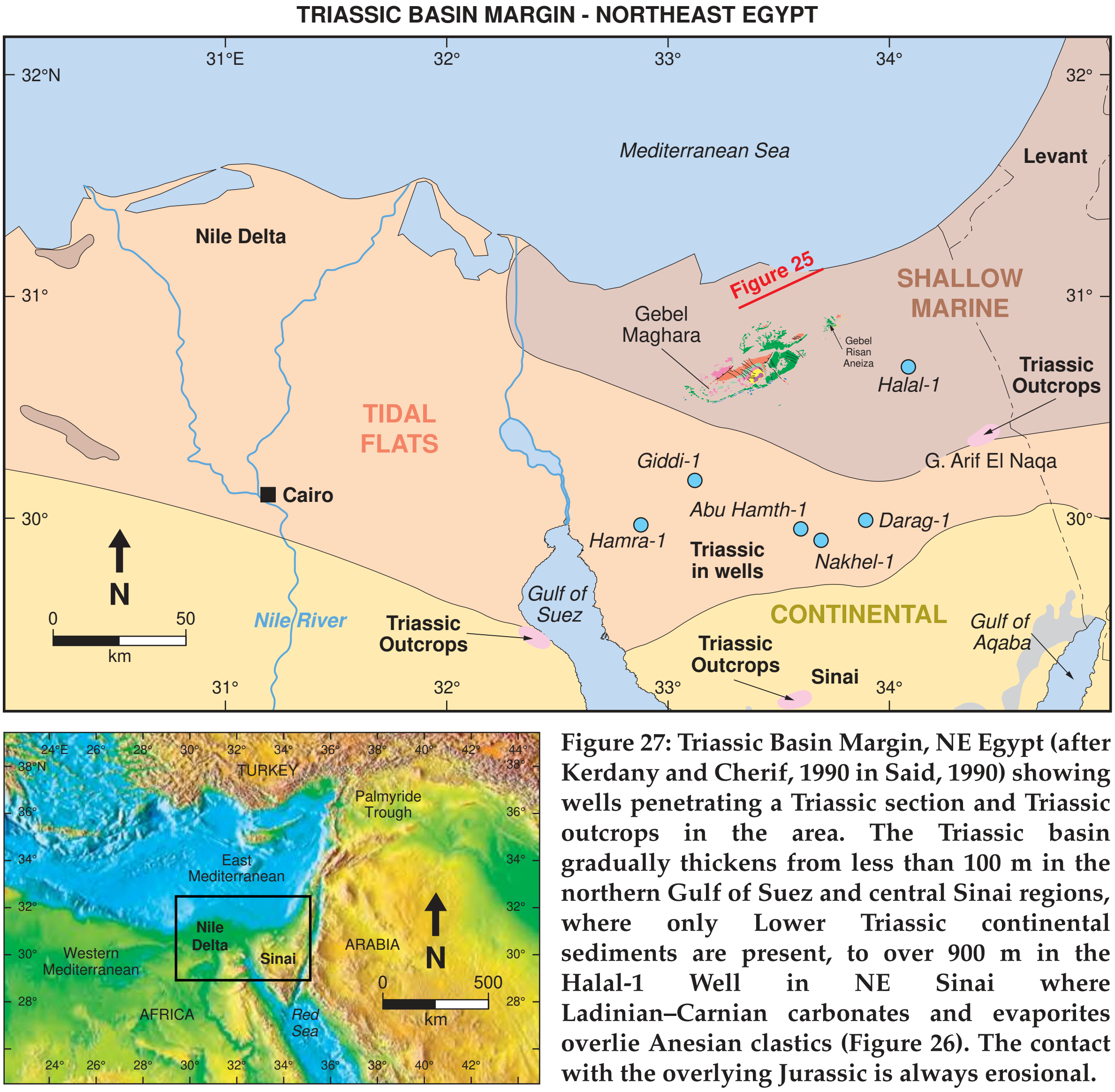


Figure 27: Triassic Basin Margin, NE Egypt (after Kerdany and Cherif, 1990 in Said, 1990) showing wells penetrating a Triassic section and Triassic outcrops in the area. The Triassic basin gradually thickens from less than 100 m in the northern Gulf of Suez and central Sinai regions, where only Lower Triassic continental sediments are present, to over 900 m in the Halal-1 Well in NE Sinai where Ladinian–Carnian carbonates and evaporites overlie Anesian clastics (Figure 26). The contact with the overlying Jurassic is always erosional.

Figure 27 is Kerdany and Cherif's (1990) interpretation of the general palaeogeography of the Triassic from the Nile Delta, east into the southern Levant. It portrays the widespread nature of shallow, subtidal to restricted marine, to evaporitic sediments on a broad shallow shelf. Of relevance here, is that 15 years later, while authors such as El-Azabi and El-Araby (2005) recognised the shallow-marine nature of the Upper Triassic, describing the deposits as being laid down on an "open shallow subtidal shelf" they failed to discuss any structural consequence of their findings. Their description of a shelf environment is in direct contrast to expected "syn-rift" facies if it is to be believed these sediments were laid down along a passive (extensional) margin. In spite of the constant mention of "tidal" and "marine shorelines", not one author has written about a possible disconnect between the structural and stratigraphic story of the area. Rather, everyone repeatedly defers to earlier authors, for example El-Azabi and El-Araby (2005) deferring to Bartov et al. (1980) who "believed that the region was under differential subsidence and probably bound by faults or

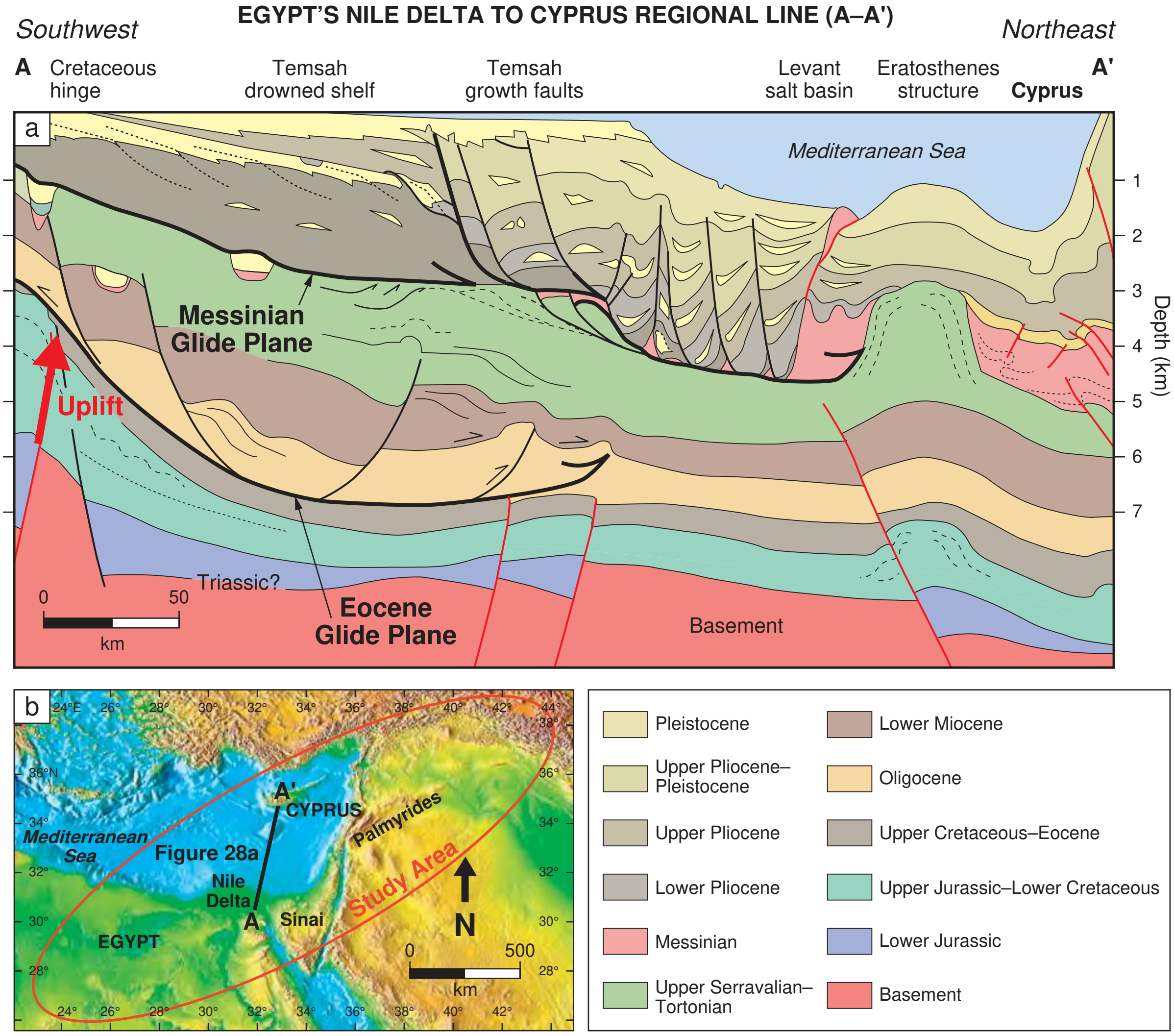


Figure 28: (a) In the Nile Delta, a geological section adopted from Dolson et al. (2001) shows at least two stages of down-slope rafting on evaporitic or soft shale intervals suggesting an over-steepening of the southern margin due to the uplift of the Cretaceous Hinge Zone (Enclosure I). The line position is shown on (b). The coincidence of the rafting during Alpine period here and along the southern margin of the Palmyride Trough, suggests a common tectonic event, and as it was driven by the ongoing inversion of the Rutbah High in Syria, it stands to reason the same mechanism and force drove the structuring here in northern Egypt. Dolson et al. (2001) fail to indicate the reasonable possibility of Triassic evaporite beds underlying at least the eastern Delta (Figure 27) but if present, at least one underlying glide plane (the Middle Triassic) should be present.

flexures during the Late Triassic–Early Jurassic". It is more probable that there was no rifting, rather the Triassic was laid down in a broad unstructured trough fully connected to the east and west along the full length of the southern Tethyan margin.

Nile Delta, Egypt

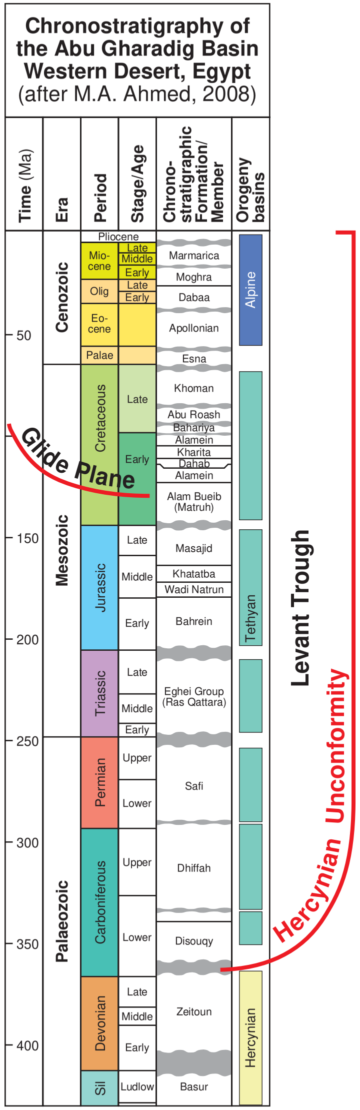
Moving west to the Nile Delta, a well-used geo-seismic section adapted from Dolson et al. (2000, 2001) highlights the rafting of sediments on multiple glide planes (Figure 28). With no down-slope constraint as there was in the crowded, narrow Palmyride Trough, upper slope sediments have collapsed into the open Mediterranean Sea facilitated by listric normal faulting, all faults soling out on common detachment surfaces, here a Messinian surface and a deeper Eocene surface. This has resulted in a shallow extensional regime in the south and compression down-slope to the north where lower-slope compression has resulted in buckling and thrusting. The trigger of the down-slope motion is not as readily apparent here as it is in the Palmyride Trough as it can be argued that delta sediment loading may have been the driving force. However the timing of the rafting coincides with regional "Syrian Arc" inversion processes from the Western Desert to the northern Sinai (Moustafa and Bevan, 2010) so marginal uplift cannot be ruled out. It is interesting however, that Dolson et al. (2000, 2001) noted just two glide planes, both within the Cenozoic section. With respect to the deeper section, in spite of documented Triassic evaporites in wells and outcrops to the east, it is curious why they failed to first, show any Triassic present under the delta preferring to show a Jurassic section resting directly on basement and second, to suggest any deeper possible detachment surfaces. As the basement has never been penetrated under the Nile Delta, their interpretation of the lower section is clearly open for discussion. Therefore, if there is Triassic at depth as Kerdany and Cherif (1990) and others have proposed, the new "Palmyride" model suggests that the laterally extensive Triassic evaporites may have formed a deeper detachment and facilitated deeper down-slope movement and structuring.

Western Desert, Egypt

Figure 29 shows a NS seismic section (based on seismic) offshore the Western Desert (Tari et al., 2012). An inset, a stratigraphic column from the Abu Gharadig Basin to the south (Ahmed, 2008), is assumed to illustrate the stratigraphic section under the coastal Western Desert as deep seismic data is poor under the coast and the offshore and the deepest section has not been drilled. The column suggests that a complete post-Hercynian Orogeny sedimentary column is present with the same distinct periods of non-deposition separating discrete basins. It is therefore suggested that the post-Hercynian section consists of a set of basins, the same basins described in the Palmyride Trough of Syria, and that these basins sit within a single continuous trough, the Levant Trough, effectively extending throughout the area of this study (Enclosure I).

The schematic section, while not showing Triassic or older units, displays rafting that has occurred during the early Alpine Orogeny, however here facilitated by a detachment surface along the basal Abu Roash shales of probable Late Cenomanian age. Without a thick deltaic section, it is difficult to argue for sediment loading to have triggered the rafting so it is suggested that margin uplift resulted in an over-steepening of the coastal area coincident in time with other "Syrian Arc" deformation. As the deeper section is not imaged well on seismic, the structural configuration of the underlying section is not clear. However, as in the area of the delta, there may be both Triassic and Palaeozoic sections present and deeper glide planes may be active.

Southwest of Cairo, widely occurring volcanics, deposited at or near the Oligocene/Miocene boundary (Perrin et al., 2009), are exposed at the surface and associated cinder cones (Figure 30) create a scene reminiscent, albeit older, of the volcanics and cinder cones of the Druze Plateau in Syria. Furthermore, as suggested when discussing the age-equivalent dyke just south of Gebel Maghara in the Sinai, the very presence of volcanics, and surface lineaments formed by eruptive cones, indicates both an association with widespread, deep-seated shearing and tension. The NW orientation of the lineaments also suggests they were formed under NW-oriented compression. Abdel-Fattah et al. (2013), using earthquake data, confirmed the presence of deep, NW-oriented, active, regional, faulting of the upper crust of northern Egypt and attributed the faulting to the



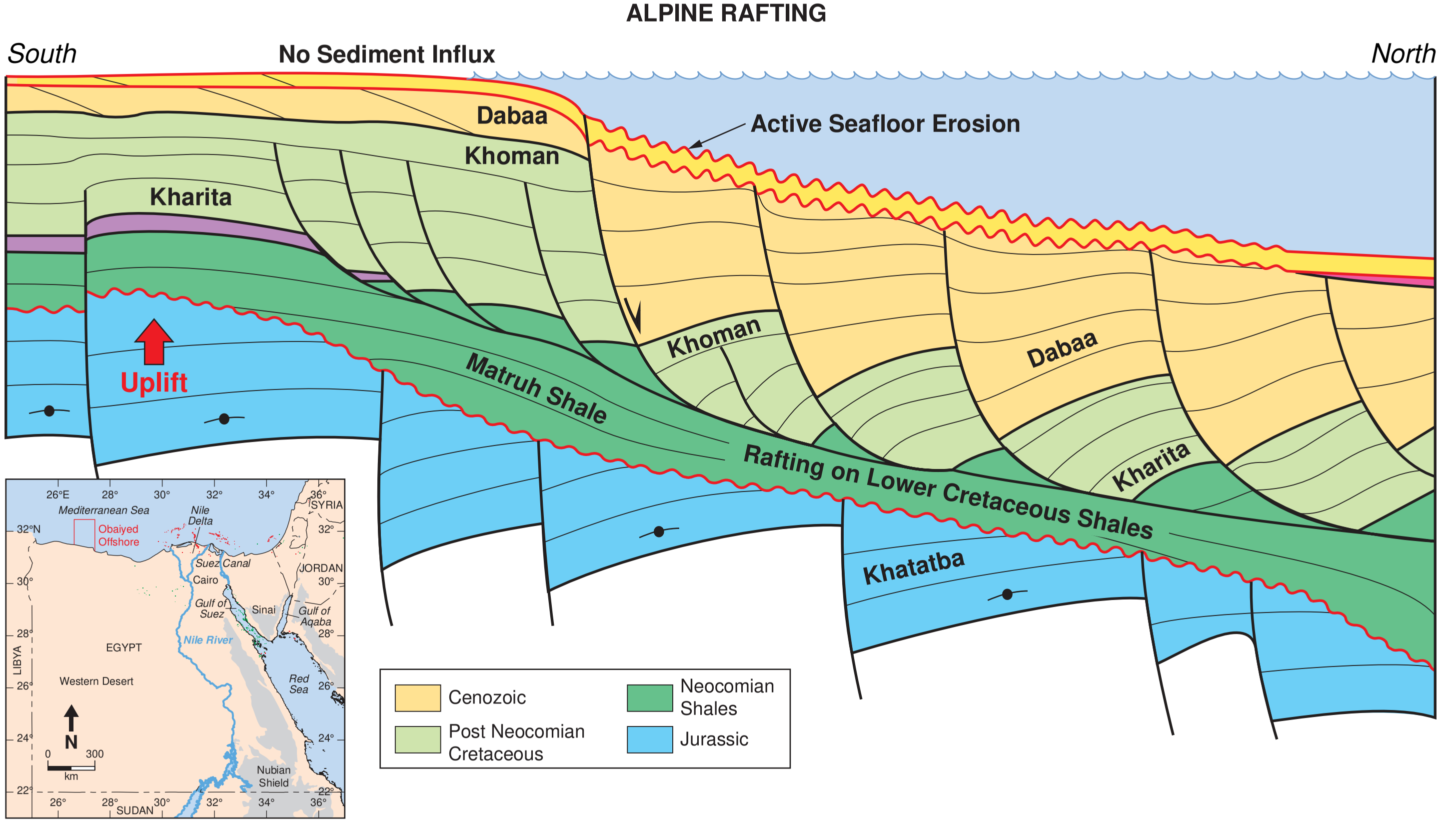


Figure 29: A schematic cross section in the Obaiyed Offshore Concession, Western Desert, Egypt, is after Tari et al. (2012). Alpine age uplift along the coastal area of the northwestern desert triggered down-slope rafting of sediments on a Lower Cretaceous detachment surface. Away from the Nile Delta with no sediment influx, sediment loading cannot be deemed to have initiated the offshore collapse. Coincidence with similar uplift along a trough margin extending from Syria to Egypt (the Levant Trough), suggests a common sphere of influence by a common driving force.

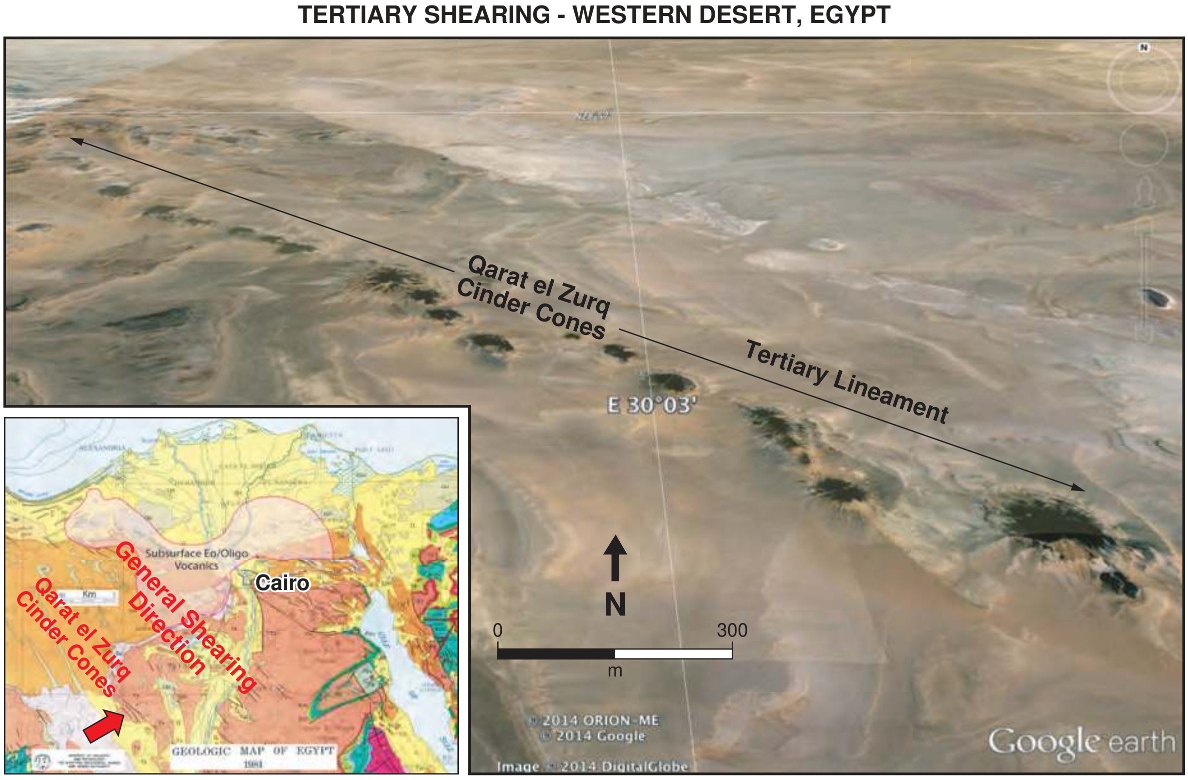


Figure 30: Widespread shearing and volcanism southeast of Cairo predates opening of the Gulf of Suez in the early Cenozoic. As in Syria (Figure 16), lines of cinder cones mark the position of fissures (tension fractures) responsible for the outpouring of basalts plus indicate the direction of compression.

opening of the Red Sea and the simultaneous closure of the Neo-Tethys Ocean. Their northwest orientation, parallel to lineament trends in the Sinai, offshore in the Mediterranean, Jordan and Syria, suggests a common origin and one regional driving force.

DISCUSSION AND CONCLUSIONS

It would appear that the geological community has resigned itself to the idea that the region of NE Africa and NW Arabia deformed passively under tension during the post-Hercynian disintegration of northern Gondwana. Further, it is generally accepted, without proof, that sedimentation generally occurred within graben structures controlled by regional rifting along the length of the southern margin of the Tethyan Ocean. Consensus is that Alpine-age compression then forced inversion of these half- and/or full-graben (extensional) structures to form the well-known Syrian Arc structures that stretch from central Syria to the Western Desert of Egypt. There is also widespread consensus that the passive southern margin of Tethys formed as a slab-pull mechanism opened successive oceans, ocean crust then disappearing under the Eurasian continent to the north due to an unknown driving force.

Unfortunately widespread rifting does not fit with "low-energy" blanket sedimentation common to the NE African and NW Arabian area, nor does it fit with an area effectively under a constant pincer movement of Afro-Arabia and Eurasia. Invoking varying plate stresses and hypothetical mechanisms unfortunately offers a model that cannot be tested, offers no predictive elements "on the ground", and is difficult to reconcile with actual data.

A good data set in Syria demonstrates that distinct Tethyan sequences (basins), predominantly composed of "low-energy" sediments such as muddy limestones, thick dolomites and evaporites that are laterally very extensive, lie within the present Palmyride Trough on a deeply eroded Hercynian Unconformity surface. A subcrop map of this basal surface confirms the pre-trough presence of the massive, plate-scale, Levant Arch that extended from NE Syria, through the Levant and NE Egypt and, arguably, to the southwestern corner of Egypt. Two sister arches, the Al-Batin and the Hadramat, lay across Arabia with crest-to-crest distances a massive ca. 1,200 km suggesting the presence of continental-scale folding of a plate under compression since at least the end of the Hercynian Orogeny in the early Carboniferous. Northwest by southeast continued shortening resulted in the deformation of the northerly Levant Arch by refolding, with the appearance of a new fold train reduced to crest-to-crest distances of 250 to 400 km. The Hercynian Unconformity surface became the confining walls of a new trough in Syria, the Palmyride Trough that continued to slowly narrow and deepen under compression. This new trough began to fill with fine-grained clastics in the late Palaeozoic and continued to fill with low-energy carbonates and evaporites through the Mesozoic with persistent shortening forcing intermittent trough crowding and long-lived regional uplifts.

Individual basin sequences are well defined by easily correlatable sediments that reflect long periods of slow, low-energy, laterally-persistent, sedimentation in contrast to an expected heterogeneity of fill had the region been deforming under tension with its inherent rifting and rift-fill sequences. Also, in contrast to a rift model of deformation, effectively no basin-parallel (northeast by southwest) margin faults can be confirmed by seismic. In contrast to the expected fault pattern, deep-seated cross-basin (northwest by southeast) fractures dissect the basin into NW-oriented strips, each strip independent of its adjacent neighbour. While these cross-basin fractures and the confining Rutbah and Aleppo highs controlled the marginal shape of the Palmyride Trough, the fractures are parallel and appear to connect to more regional lineaments suggesting they could be of plate-scale relevance.

Inter-basin hiatuses of non-deposition or blanket-like regional erosion, from 15 Myr to as long as 25 Myr, are surprisingly of the same scale as the periods of sedimentation. In addition, inter-basin breaks are coincident with increased regional structuring and volcanism. Finally, following these long periods of strong structural activity, each new basin found itself nested within its predecessor with the older basin lying counter-clockwise with respect to the younger one. It is proposed that inter-basin periods of erosion or non-deposition were due to whole-basin (regional) uplift, forced by trough narrowing. Further, it is also proposed that regional (and basin) rotation was facilitated by now documented, NW-oriented cross-shears that probably originated as plate-scale tension fractures.

The scale of the underlying Levant Arch, and the fact that the Palmyride Trough formed through refolding of it, suggests that the Palmyride Trough is but a small part of a larger trough formed by the same refolding mechanism along the length of the underlying arch. Albeit brief, several examples of common sedimentation and common structuring suggests this could be true with a younger "Levant Trough" stretching from the Palmyrides through Lebanon and the eastern Mediterranean into the Western Desert of Egypt, basically within the outline of the study area shown on Enclosure I. There is definitely a need to rethink the presence, distribution and structuring of individual basins within this trough, especially the older ones.

While such a rethink would benefit "on-the-ground" efforts, the ideas presented here should also encourage a reconsideration of present tectonic convictions. First, there is the sheer size of the Levant Arch, its sister arches to the southeast and the proposed Levant Trough. Second, there are observed basin-scale geologic features that are the rule not the exception. These features, such as basin-wide, low-energy environmental continuity, basin-margin uplift coinciding with basin crowding, stratigraphic thinning towards unfaulted basin flanks, nesting of successor basins, cross-basin fracturing coinciding with regional fracturing and coincident Alpine age gravity sliding along the entire margin of the trough, taken together, can all be related to a common, continuous regional-scale (lithospheric?), NW-directed compression as the underlying driving agent. Finally, counter-clockwise rotation, effectively coincident with the cessation of each basin sequence, suggests the basins were sequentially formed by, then moved away from, a common stress direction. The basins appear to be responding to not only a common force but also a force of constant direction through time. Understanding the correlation of sedimentary fill to local and regional structural events brings new insight to the deformation of the northern regions of Gondwana.

ACKNOWLEDGEMENTS

The author would like to thank the Syrian Petroleum Corporation and Ministry of Energy of Syria for providing data for his original study of Western Syria in 2001 and their challenging discussions. Also, a thank you to the management and personnel of NPC, Egypt, again for, not only their release of data, but also their valuable feedback on ideas specific to the Sinai. A special thanks to friends who, over the years, have encouraged me to write this paper and finally, a thank you to GeoArabia's editors and staff, specifically GeoArabia's Production Co-manager, Arnold Egdane for designing the paper for press and Assistant Editor Kathy Breining for her fine editing skills, and two anonymous reviewers for significantly improving the manuscript.

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ABOUT THE AUTHOR

***Barry Wood** began his career as a Geologist with Shell Canada working on Canadian frontier basins under the tutelage of giants of the industry such as Bert Bally and Bob Ginsburg. Moving overseas, he spent the core of his career with Marathon Oil Company, managing New Ventures efforts across Southeast Asia, the Middle East, Africa and Europe before directing exploration and appraisal projects in Syria and Egypt. In 1985 and 1986 he published papers on a lithospheric scale model for Southeast Asia explaining the progressive deformation of crustal plates in the region and demonstrating its direct applicability to oil and gas exploration. Retiring from Marathon in 1997, he moved to the University of Oxford where he received a DPhil in 2001 for his research into lithospheric scale basin development of northwest Arabia focusing on the Palmyride Trough of Syria. Based on his long career in New Ventures and exposure to a vast amount of data, this paper is an effort to offer a working hypothesis on the origin and the structural and sedimentological development of the Palmyride Trough of Syria, and its possible extension as far as western Egypt, that impacts work "on the ground". It also has implications for understanding tectonic level deformation. He now acts as an exploration advisor and geological consultant for small but expanding companies, mainly in Africa and the northern Middle East.*

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Manuscript submitted November 7, 2014

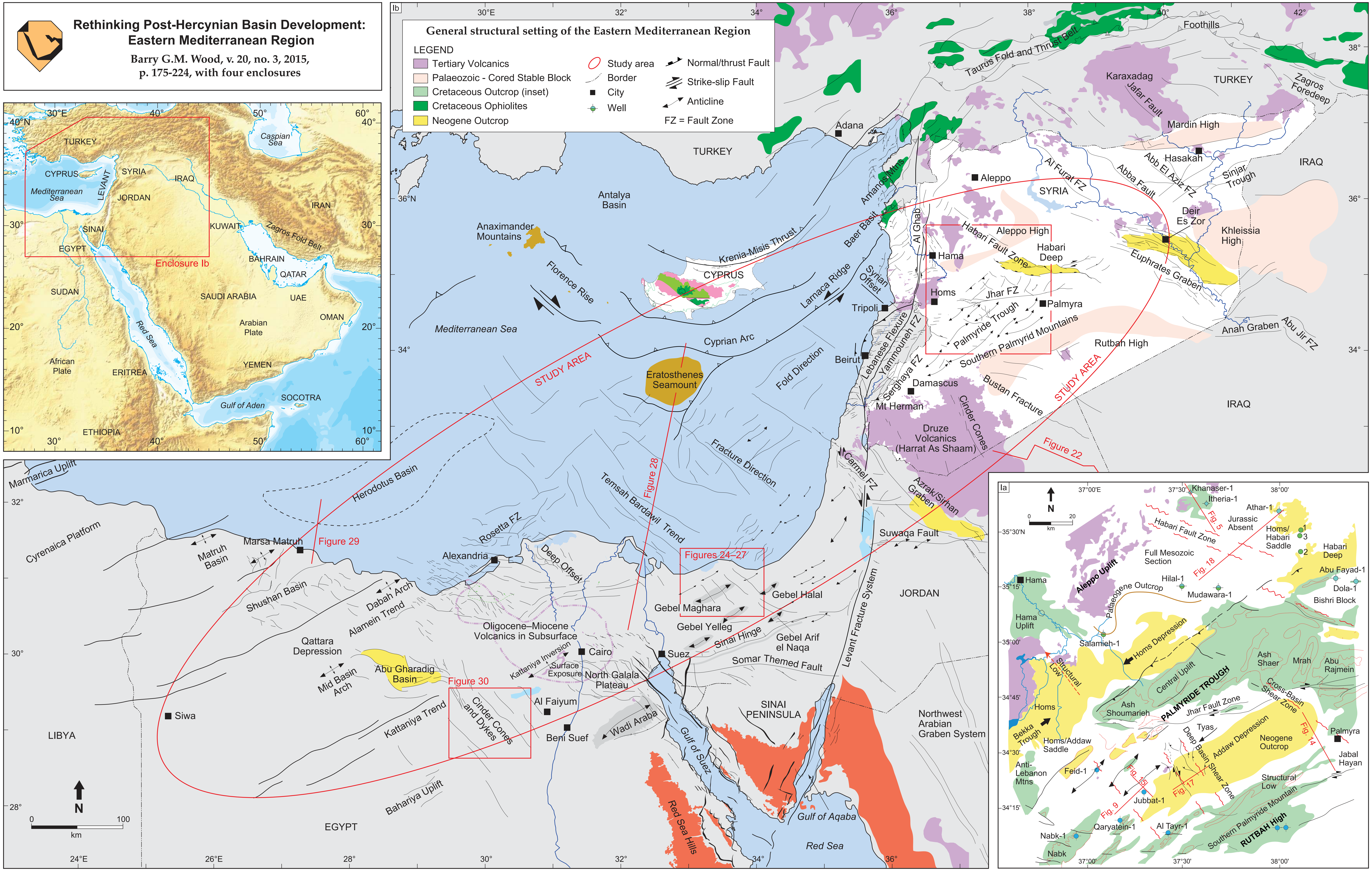
Revised January 11, 2015

Accepted March 8, 2015

ENCLOSURE I

Rethinking Post-Hercynian Basin Development: Eastern Mediterranean Region

Barry G.M. Wood, v. 20, no. 3, 2015,
p. 175-224, with four enclosures



Enclosure Ib: The study area covers the present-day Eastern Mediterranean Region, including Syria, NW Jordan, the Levant, northern Egypt and their respective offshore areas. This region lay along what was, during the Late Palaeozoic to Early Cretaceous, the southern margin of the Neo-Tethys ocean. This "Tethyan" period saw the deposition of remarkably similar, correlatable, thick sections of marine, carbonates, shales and evaporites from NE Syria to the Western Desert of Egypt indicating the presence of a highly inter-connected seaway. Cycles of deposition and exposure were also remarkably similar across the region indicating regional structuring was under the influence of a common force. Alpine age (Upper Cretaceous and Cenozoic) structures, such as the massive Levant Fracture Zone and its associated mountain ranges and depressions, have severely overprinted the entire region making an assessment of the make-up of "Tethyan" age basins a challenge. With an extensive data set in Syria, this paper describes the older stratigraphic and structural make-up of the Palmyride Trough then demonstrates, with public domain information, that this trough was simply the northeast extension of a much greater Levant Trough that covered the full extent of the Eastern Mediterranean.

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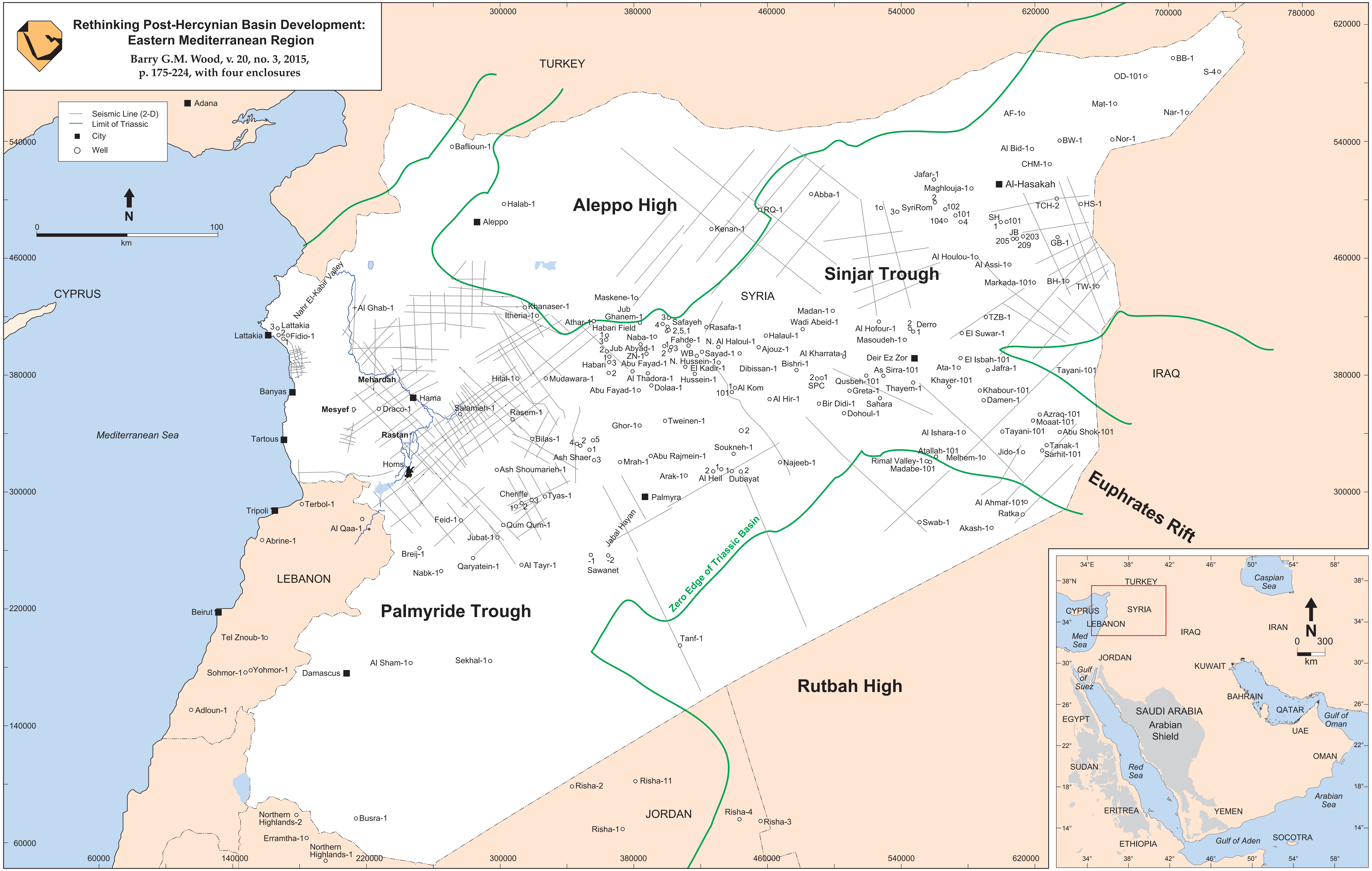

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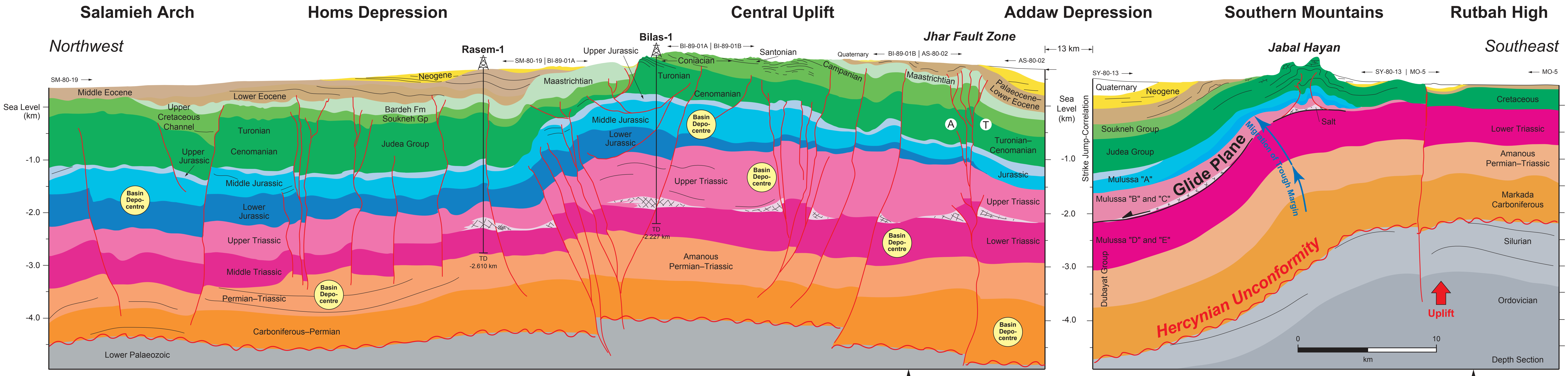
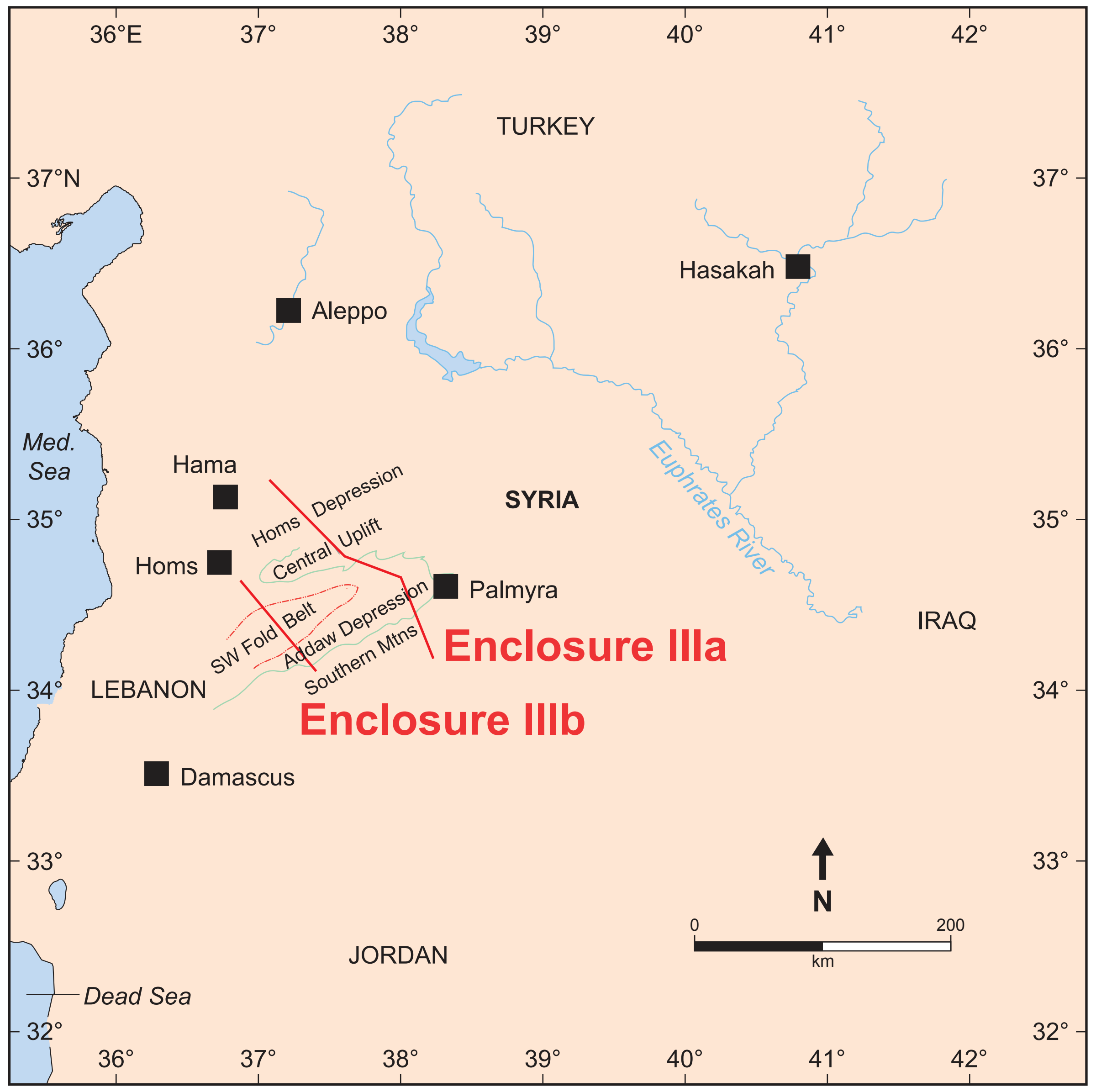
ENCLOSURE III

Enclosure IIIa





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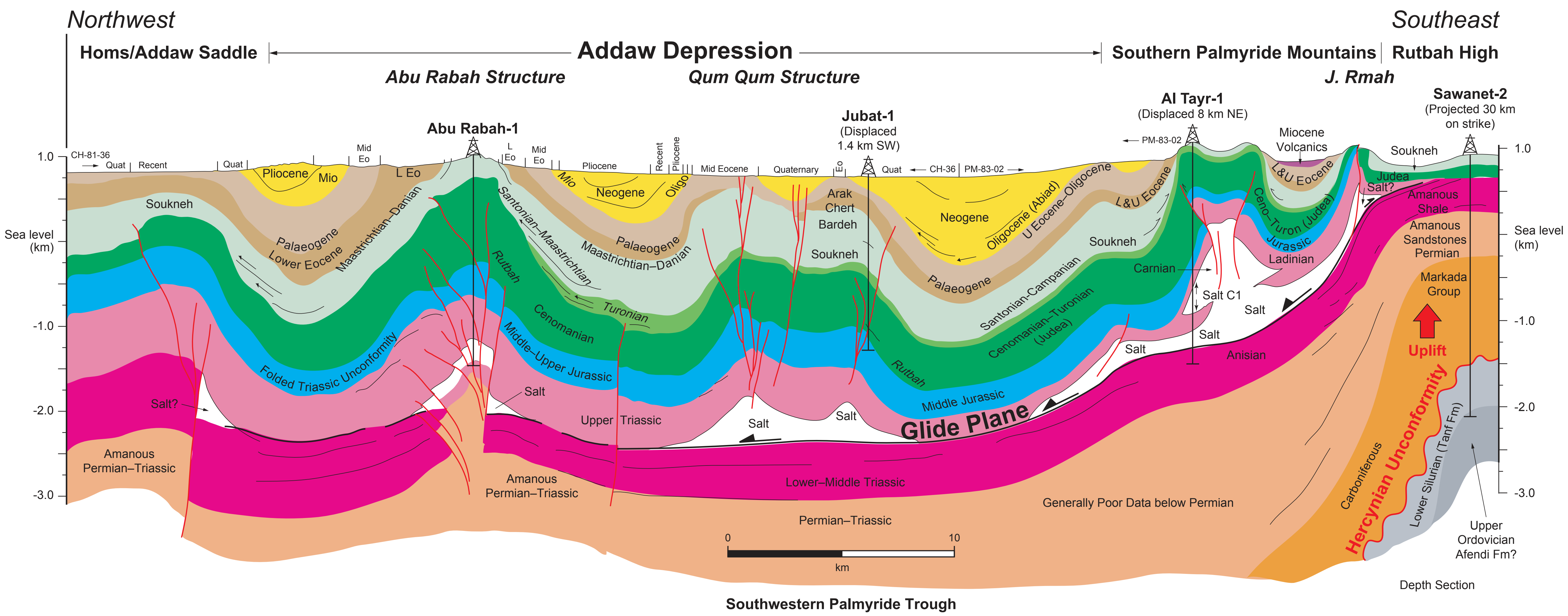
Enclosure IIIb



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ENCLOSURE IV

Rethinking Post-Hercynian Basin Development: Eastern Mediterranean Region

Barry G.M. Wood, v. 20, no. 3, 2015,
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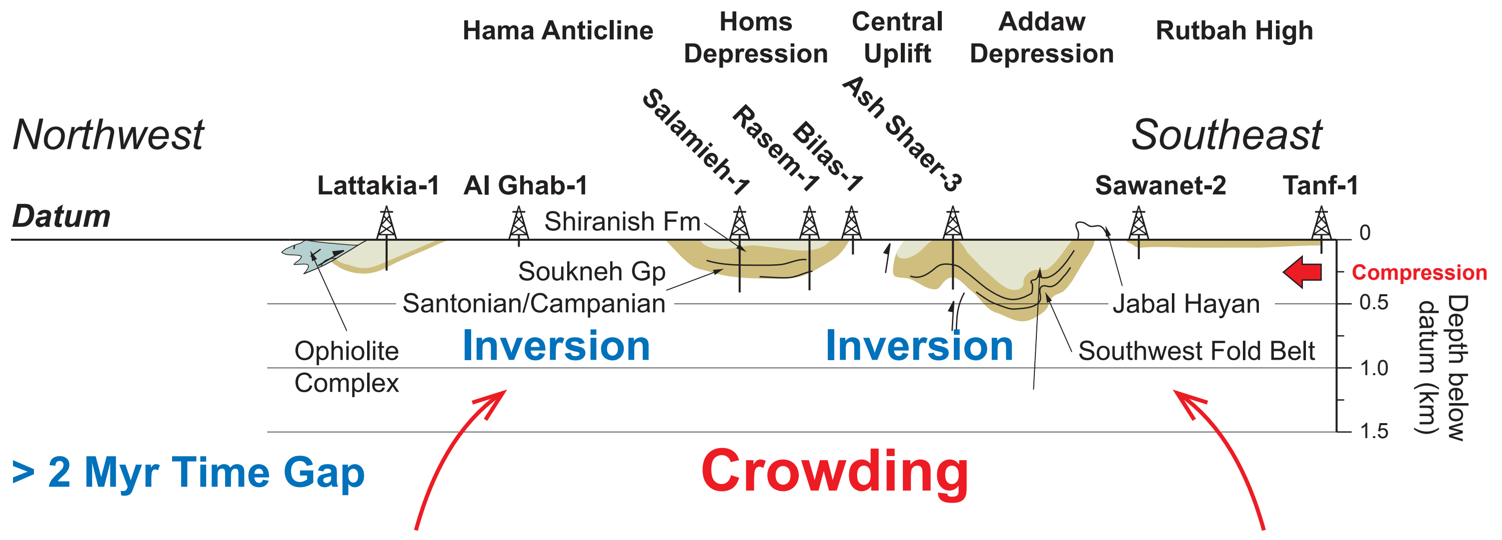
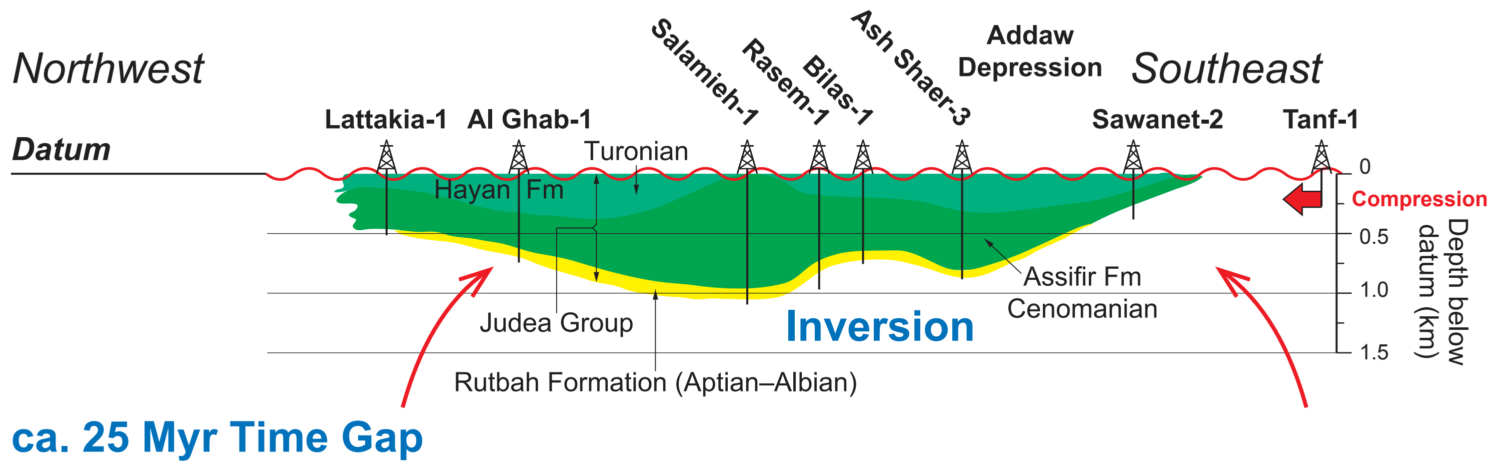
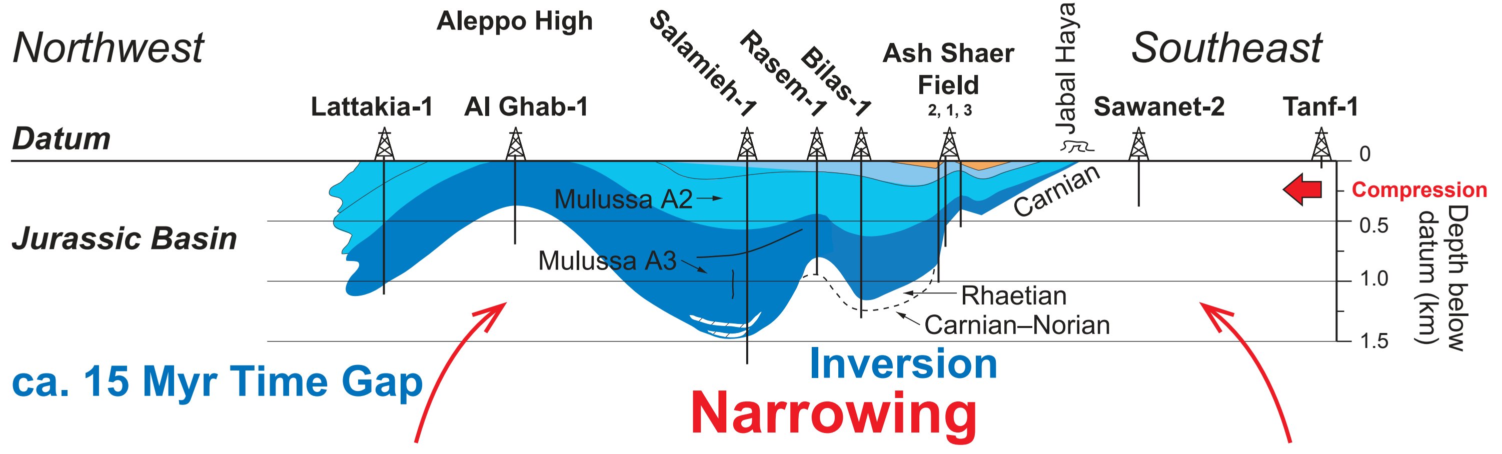
(a) Datum at Top Maastrichtian



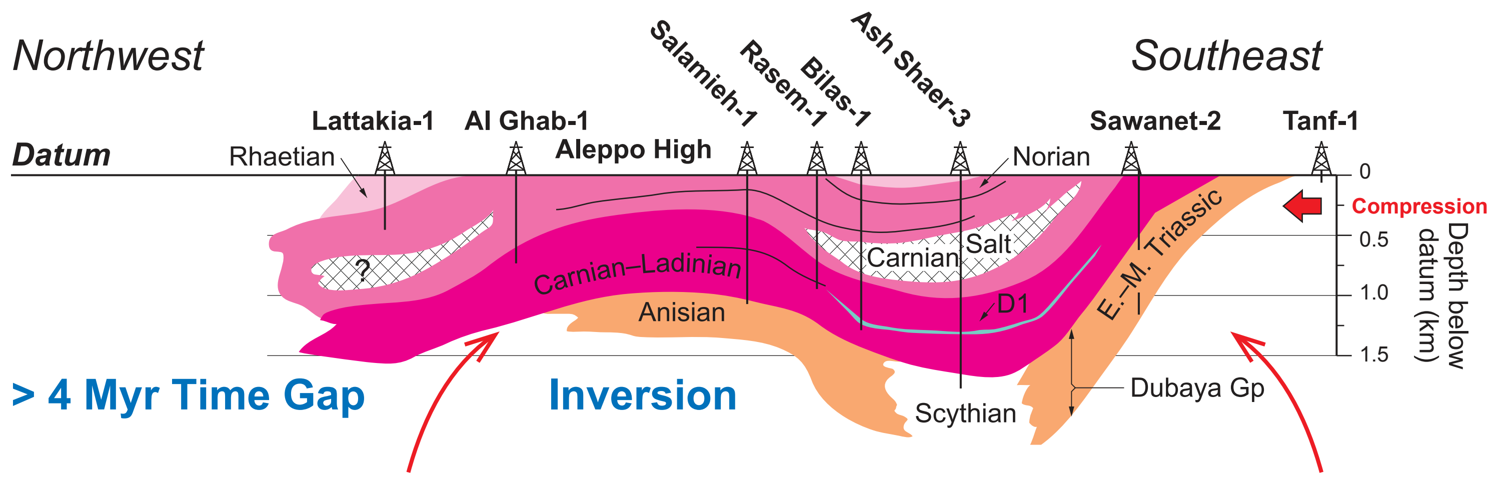
(b) Datum at Late Turonian Unconformity



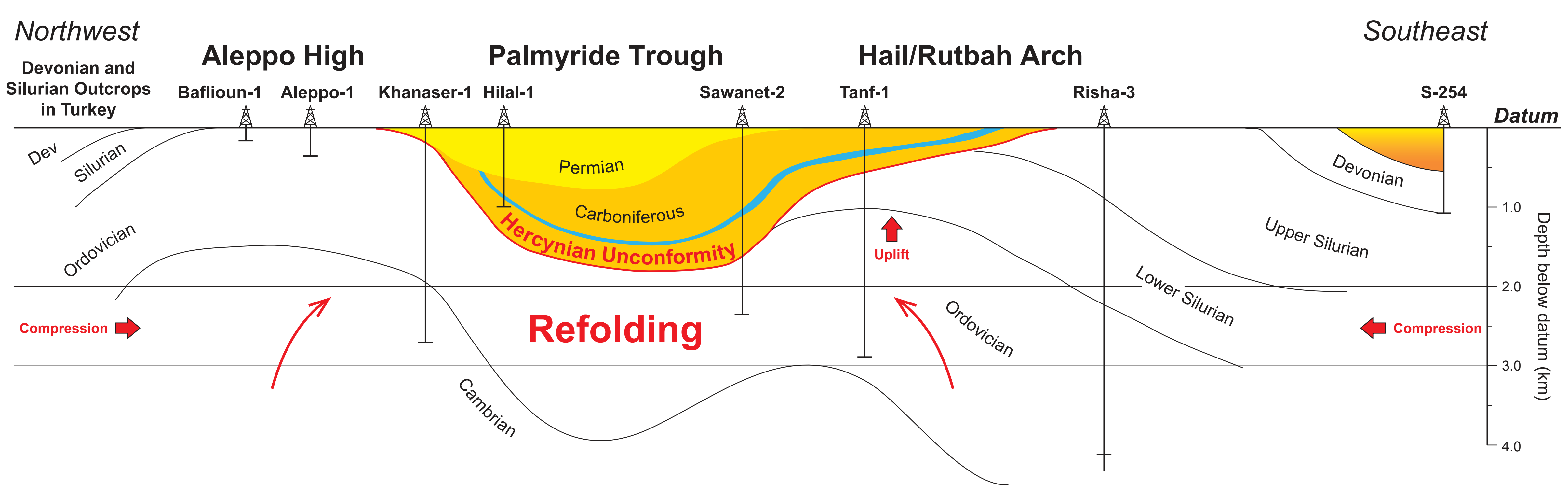
(c) Datum at Top Jurassic



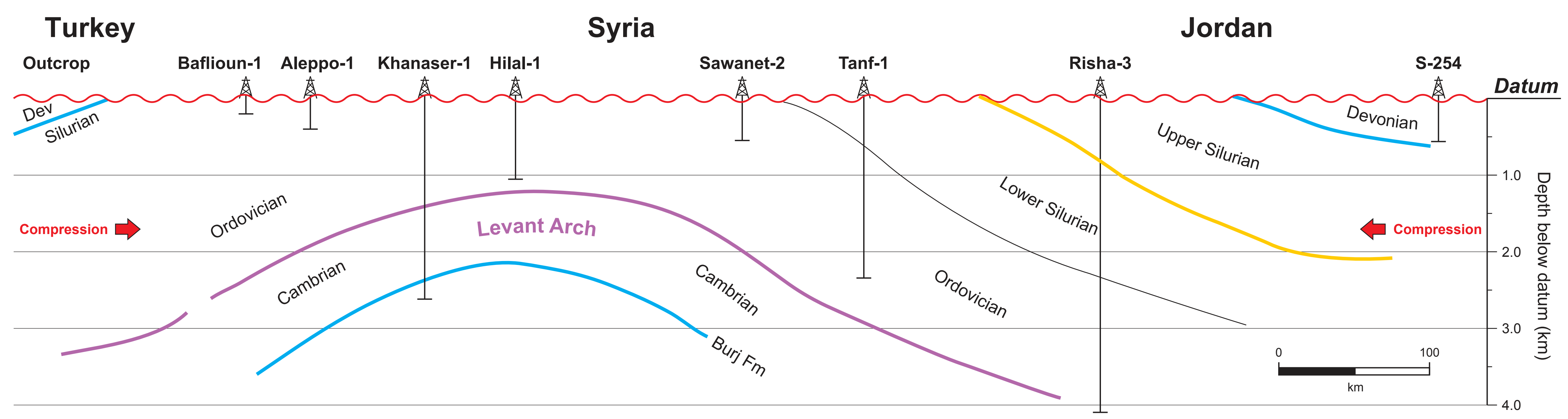
(d) Datum at Top Triassic

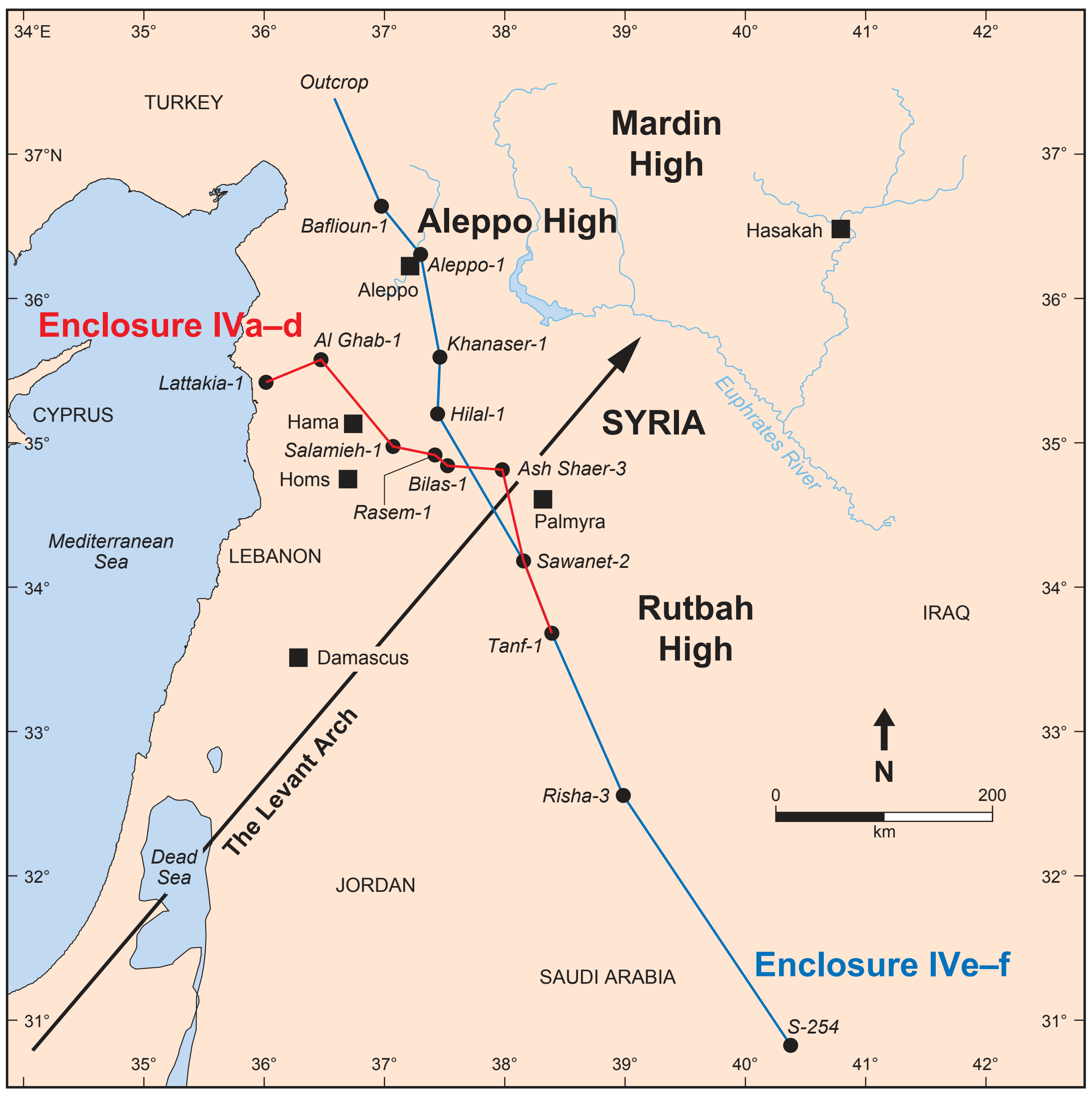


(e) Datum at Top Palaeozoic



(f) Datum at Hercynian Unconformity





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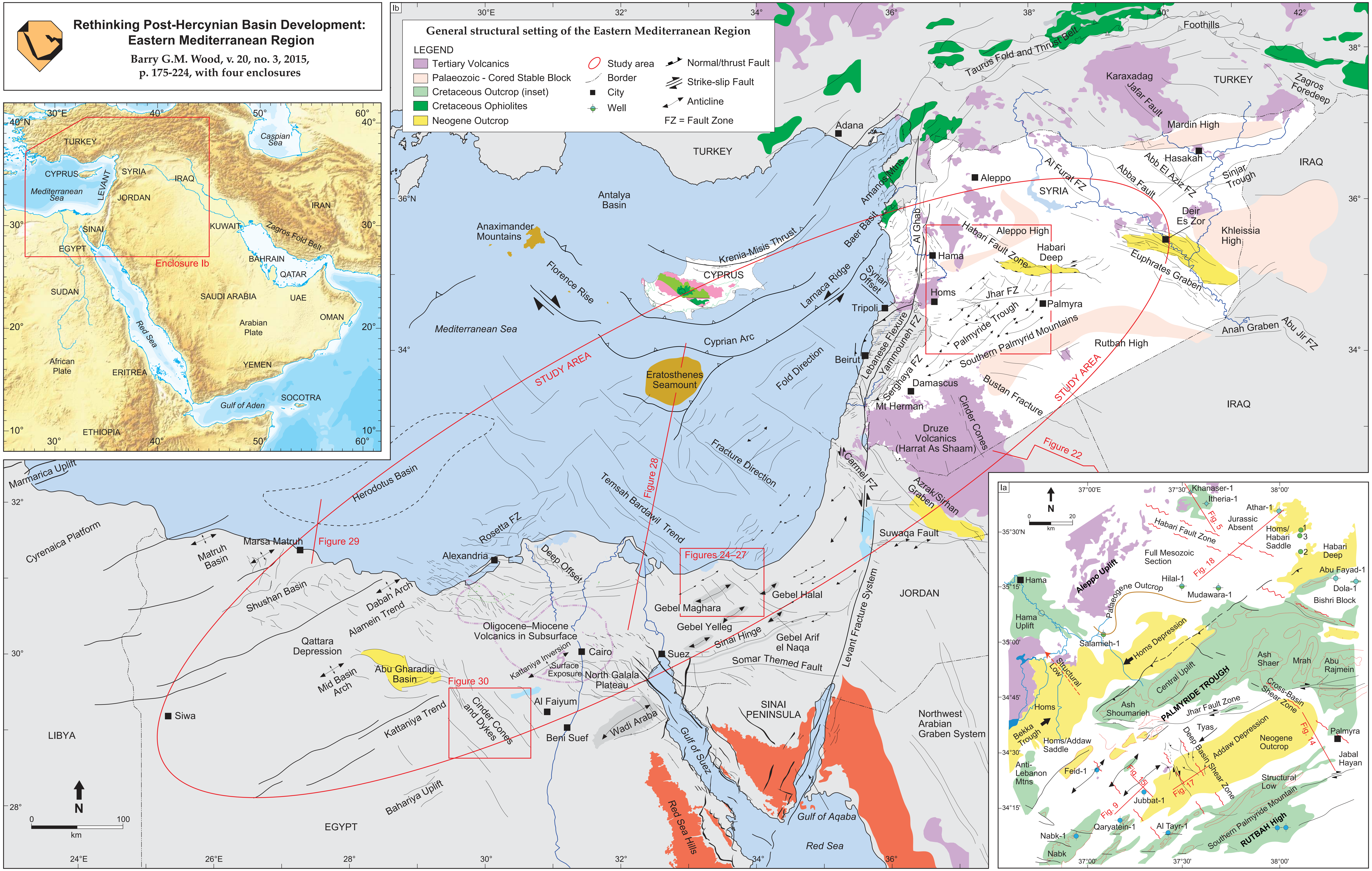

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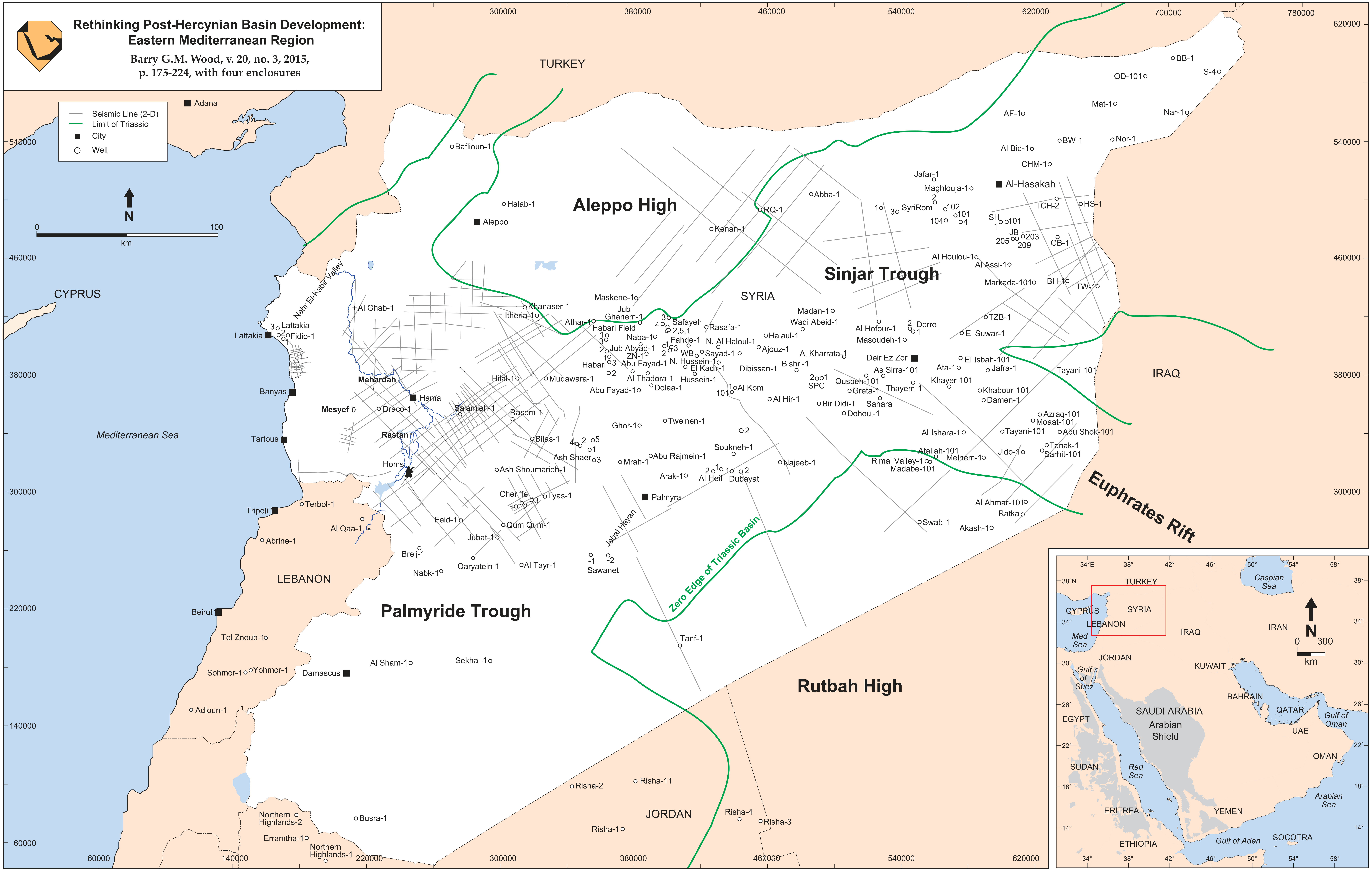

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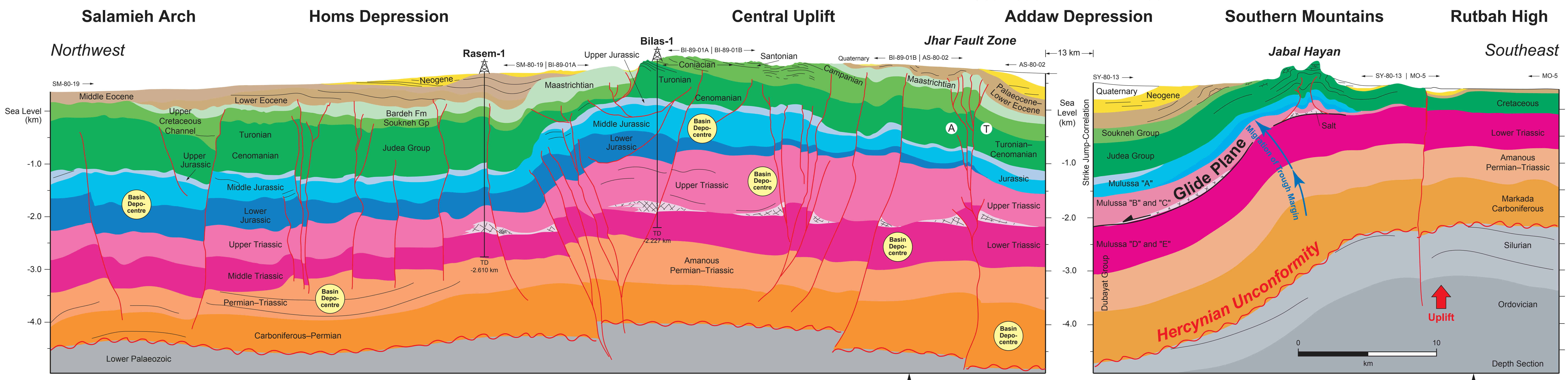
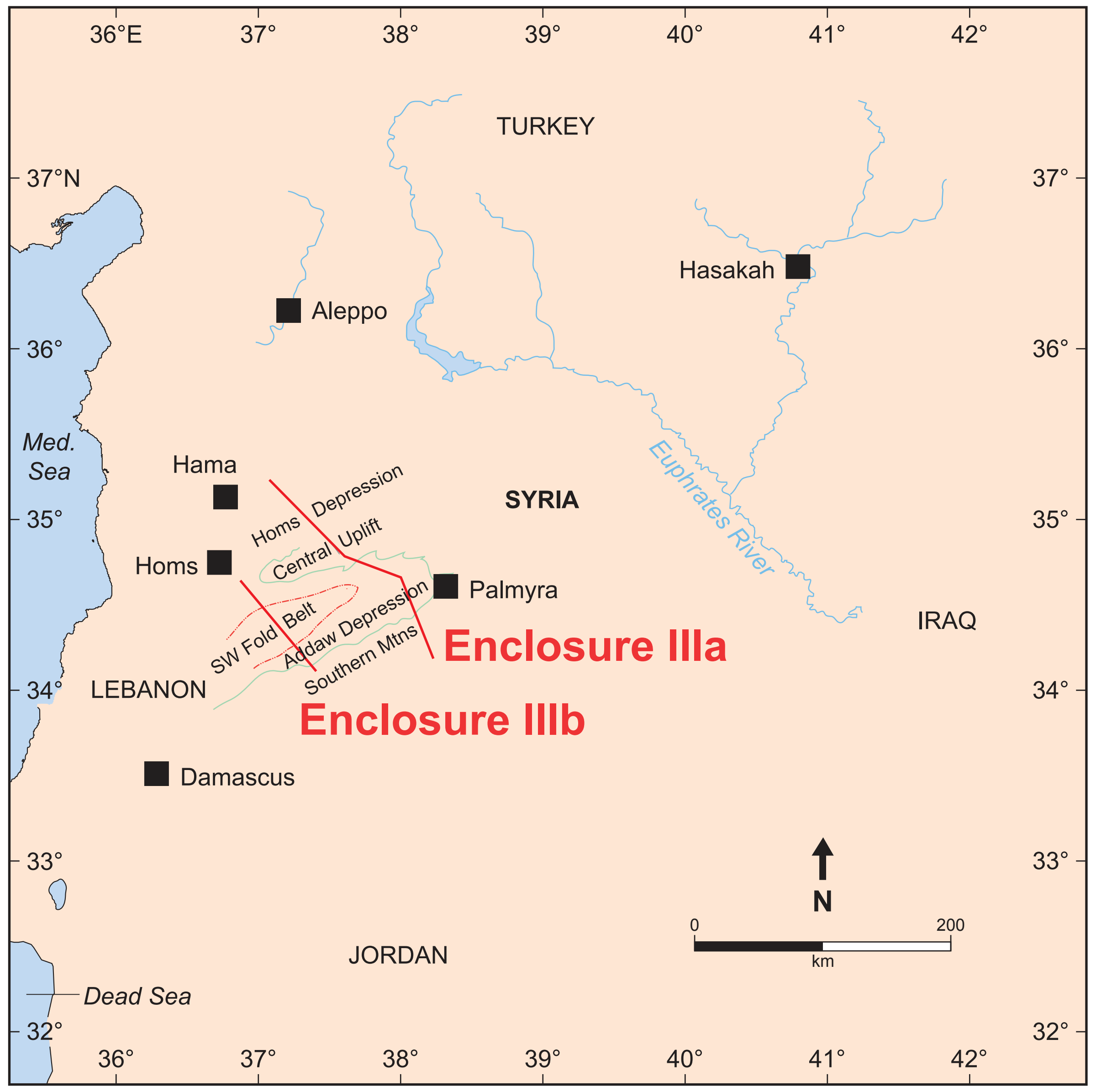
ENCLOSURE III

Enclosure IIIa





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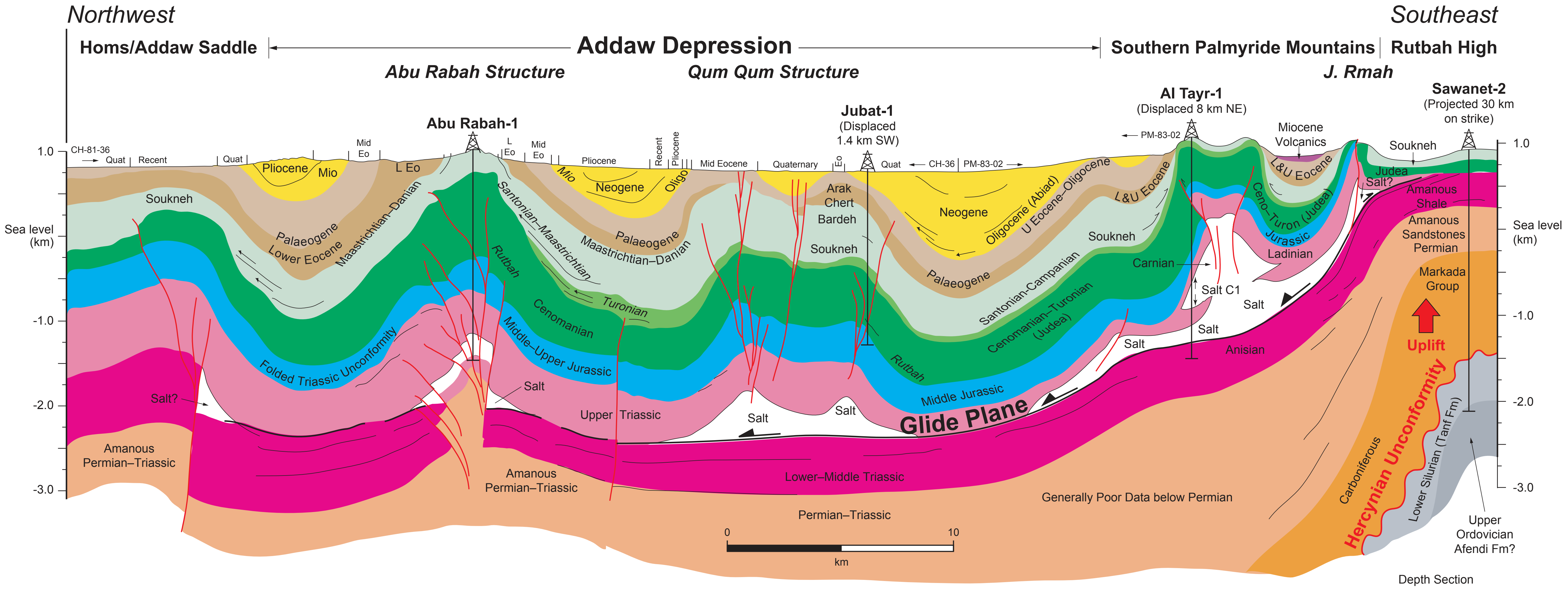

Southwestern Palmyride Trough

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ENCLOSURE IV

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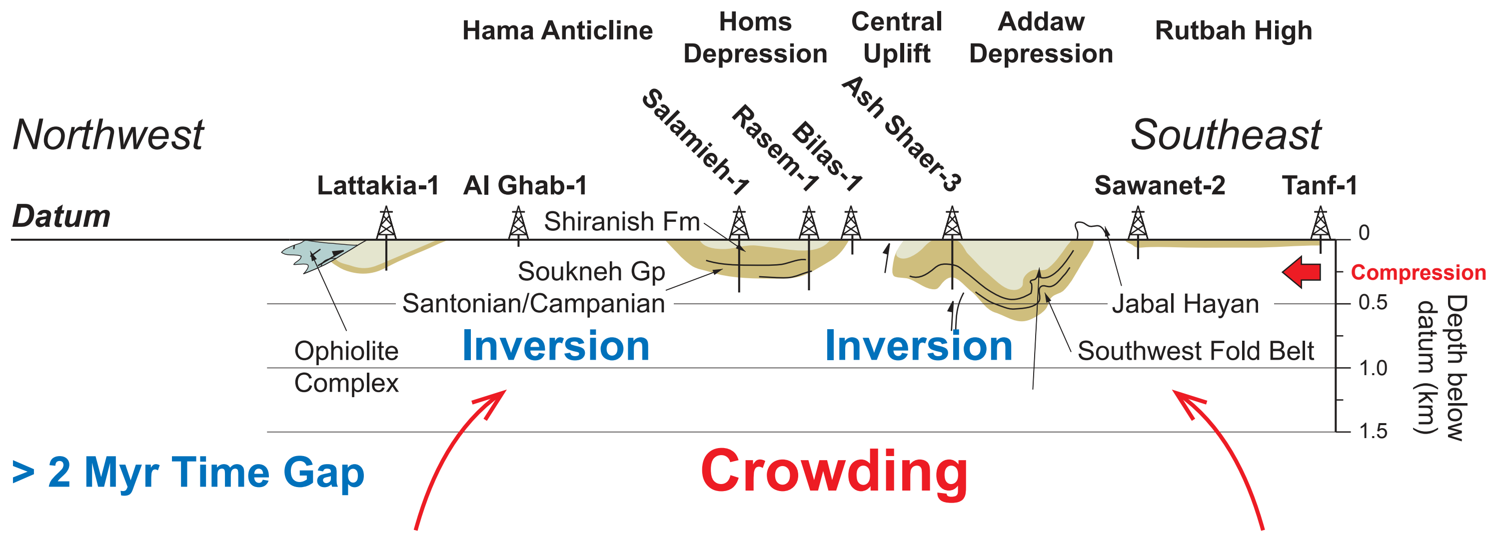

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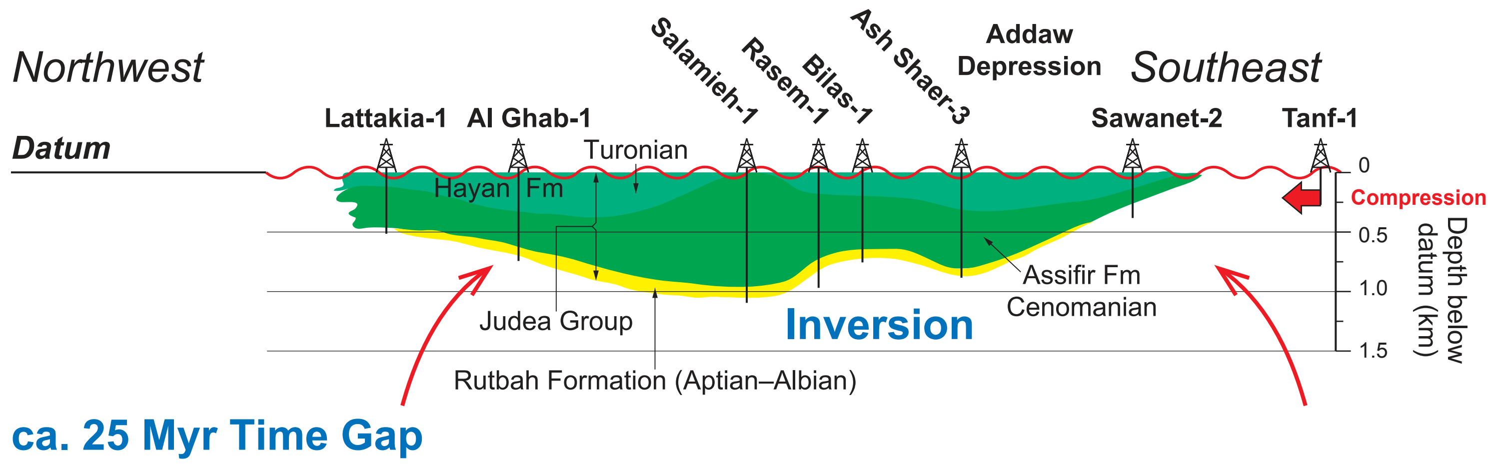

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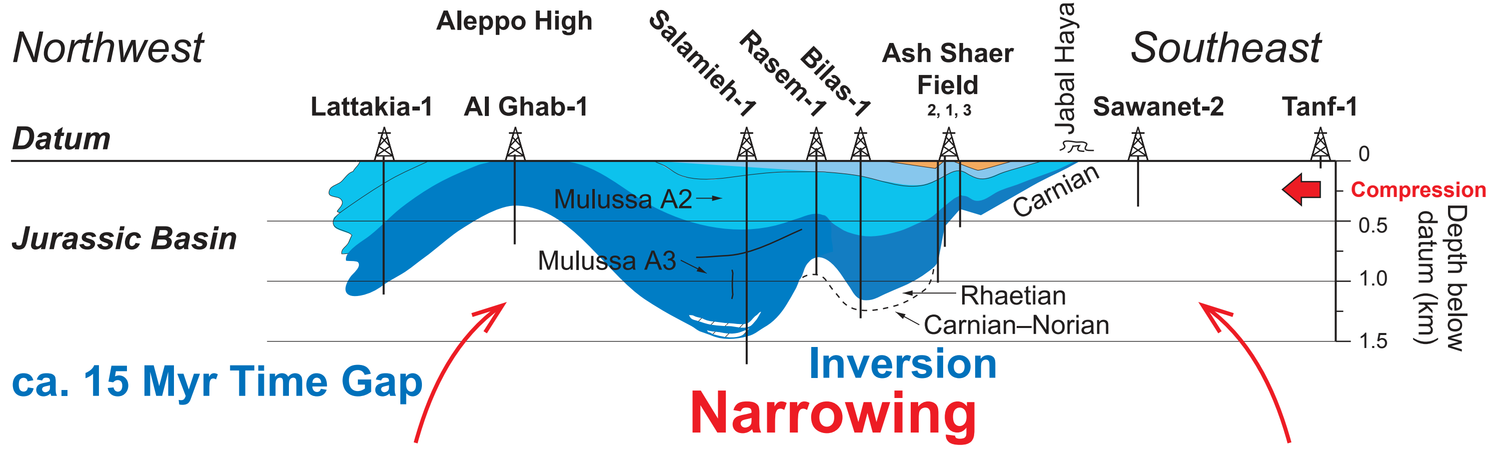

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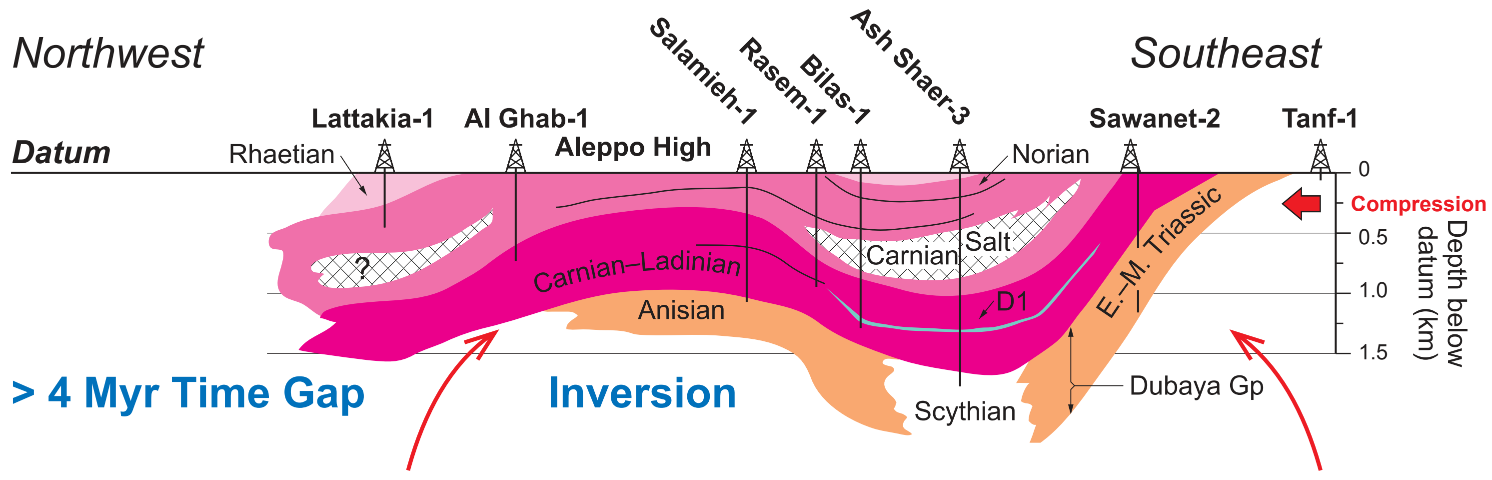

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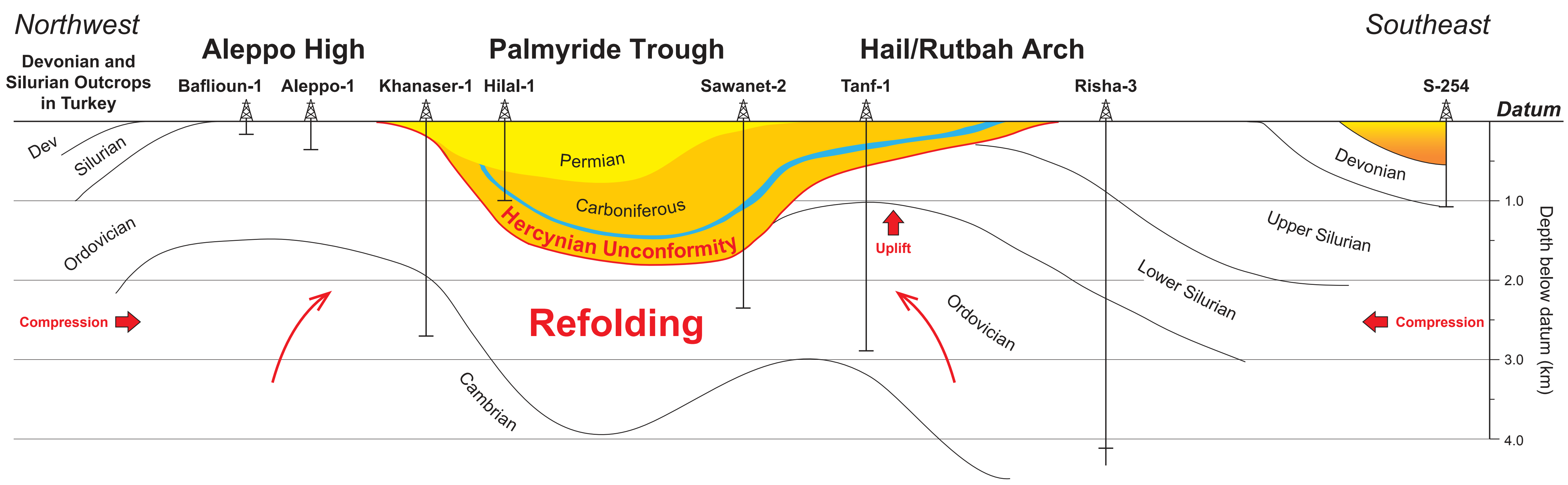

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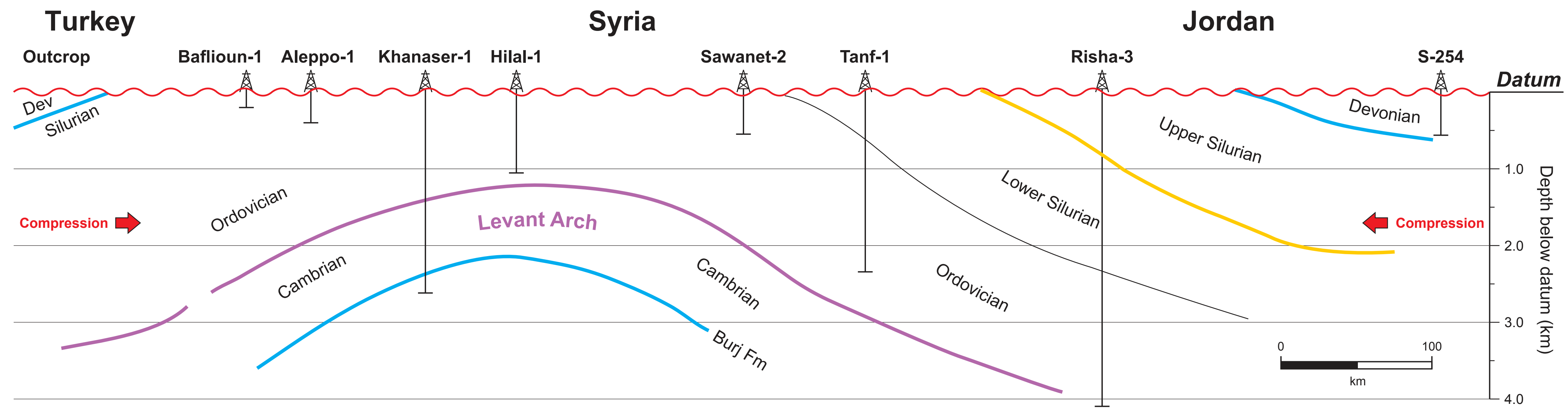

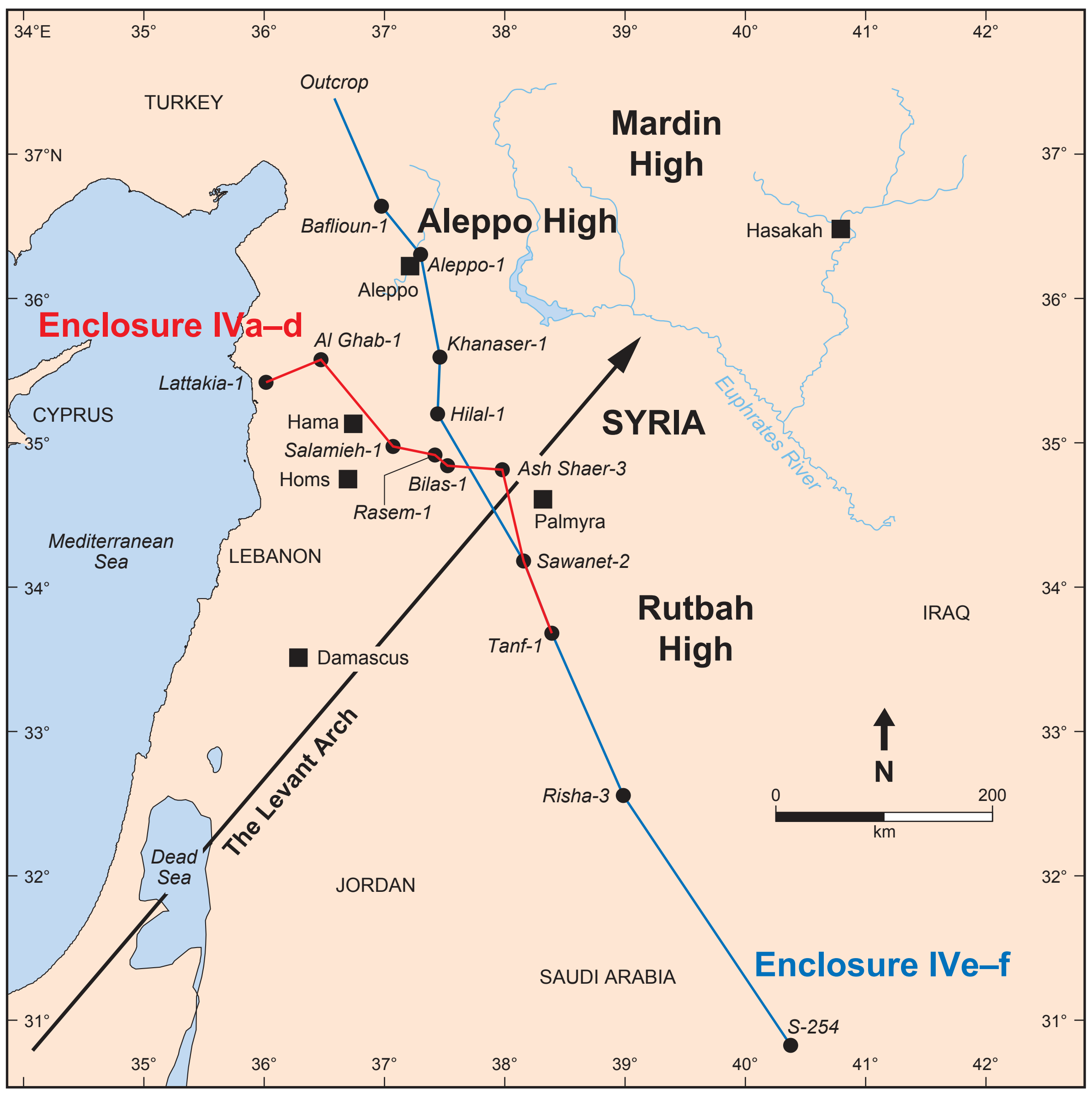

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